# CEN WORKSHOP AGREEMENT

# CWA 17453

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# Bionic Aircraft - Optimized ALM support structures made from Al alloys

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# European foreword

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The research leading to these results has funding from the European Union's HORIZON 2020 Programme under the grant agreement numbers 690689 (Bionic Aircraft).

The final text of CWA 17453 was submitted to CEN for publication on 2019-07-19. It was developed and approved by:

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# Introduction

The goal of the present investigation was to optimize support structures in Laser beam melting of metals and provide yet missing design guidelines for support generation. The latter then set the framework for automated support generation within pre-processing tools for additive manufacturing (AM), which is crucial to speed up the data preparation and pave the way for industrialization of the AM technology for metal parts. Adequate application of supports increases the productivity by preventing build job failures and is one key factor to ensure a reproducible part quality. The research approach aims at an optimization by adequate selection of various support types rather than a parameter optimization of those. Herefore five different support types in total have been chosen and characterized with regard to various target figures: Material consumption, removability and tensile strength of the supports themselves, as well as surface influence on and dimensional accuracy of the supported part. Additionally, novel biomimetic support structures have been developed and tested for material consumption and removability.

Results reveal that proper selection of supports can greatly reduce post processing effort regarding removability of supports and overall material consumption, while the post processing effort for surface finishing is not positively affected. The novel biomimetic support structures show promising results considering material consumption and removability and will therefore be further investigated.

This document represents part of the work as performed in Task 'Integration of ALM pre-processor in commercial 3D-CAD software' of WP3'Bionic Design & Optimization'. In the scope of the respective WP3 the design process of parts for additive manufacturing, and more specifically laser beam melting, should be simplified and shortened by developing a software toolkit. This tool comprises all necessary functionalities to achieve a final part design that is Additive Manufacturing (AM-) suitable and allows the needed data preparation in order to obtain an output file that can directly be processed by the AM machine.

This document displays the currently available support structures in laser beam melting (LBM) for metal parts. The need for optimized support structures will be shown with regard to the criteria and requirements that apply. Furthermore, the chosen approaches for achieving optimized support structures are laid out.

# 1 Scope

This document provides a mutual international understanding of optimized support structures in the laser beam melting of Al alloys. It provides the missing design guidelines for the choice of adequate support types for different use cases. Therefore, five different support types in total have been chosen and characterized regarding various target figures: Material consumption, removability and tensile strength of the supports themselves, as well as surface influence on and dimensional accuracy of the supported part. Additionally, novel biomimetic support types have been developed and tested for material consumption and removability, showing great potential for further optimization.

Adequate application of supports increases the productivity by preventing build job failures and is one key factor to ensure a reproducible part quality. The novel biomimetic support structures show promising results considering material consumption and removability.

# 2 Normative references

There are no normative references in this document.

# 3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

# 4 General approach

## 4.1 General

The respective research method and results are described and summarized in a proposal for optimized support structures.

## 4.2 Needs and functions of support structures in metal LBM

Support structures are separate structures that are only needed throughout the build job process itself to ensure a stable buildup. They do not belong to the actual part and therefore need to be removed once the part has been manufactured. In metal laser beam melting (LBM) the use of so called support structures becomes necessary for several reasons: On the one hand, they need to compensate mechanical loads and fixate the part on the platform. On the other hand they need to dissipate process heat in order to prevent deformations (refer to TÖPPEL ET AL. 2016). Next to these major functions of support structures there are other requirements posed from a manufacturing point of view: Production time, the amount of material necessary for supports (including possibly enclosed powder) and how to build and remove the support structures (PIILI & SALMINEN 2014).

## 4.3 Currently used support structures and their downsides

When it comes to data preparation in additive manufacturing there are a few software providers that dominate the market: Materialise, Autodesk, Dassault Systemes and Siemens. Out of these Materialise's software package *Magics* offers the most elaborate choice of support types and adaption of these, which is the reason why the present study has been done based on supports available in *Materialise Magics*.

The most commonly used support type at the moment is the so called block support. It is made of a network of single track walls that are attached to the part and/or platform by teeth like connection features. The major variations that come along with this support type are the possibility to fragmentise and perforate the support structure, both aiming at a better removability of the support itself as well as of the enclosed powder. Other, rather established support types are the pin and gusset support (Figure 1). Additionally there is always the option of using a solid volume as supporting structure, but since this can be viewed as an integral feature of the part itself rather than a separate support structure, it has been decided to exclude volume supports from the given investigation.

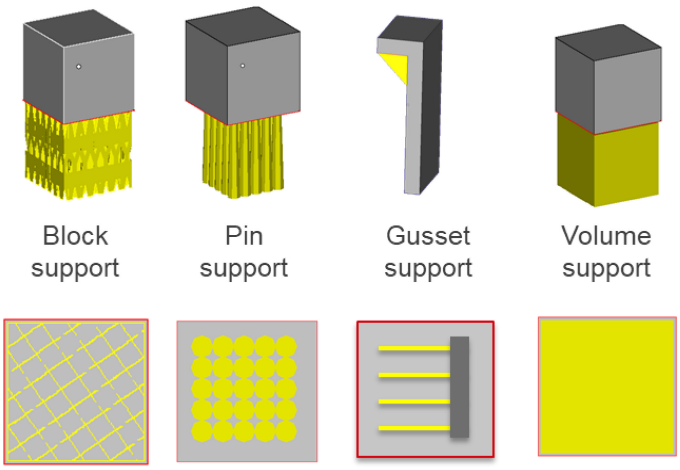



**Figure 1 — Commonly used support types (Top row, supports marked in yellow as available in Materialise Magics) and their respective cross section (bottom row)**

Only a few studies have been done on the appropriate use and optimization of support structures (e.g. CALIGNANO 2014, ZENG 2015, KROL et al. 2011) and hence the use of support structures is rather based on experience and best practice than on scientific fundamentals. For this reason there are several downsides to the currently used supports that should be addressed: In general, support structures that possess a large contact area to the main part are difficult to remove and it might damage the part surface after removal, leaving a bad surface quality (PIILI & SALMINEN 2014). Furthermore large amounts of support for delicate parts would increase the difficulties and time of support removal, causing small pieces of the part to break off. Additionally the commonly used block support has been criticized for trapping raw loose powder within the support structure during the build process (HUSSEIN ET AL. 2013). So from a manufacturing point of view removability of the support structures from the part, removability of the lose powder from the support structures and surface influence on the supported part need to be investigated. Overall a minimum amount of support structures and prevention of stress-induced deformations is desirable.

When it comes to support generation the software *Magics* is offering the option to display surfaces that need support structures according to the given material and its critical overhang angle. The adequate support type itself needs to be chosen manually, though. This approach mainly focuses on one of the functions that supports have, which is the actual supporting of overhanging surfaces. It does not consider the second major function of heat transport. This would be necessary however to guarantee the dimensional accuracy of the final part and prevent deformations due to residual stresses throughout the building process. Support generation itself as by nowadays standards is a highly complex and time-consuming part of the data preparation.

# 5 Research approach

## 5.1 Aim of the work

Laser beam melting (LBM) poses new possibilities but at the same time new challenges on part design and data preparation. Among them the need for support structures with multiple functions as outlined in the introduction.

As opposed to the design process for LBM parts for which design guidelines have been developed and formulated there are no guidelines available on how to apply support structures. Due to the lack of guidelines, support structures are inserted based on experience and knowledge of the designer. Since there is a tendency of LBM parts to become more complex the prediction of an adequate support strategy is increasingly challenging. Therefore, the need for design guidelines grows in order to avoid fabrication failures. The proper choice of support structures is a rather complex task, for which reason the need for software solutions aiding in this task is highly beneficial. The ultimate goal is to get away from a try and error approach and move towards automated generation of support structures based on guidelines that take complex and individual requirements of each part design into consideration. This will significantly accelerate the data preparation, which is highly time consuming due to the manual support generation as pointed out before.

## 5.2 Optimization approach

Different types of optimization are possible in the case of support structures. First of all even before supports are being generated the part design itself could be optimized (especially with regard to its orientation) in order to minimize the needed support amount. The focus in the given investigation, though, lies on the support structures themselves and hence the part design including the orientation is taken as given and sets the frame for the respective support optimization.

The latter offers four different options:

- Parameter optimization of existing support features
- Process parameter optimization for manufacturing of supports
- Choice optimization of adequate support types
- Support structure design optimization

Parameter optimization of given support features intends to alter the available feature parameters of existing support types (Figure 2). In order to find out about optimal sets of parameters and correlations between single parameters and the final part quality a full factorial test procedure is required. This represents a high experimental effort while at the same time only minor improvements of the support structure performance are the expected outcome.

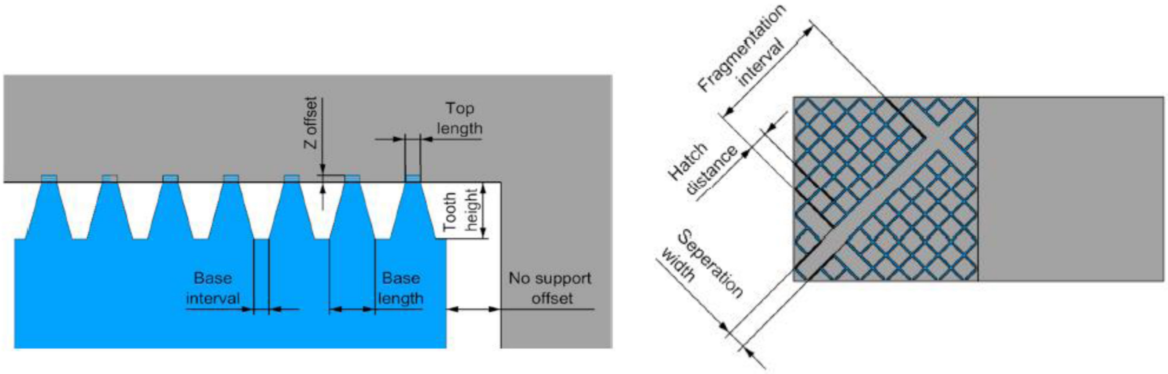



**Figure 2 — Support feature parameters of a standard block support as available in Materialise Magics Software (adapted after POYRAZ ET AL. 2015)**

Process parameter optimization describes the approach of altering process parameters like laser power and velocity in order to achieve a more reproducible manufacturing result of the support structures themselves and increase the attachment strength with the part. Again, this requires a high experimental effort while only a medium optimization outcome is expected.

Contrary to the first two options the optimization of choice of support types offers high potential regarding the proper fulfilment of support functions while the experimental demand is moderate. The optimization by appropriate choice of support types requires design guidelines for supports on which the selection can be based. A variety of different support types is already offered by *Materialise Magics* (Figure 3).

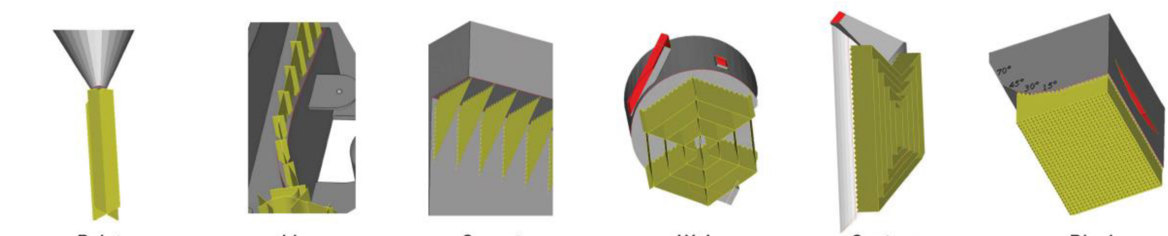



**Figure 3 — Excerpt of different support types available in Materialise Magics software (SOURCE: Materialise)**

The last option of optimizing the support structure design itself, which will lead to novel support structures, allows designing towards the function of supports. It can be done at medium experimental cost and has therefore been pursued together with the optimization through choice of support types. In a few other research articles, the great potential of newly designed support structures has been pointed out (e.g. HUSSEIN ET AL. 2013). However, in the given investigation biomimetics has been chosen as a method to generate novel support structures.

## 5.3 Characterization of standard support structures

### 5.3.1 Selection of standard support types

For the characterization of different support types, the most relevant support types that are well established, broadly used and therefore can be considered as “standard” support types were chosen. The selection has been based on experience of designers within the additive manufacturing field since no real standards are available yet. For supporting overhanging surfaces the block support and variations of it are commonly used. Therefore, a block support with an established set of feature parameters has been chosen. In addition, the two main variations of high fragmentation (intending to increase removability of supports) and high perforation (intending to increase removability of powder) have been added. For parts that are expected to evoke high tensional stresses throughout the build process, the so called pin or conus support type is widely used. A rather uncommon support type which is nevertheless worth investigating is a mixture two common support types: block and gusset support. Overall five different support types (Figure 4) have been selected for characterization.

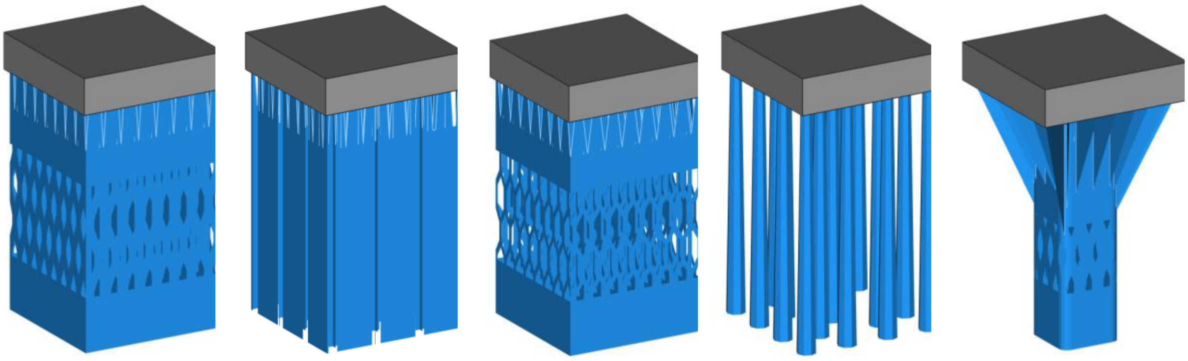


**Figure 4 — Types of investigated support structures (From left to right; Standard block -, Fragmented block -, Perforated block -, Cone- and Block Gusset-support)**

### 5.3.2 Criteria for characterization

In order to characterize the selected support types five different criteria have been chosen as follows:

- Material consumption
- Dimensional Accuracy
- Surface influence
- Removability
- Tensile Strength

All of them except for the tensile strength criteria are directly linked with the desired functions of supports:

— Low material consumption

— High dimensional accuracy

— Minimum surface influence, and

— Easy removability

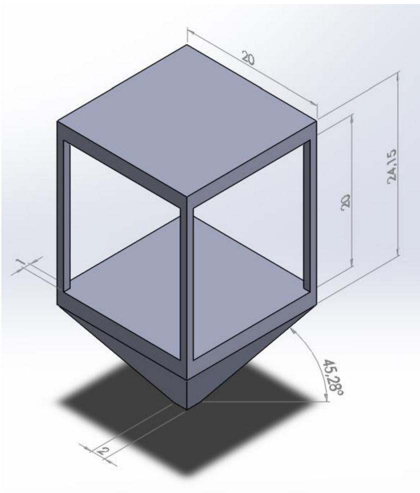
The function of compensating tensile loads during the build process is especially important for materials that induce high residual stresses, e.g. titanium alloys. At the moment there are only a few simulation tools available that can predict deformations throughout the build process. These results are required in order to adjust support structures accordingly. Once the quantity of tensile stresses that will occur during the build job is predictable the assignment of proper support structures is possible. In preparation for this task, the selected support types have been characterized with regard to their specific tensile strength. This will allow choosing the appropriate support type with regard to tensile load compensation in the future.

### 5.3.3 Definition and fabrication of test specimen

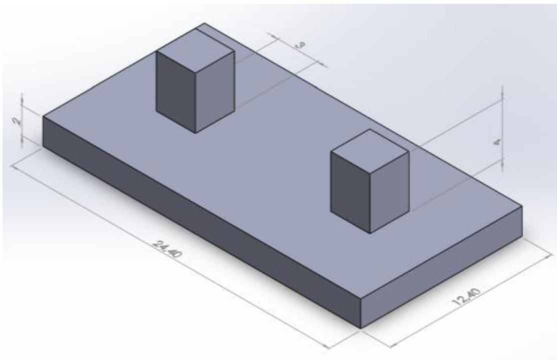
#### 5.3.3.1 Test specimen

Various test specimens have been designed in order to characterize support types according to the selected criteria. Each of the test specimens have then been supported with the different support types. All surfaces that fall below the pre-set critical angle of 40° have been assigned with support of the respective support type.

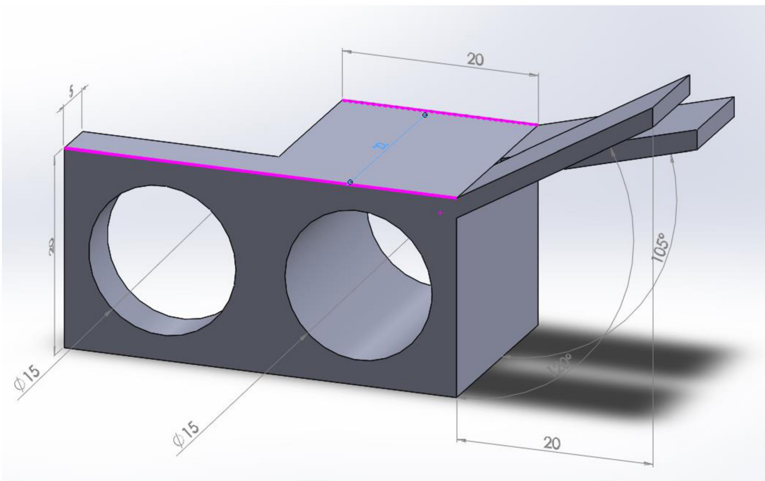
All measurements are given in mm




a)




b)

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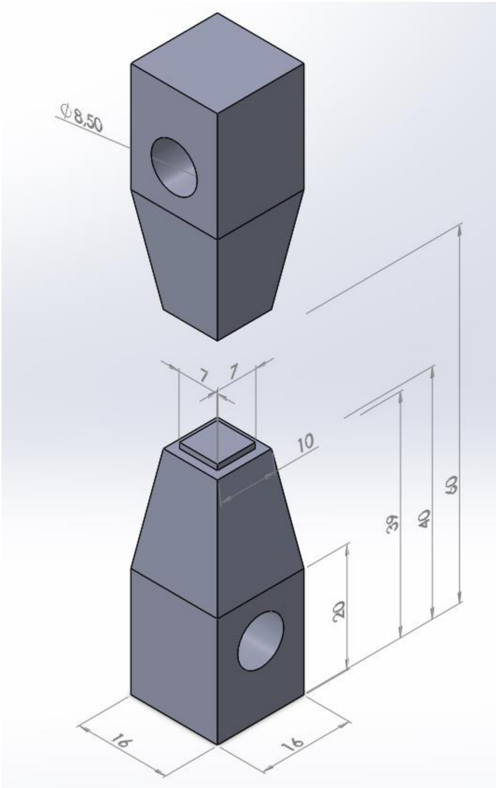



d)

**Figure 5 — Test specimen for different characterization criteria - Test specimen (a) has been chosen to quantify material consumption, test specimen (b) has been chosen to quantify surface influence, test specimen (c) has been utilized to quantify removability and dimensional accuracy and test specimen (d) offered quantification of tensile strength**

Figure 6 shows the specimens used for the investigations including the standard block support structure.

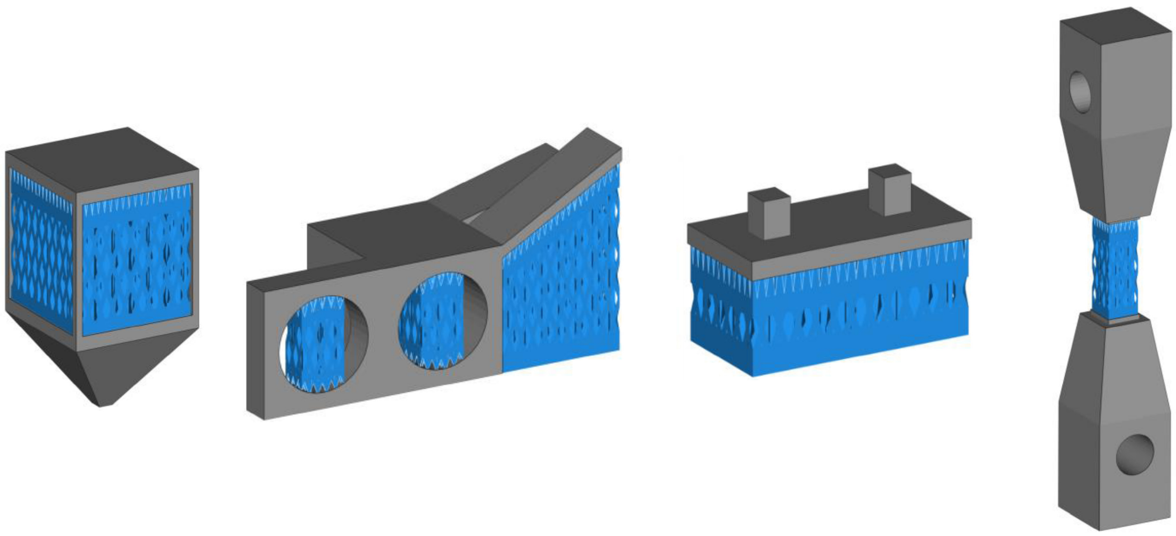


**Figure 6 — Specimens including support structure**

#### 5.3.3.2 Material

The chosen material was the aluminium alloy AlSi10Mg which represents a standard alloy for LBM.

#### 5.3.3.3 LBM Machine

Test specimen have been manufactured on an EOS M290 machine, which has a maximum laser power of 400 W and a build chamber size of 250 × 250 × 325 $mm^3$.

#### 5.3.3.4 LBM Process parameters

Laser power has been set to 370 W and scan speed to 1 300 m/s. This combination of process parameters has proven to produce robust part qualities in the past.

#### 5.3.3.5 Post treatment

Test specimen (b) and (c) that have been characterized for removability and surface influence after removal have been heat treated for stress relief following a specific time table: 2 hours at 300°. All other test specimens have not undergone a specific post treatment and have further been tested as built.

### 5.3.4 Measurement and evaluation methods

#### 5.3.4.1 Material consumption

Five test specimens per support type have been manufactured. Upon finishing of the build job they have been cleared off powder using the EOS M290 built in suction device. Within the build chamber the build platform with test specimen still attached has been turned sideways on all four sides and remaining loose powder has been cleared by knocking the platform with a rubber mallet. Afterwards test specimens have been clipped from build platform (outside the building chamber) using a gripper.

Evaluation of material consumption was based on weight measurements. The mass of test specimen including remaining loose powder and supports and the mass of test specimen without supports have been determined. Support structures themselves have then be weighed separately. The precision scale AUW 220D from the company Shimadzu has been used for weight measurements.

Actual material consumption of a specific support type has been defined as follows:

The difference in mass between test specimen including supports plus remaining powder and test specimen without support and powder.

We further distinguished actual material consumption into material consumption of the support structure itself and enclosed waste powder by subtracting the mass of supports themselves from the actual material consumption. Since a comparison of material consumption of the various support types in relation to the standard block support is of interest, the actual material consumption of the block support has been chosen as the reference material consumption and represents 100 %. The other support types' material consumption has then been determined as a percentage of the reference consumption. Measurements have then been averaged per support type (n = 5).

#### 5.3.4.2 Removability

Three test specimens per support type have been manufactured. After the stress relieving heat treatment, supports were removed and the time as well as level of difficulty for removal have been recorded. Time recording was started as soon as the tools were picked up and stopped as soon as all supports had been removed completely. To allow more consistency support removal has been performed by the same person. The tools that were used are hammer and chisel or hammer and drift pin (refer to results).

The level of difficulty for removal has been defined by four categories (see Table 1). Level of difficulty for removal was evaluated by the person removing supports and assigned accordingly. The average time and level of difficulty for removal has then been calculated (n = 3).

**Table 1 — Definition of categories for different levels of difficulty regarding support removal**

| Level of Difficulty for Removal | Definition |
|---|---|
| 1 | Very easy to remove, (almost) no resistance |
| 2 | Some resistance present, but still easily removable |
| 3 | Higher resistance, but removable |
| 4 | Very high resistance, no removal possible or extremely hard to remove |

#### 5.3.4.3 Surface Influence

Three test specimens per support type have been built (Block support + high perforation has been left out, since due to the same attachment to the surface as for the block support, no difference in the surface influence is expected). After test specimens have been heat treated for stress relief, support structures have been removed using hammer and chisel. After support removal an area of approximately 2,5 mm² × 3,5 mm² has been scanned using a Keyence microscope VK-8710. Based on different focal levels an image of the surface topology has been generated. Then the area is divided into six sectors and the values for the average arithmetic height ($S_a$) and maximum height ($S_Z$) were determined for each. Each of these roughness values has been averaged per support type (n = 3).

#### 5.3.4.4 Dimensional Accuracy

For the dimensional accuracy the test specimens for quantifying removability have been optically scanned using (Wenzel LH87 with Shape tracer and an overall measuring accuracy of 0,035 mm for each measuring point). Since the overhanging surfaces tended to break apart or were significantly deformed during removal of supports, dimensional accuracy was evaluated based on the final dimensions of the flat and deep bore hole. A 2D scan of the front surface of the bore holes has been generated before and once again after support removal. The resulting point cloud was then transformed into a surface model by means of reverse engineering (Software Pointmaster 5.5.3). Using the software tool Gom Inspect (with Inspection Kernel GOM v2.0.1) the nominal diameter was compared to the biggest diameter (diameter of envelope circle) present in the test specimen as build. The actual diameter were then averaged (n = 3) and compared with the nominal diameter.

#### 5.3.4.5 Tensile Strength

Six test specimens have been manufactured per support type, in addition two more variations have been added to the block support: standard block support + increased top length and standard block support + z-offset value. These adaptions are aiming at an increased attachment to the part itself and are therefore expected to have a higher tensile strength. Tensile test specimens were cleared off supports that only aided in building the specimen throughout the build job. Tensile tests were then performed on a testing machine of the ZMART.PRO series from the Zwick/Roell AG. Using the software testXpertII the displacement and corresponding tensile force during the tensile test is recorded. The values for the tensile force were then averaged for each support type (n = 6).

### 5.3.5 Results

#### 5.3.5.1 Material consumption

As an example, Figure 7 shows some of the specimens for material consumption directly after they were removed from the LBM machine. Subsequent the results of the material consumption are presented (see Figure 8).

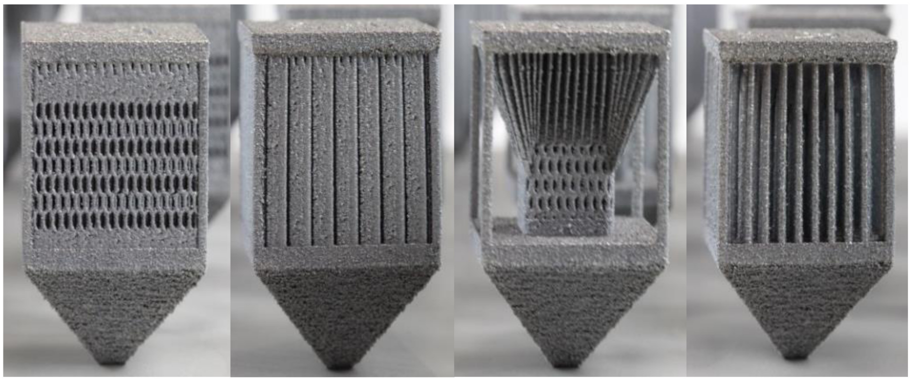


**Figure 7 — Material consumption specimens after manufacturing (From left to right; Standard block, Fragmentation, Block gusset, Cone- support)**

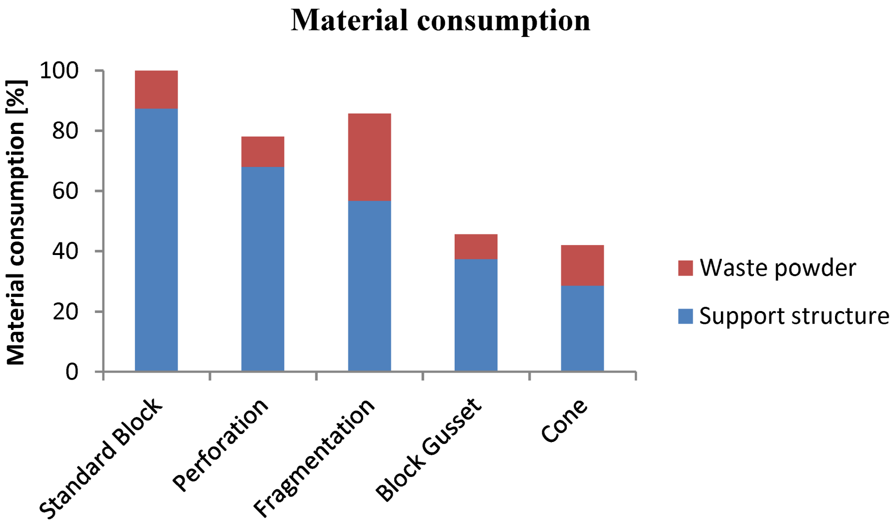



**Figure 8 — Material consumption of different support types**

The results show that every new support type requires less material then the standard one. The residuals of powder inside the structures are agglutinated, which is why they were not removed by the suction device. While the perforated block support requires more material then the fragmented one the perforated structure provides better removability of the powder and have less overall material consumption. The least material is consumed by the cone structure followed by the block gusset support.

### 5.3.5.2 Removability

Since most of the overhanging elements were destroyed while removing the support structures (see Figure 9), the removability at the inclined areas could not be determined. If the removability for such areas has to be investigated, a redesign of the specimen is necessary.

**Figure 9 — Specimen C after support removal**

The following two figures show the results of the investigation concerning support removability.

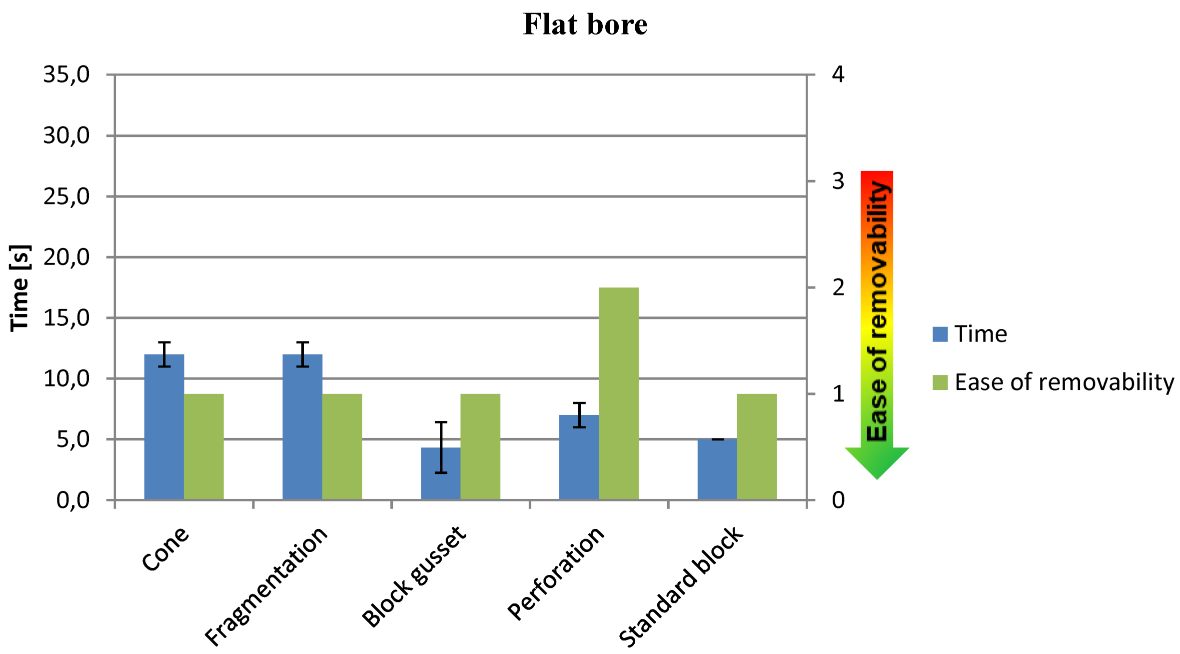



**Figure 10 — Removability of support structures for flat bore**

All structures were easy removable. Only the perforated block support needed slightly more effort. Due to the fact that cone and fragmented structure consist of single elements, their removal took a bit more time because they could not be removed all at once.

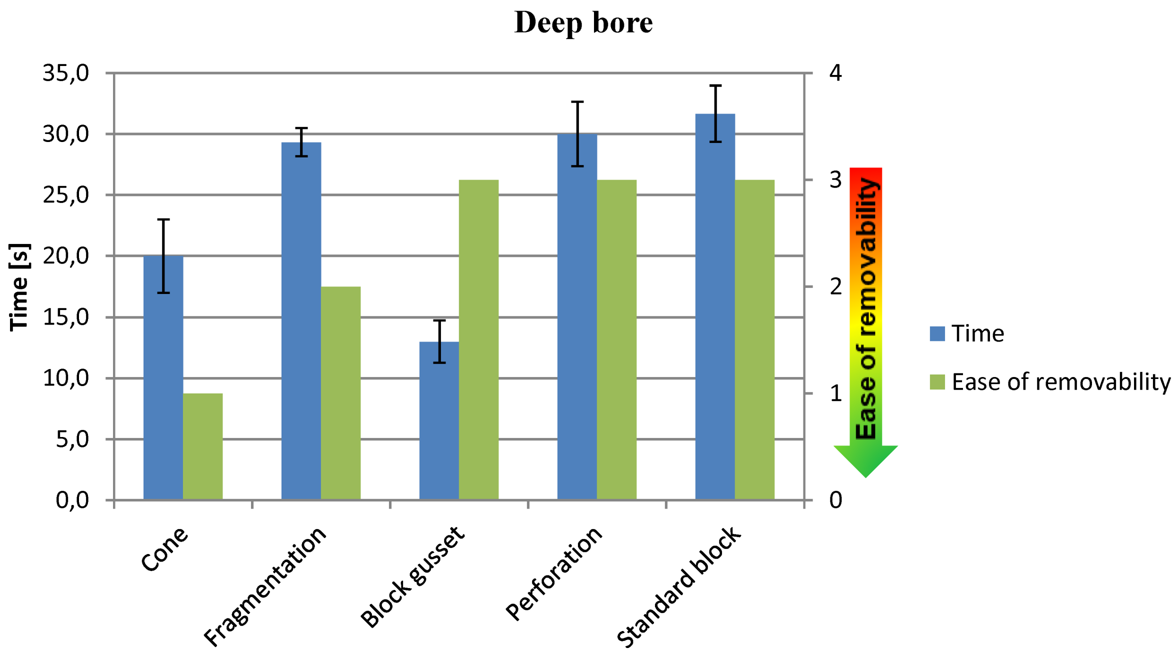



**Figure 11 — Removability of support structures for deep bore**

Because of the increased amount of support structures for deep bores the required time for removal is higher and the ease of removability is reduced. In addition it transpires that the structures with fragmentation and the cone supports were easier to remove, while all other required more effort, which is represented by the values for the ease of removability. The relatively high amount of time needed for the removal of the fragmented block support and the cones is caused by its single walls. After the majority of the structures was stripped off, single elements were still connected to the part and had to be removed one by one. The block gusset version could be removed all at once and the standard block support as well as the perforated block support in two steps, which is why they required more effort.

#### 5.3.5.3 Surface influence

Figure 12 shows the determined roughness values for the respective support types. For comparison the same values for a non-supported downward pointing surface are also given.

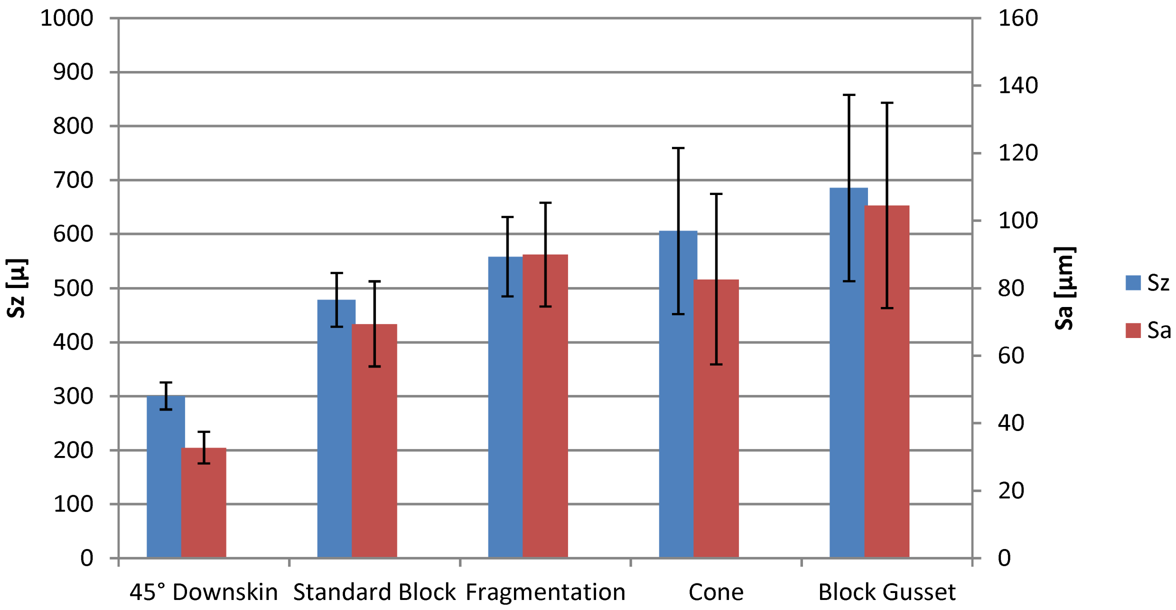


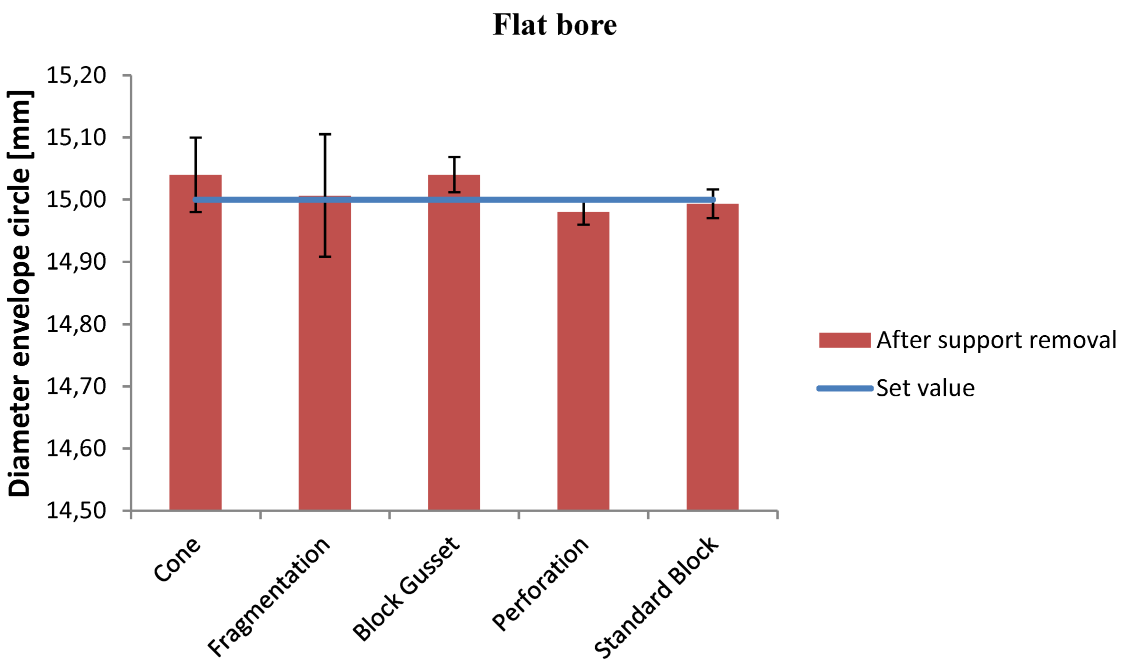

**Figure 12 — Influence of different support types onto the surface roughness**

It is apparent that all supported surfaces have higher roughness values and also higher standard deviations. In general, both values behave similar to each other, which mean that they are representative for the quality of the surfaces. While the standard block support provides smoother surfaces (Sa = 69 µm), the block gusset structure lead to the roughest surfaces within these investigations (Sa = 104,5 µm). In general the increased roughness values are caused by small residual elements of the structures, which are still connected to the part. In each case the structures fractured above the surfaces which mean that there is no pitting.

Although there are differences between the roughness values of the different support types, further post processing is still required. This means that effort for surface finishing is independent from the investigated support types and could not be reduced.

#### 5.3.5.4 Dimensional accuracy

In the following to figures the results for the specimen's bore diameters are presented. They were determined after the support structures were removed.



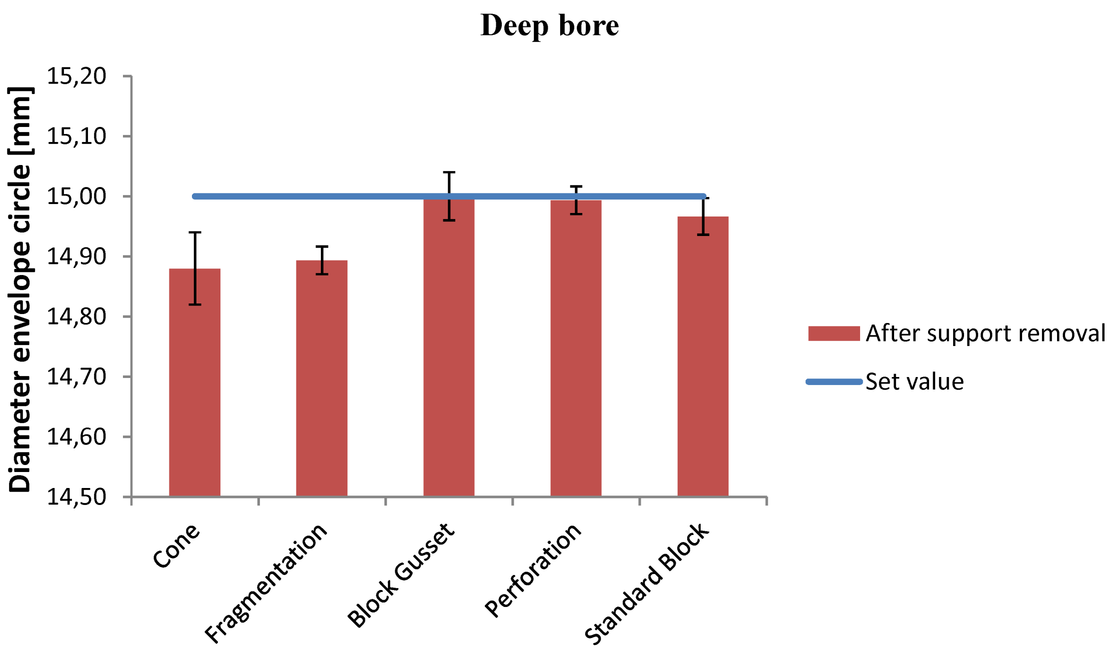




**Figure 13 — Dimensional accuracy of bores in dependence of used support structures**

In general the deep bores show higher accuracy. Except the block support with increased perforation, every other type leads at least once to a bore with a dimeter above the set value.

Since the flat bores are slightly oval in a certain orientation to the cheeks of the vice, it can be assumed that the specimens were deformed during the support removal due to unsuitable clamping. Also the required forces for the removal of some support structures of the deep bores could have an effect. With these influences and the fact that there is an additional deviation due to the measuring accuracy of the optical measuring system, no clear statement for the accuracy of bores can be made.

#### 5.3.5.5 Tensile strength

Within this chapter the results of the tensile tests are described. Figure 14 shows one specimen of each investigated support type after manufacturing.

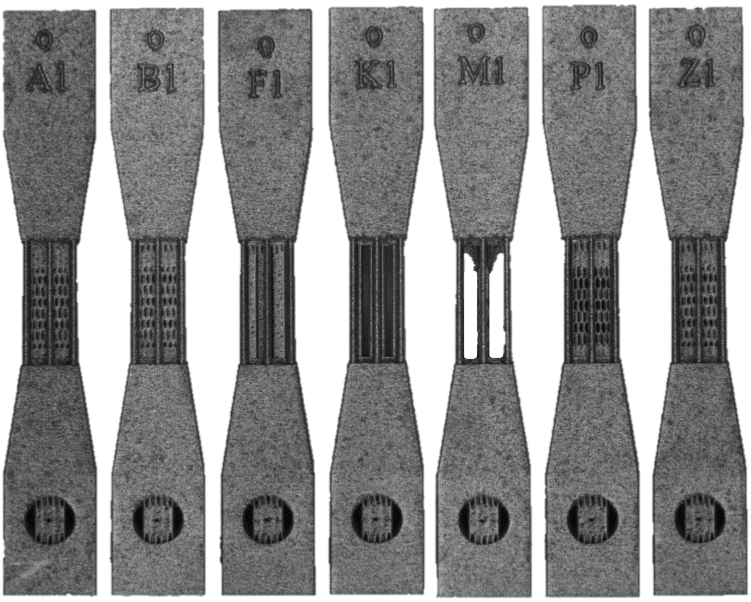



**Figure 14 — Tensile specimen after manufacturing**

Below three striking force-displacement curves are presented. The missing pronounced yield strength indicates macroscopically or structurally brittle deformation behaviour.

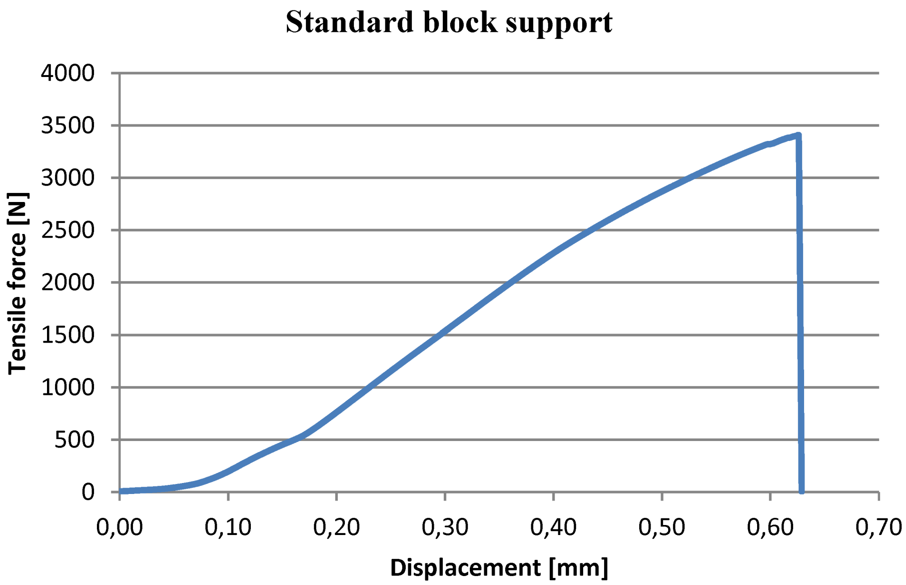



**Figure 15 — Force-displacement curve of standard block support**

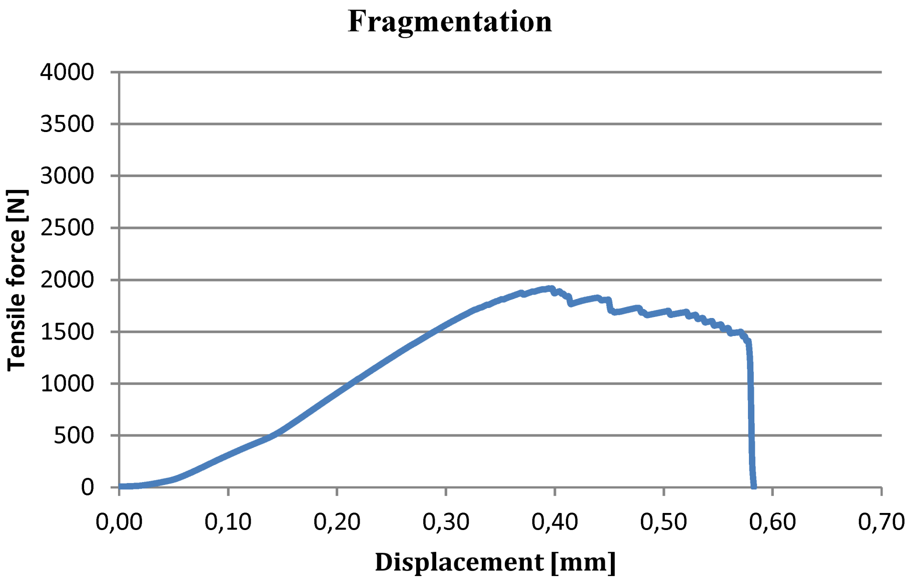



**Figure 16 — Force-displacement curve of standard block support**

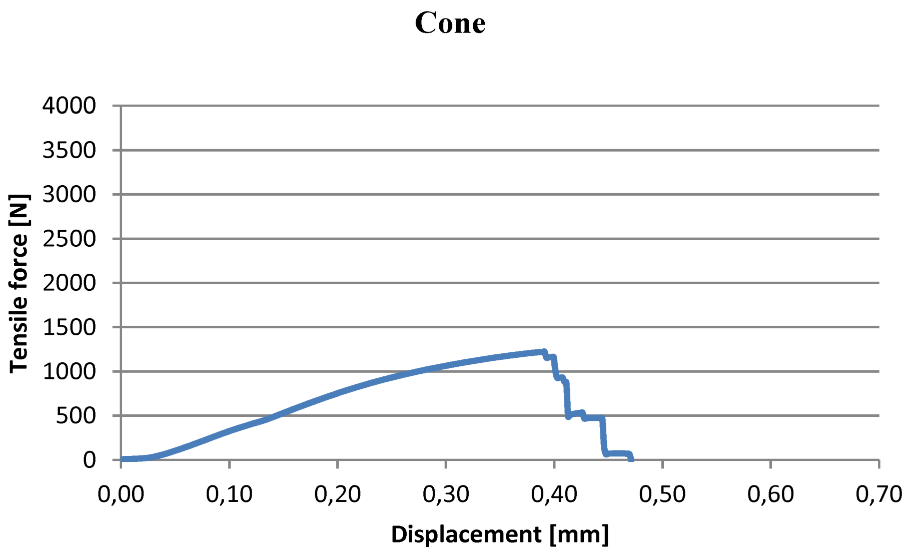



**Figure 17 — Force-displacement curve of cone support**

In contrast to the standard block support the fragmented one and the cone supports show a failure over a small period of time. While the standard version broke all of a sudden, the cones and fragmented elements fractured one after another. The other types of support structures showed similar fracture behaviour like the standard block support.

In Figure 18 the averaged values for the tensile forces of the specimens are presented (n = 6). According to their fraction behaviour the fragmented support structures have reduced tensile forces, although they have the same tooth geometry like the standard block structure. The increased top length did not lead to significant higher tensile forces, because the fragmentation was too weak.

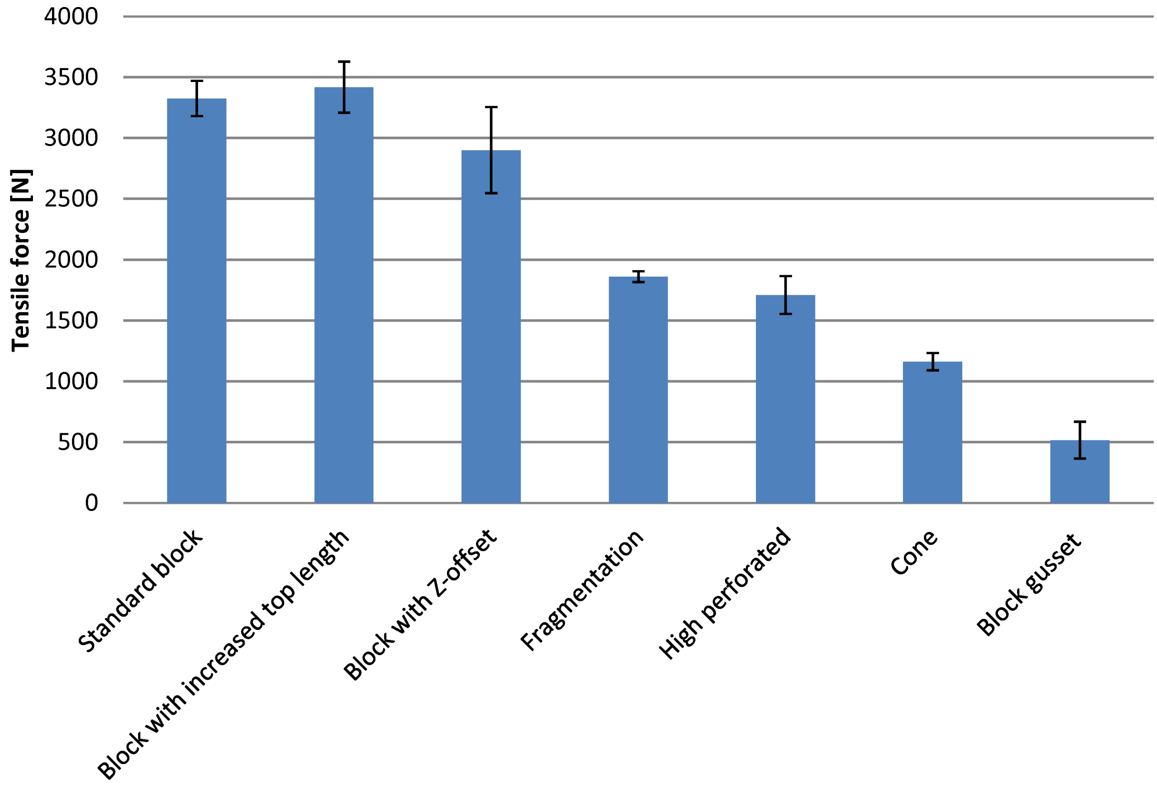



**Figure 18 — Tensile forces of different support structures**

The standard block support, the cone support and the block support with Z-offset fractured at the upper support part interface. The fragmented structure, the block support with increased top length and the structure with higher fragmentation fractured undefined over the complete height or rather over the height of the perforation (see Figure 19). The block gusset structure fractured at the lower end of the perforation.

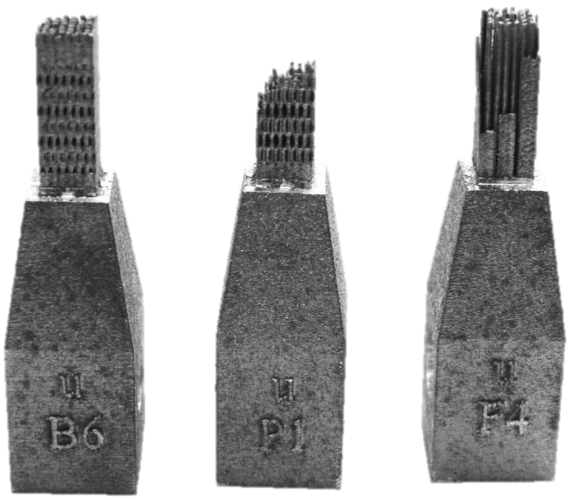



**Figure 19 — Fractured tensile specimen (From left to right; Standard block-, High perforated block-, Fragmented block support)**

## 5.4 Novel biomimetic support structures

### 5.4.1 Optimization goal and criteria

For the second research approach of optimizing the support structure design itself an optimization goal had to be set, since a novel support structure cannot equally be optimized towards multiple criteria. Due to the fact that for Aluminium alloys residual stresses play a minor role throughout the build process, it was decided to focus on the supporting of overhanging surfaces and bore holes. In detail the goal was set on **reduced material consumption** and an **easier removability** in comparison with the standard block support.

For both the use case of overhanging surfaces and bore holes a novel structure was developed each, following the methodology of biomimetics.

### 5.4.2 Biomimetic development of support structures

Biomimetic is a field of studies in which principles that can be found in biological models are extracted and then transferred to technology. In the area of additive manufacturing it is increasingly used to develop and design novel structures that are lightweight and yet achieve the same mechanical properties as the original structure.

In this study at first the required functions of the support structure had been defined:

- Support downward facing surface
- Low Volume/Mass
- Fixate Part onto build platform
- Transport heat

Based on those a search for analogue biological models was performed, followed by a down selection process. Choice of final biological models was based on similar loading conditions, structure size and material. Novel support structures consist of a base structure and connection structures.

For overhanging surfaces a fractal lattice structure including a gradient in unit cell size has been generated. On the bottom unit cells are bigger and become smaller towards the supported overhanging surface. In addition two different types of teeth were designed: cone and bulb shaped (Figure 22).

For bores two tree shaped structures have been generated. One consists of several 2-dimensional trees arranged in a row and the other of one rotationally symmetric tree.

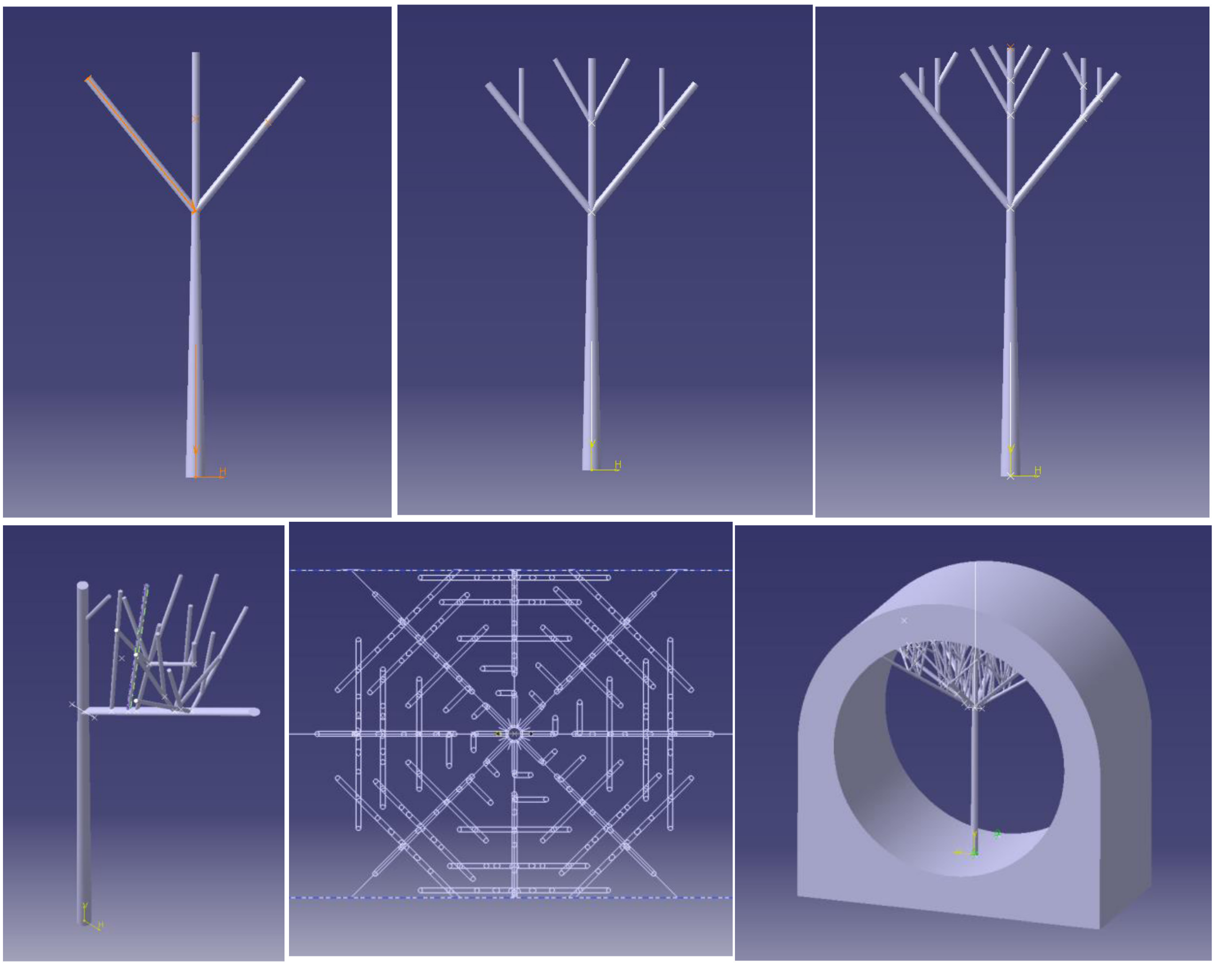
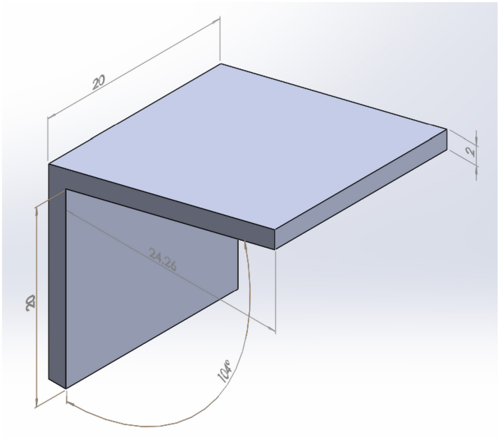


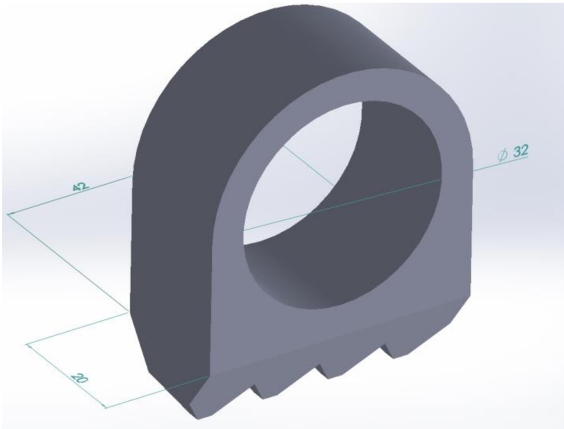
**Figure 20 — Design steps for tree support (Upper row 2-D tree, lower row 3-D tree)**

### 5.4.3 Definition and fabrication of test specimen

For the investigations of the biomimetic support structures two new test specimens were designed (Figure 21). All surfaces that fall below the pre-set critical angle of 40° have been assigned with support of the respective support type.




e)




f)

**Figure 21 — Test specimen for removability investigation; test specimen (e) has been utilized to quantify removability for the fractal lattice structure and test specimen (f) has been utilized to quantify material usage and removability for tree supports**

The subsequent figure shows specimen e) including the fractal lattice support and the two different types of teeth. Figure 23 shows specimen f) including the two types of tree support.

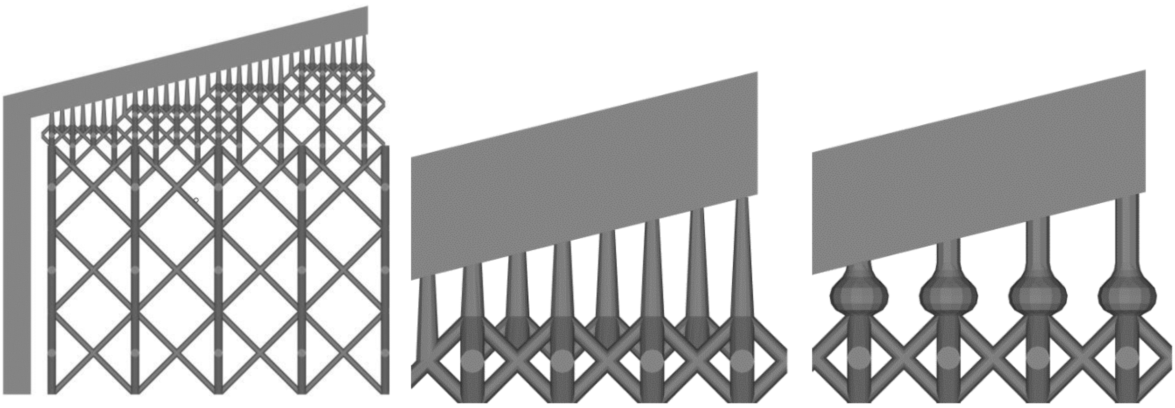


**Figure 22 — Specimen e) with fractal lattice support; cone shaped teeth and bulb shaped teeth**

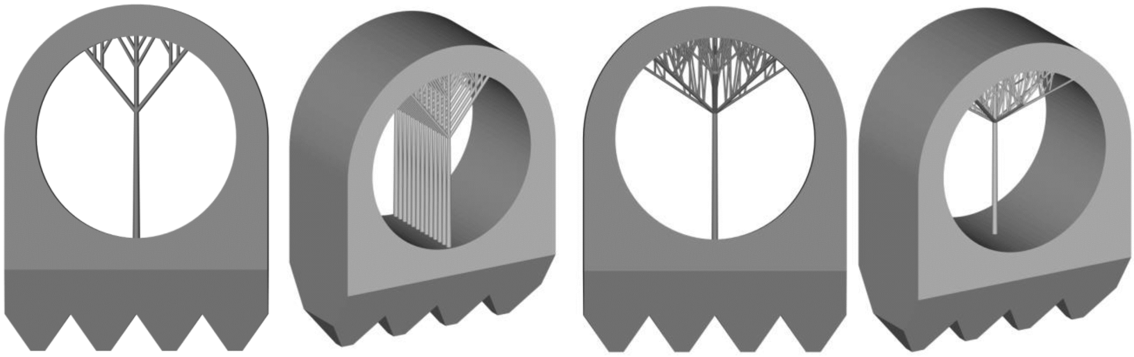


**Figure 23 — Specimen f) including tree support (left: 2-D tree; right: 3-D tree)**

### 5.4.4 Measurement and evaluation methods

#### 5.4.4.1 Material consumption

To quantify material consumption for fractal lattice structures, the experiments were performed in the same way as for standard support structures (5.3.4 Removability). For the bores material consumption has been calculated in similar fashion.

#### 5.4.4.2 Removability

Removability was evaluated in the same way as for the standard support structures (5.3.5) based on test specimen e) and f).

### 5.4.5 Results

Below the specimens including their support structures are presented. All structures could be manufactured successful and without failure.

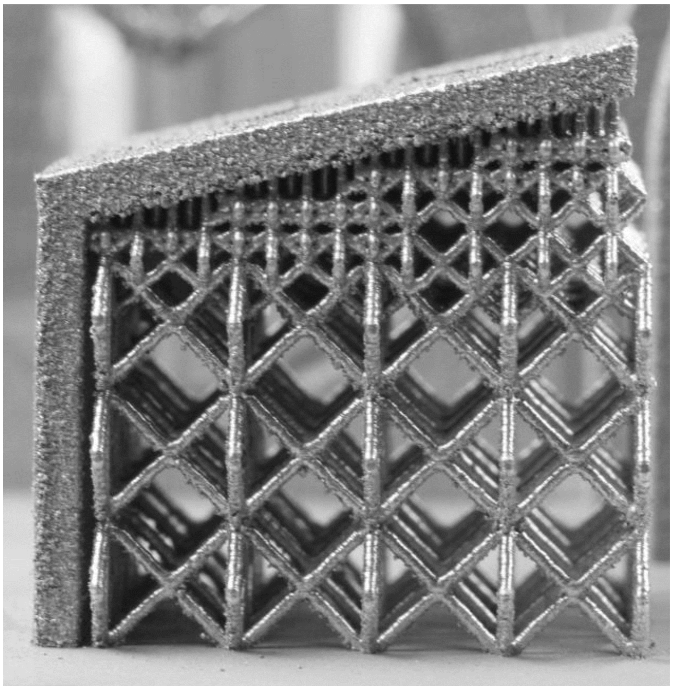


**Figure 24 — Specimen e) with lattice structure and cone shaped teeth**

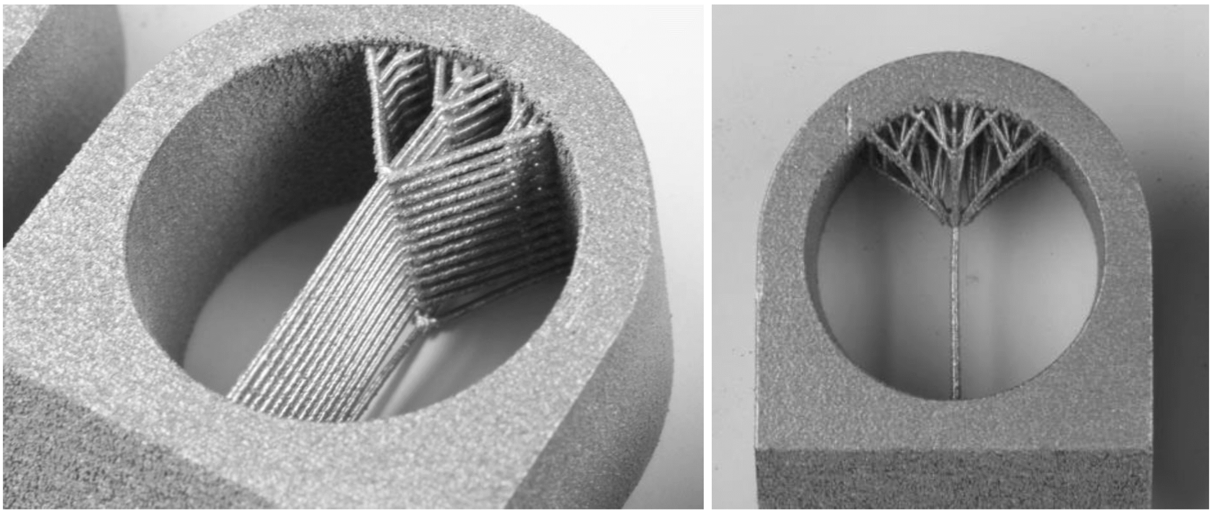


**Figure 25 — Specimen f) with tree support (Left 2-D tree; right 3-D tree)**

### 5.4.6 Material usage

The subsequent figure presents the results of the material usage investigations for the new biomimetic support structures. In contrast to the results of the conventional supports (5.3.5) these data include the values for material consumption of the support structure itself and enclosed waste powder.

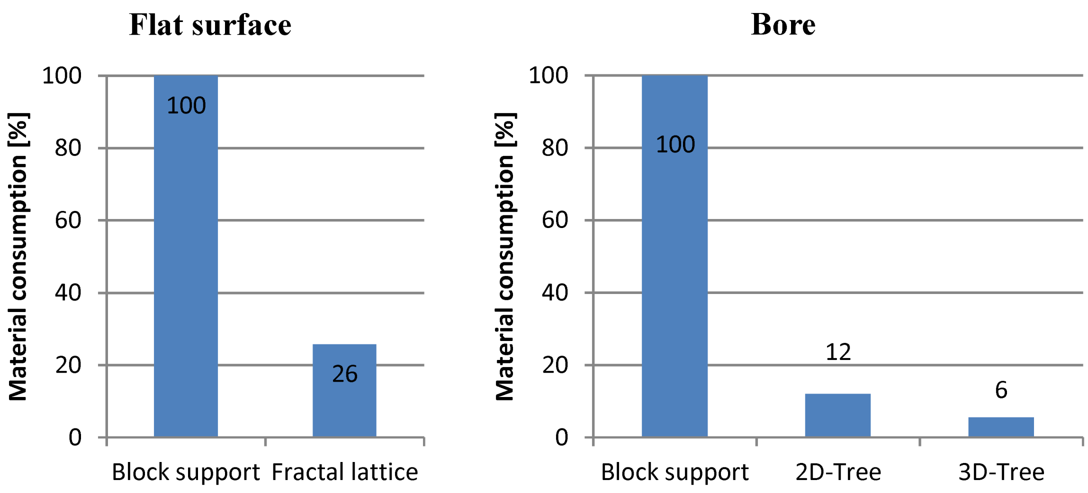



**Figure 26 — Material usage of new biomimetic support structures**

It is apparent that for flat surfaces as well as for bores the new biomimetic support structures require significantly less material than the standard block support. Due to the open structure of the new supports there was nearly no residual powder after removing the specimens.

### 5.4.7 Removability

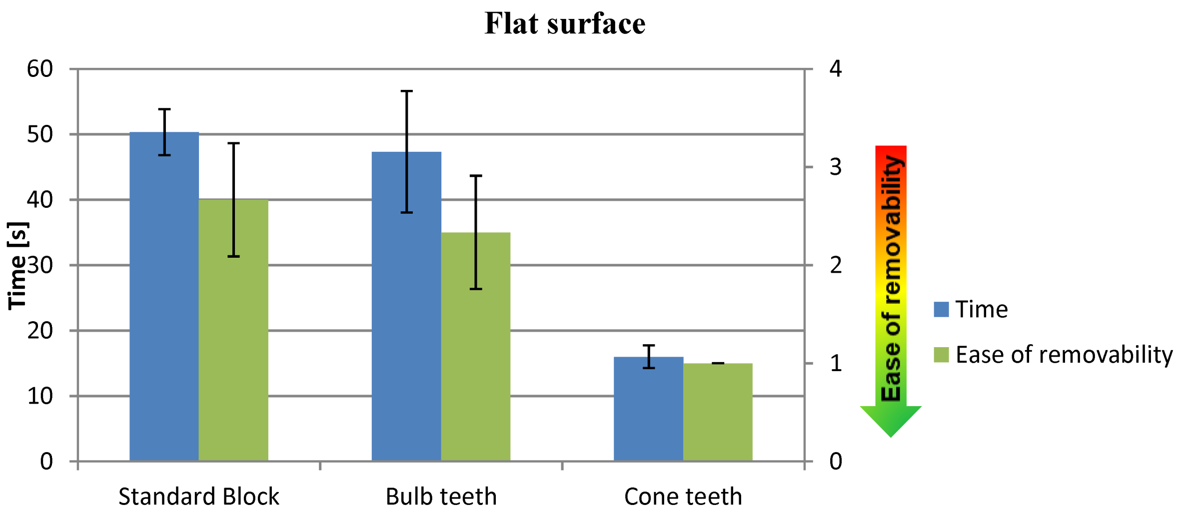



**Figure 27 — Removability of new biomimetic supports for flat surfaces**

In comparison to the standard block support the lattice structures with bulb teeth did not show significant improvements concerning removability. However the use of fractal lattice structures in combination with cone supports could substantially reduce the effort for removal.

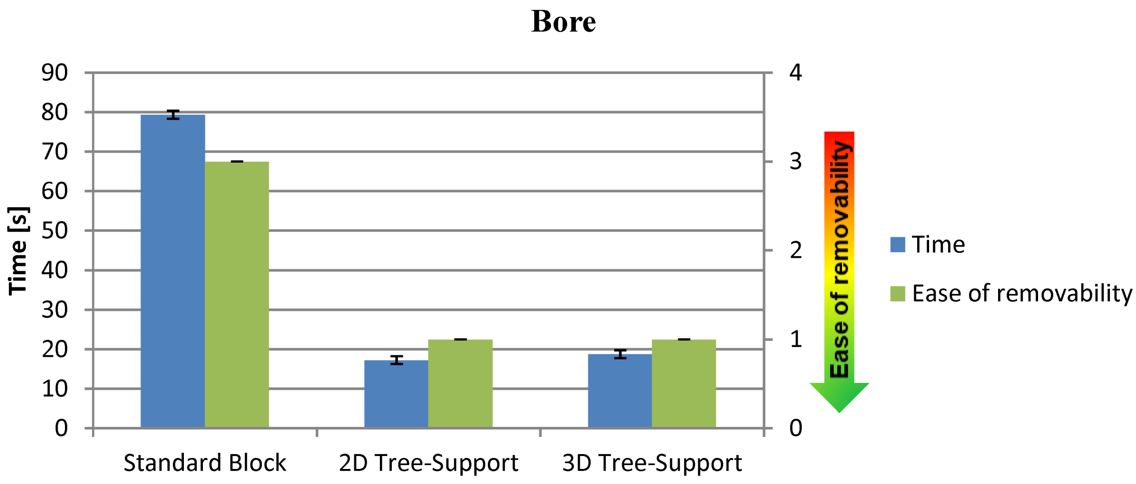



**Figure 28 — Removability of new biomimetic supports for bores**

For bores both new support types lead to an improvement of removability. Primary this is due to the reduced support-part interface area.

# 6 Conclusions

## 6.1 Conclusions for design guidelines

The investigations revealed that the properties of support structures differ substantially in dependence of their type. Depending on the use case and the target figure to optimize (e.g. material consumption or tensile force), other types of structures are preferable. For an optimization concerning material consumption the cone and the block-gusset structures are most preferable.

Relating to accuracy of bores there is no significant difference between the support types.

For an easy removability it is essential to use block support with fragmentation or cone supports. If the support area is small enough (edge length between 2 mm and 5 mm) non fragmented structures are preferable. This leads to a fragmentation interval up to 5 mm.

The influences of support structures to the specimen´s surfaces are not significant enough to have a positive effect for the post processing effort regarding surface finishing and can be neglected.

The results of the tensile tests revealed that a perforation introduces a new weak point, if the beam width of the perforation is smaller than the top length of the teeth. Although the introduction of a Z-offset value should increase the tensile strength it led to a reduction of the force. If support structures consist of single elements (e.g. cone or fragmentation) the tensile force is reduced. The block gusset support is just suitable for applications where only low residual stresses occur since it withstood just a relatively small tensile force, which is due to the reduced cross section at the lower part of the structure.

## 6.2 Conclusions for optimized biomimetic support structures

Like the standard support types the new biomimetic structures were investigated in the same way. The results revealed that a new and biomimetic support design could significantly reduce the amount of used material for support structures and simplify their removability. For flat surfaces the fractal lattice structure with cone shaped teeth provides the best results concerning removability. In addition the lattice support requires just about a quarter (26 %) of the material than the standard structure.

For bores a tree like shaped structure is most preferable. The rotational symmetric version provides a good combination of material consumption and removability.

### 6.3 Outlook

With these experiments first investigations concerning behaviour of aluminium support structures were performed.

In the following steps these results can be used to create guidelines for the application and optimal parameterization of support structures in dependence of their use case. With further experiments concerning support structure properties, these guidelines can be extended.

Although the design guidelines give assistance for optimal choosing and parametrizing of support structures, experience about the component behaviour and requirements is still necessary. Hence a long-term goal could be the combination with a process simulation to determine the requirements for the support structures and enable their automated and adjusted generation, which could lead to a significant reduction of manually pre-processing efforts and manufacturing costs.

Furthermore influences of the support structure onto the edge region, for example density or microstructure are worth to be investigated also, since they are unknown.

Because the new biomimetic support types showed promising improvements concerning material consumption and removability, they should be considered for further investigations e.g. for tensile tests and dimensional accuracy.

## 7 Appendix

EOS material data sheet for AlSi10Mg

## Material data sheet

### Mechanical properties of the parts

| | As built | Heat treated [9] |
|---|---|---|
| Tensile strength [6] | | |
| - in horizontal direction (XY) | 460 ± 20 MPa<br>66.7 ± 2.9 ksi | 345 ± 10 MPA<br>50.0 ± 1.5 ksi |
| - in vertical direction (Z) | 460 ± 20 MPa<br>66.7 ± 2.9 ksi | 350 ± 10 MPa<br>50.8 ± 1.5 ksi |
| Yield strength (Rp 0.2 %) [6] | | |
| - in horizontal direction (XY) | 270 ± 10 MPa<br>39.2 ± 1.5 ksi | 230 ± 15 MPa<br>33.4 ± 2.2 ksi |
| - in vertical direction (Z) | 240 ± 10 MPa<br>34.8 ± 1.5 ksi | 230 ± 15 MPa<br>33.4 ± 2.2 ksi |
| Modulus of elasticity | | |
| - in horizontal direction (XY) | 75 ± 10 GPa<br>10.9 ± 0.7 Msi | 70 ± 10 GPa<br>10.2 ± 0.7 Msi |
| - in vertical direction (Z) | 70 ± 10 GPa<br>10.2 ± 0.7 Msi | 60 ± 10 GPa<br>8.7 ± 0.7 Msi |
| Elongation at break [6] | | |
| - in horizontal direction (XY) | (9 ± 2) % | 12 ± 2% |
| - in vertical direction (Z) | (6 ± 2) % | 11 ± 2% |
| Hardness [7] | approx.119 ± 5 HBW | |
| Fatigue strength [1] [8] | | |
| - in vertical direction (Z) | approx. 97 ± 7 MPa<br>approx. 14.1 ± 1.0 ksi | |

[6] Mechanical strength tested as per ISO 6892-1:2009 (B) annex D, proportional specimens, specimen diameter 5 mm, original gauge length 25 mm (1 inch).

[7] Hardness test in accordance with Brinell (HBW 2.5/62.5) as per DIN EN ISO 6506-1. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

[8] Fatigue test with test frequency of 50 Hz, R = -1, measurement stopped on reaching 5 million cycles without fracture.

[9] Stress relieve: anneal for 2 h at 300 °C (572 °F).

[10] These properties were determined on an EOSINT M 280-400W. Test parts from following machine type EOS M 290-400W correspond with these data.



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Material data sheet

### Thermal properties of parts

| | As built [1] | Heat treated [1] [9] |
|---|---|---|
| Thermal conductivity (at 20 °C) | | |
| - in horizontal direction (XY) | approx. 103 ± 5 W/m°C | approx. 173 ± 10 W/m°C |
| - in vertical direction (Z) | approx. 119 ± 5 W/m°C | approx. 173 ± 10 W/m°C |
| Specific heat capacity | | |
| - in horizontal direction (XY) | approx. 920 ± 50 J/kg°C | approx. 890 ± 50 J/kg°C |
| - in vertical direction (Z) | approx. 910 ± 50 J/kg°C | approx. 890 ± 50 J/kg°C |

### Abbreviations

approx. approximately
wt weight

### Notes

The data are valid for the combinations of powder material, machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.





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