Examination of the Geometry-dependent Anisotropic Material Behavior in Additive Layer Manufacturing for the Calculation of Mesoscopic Lightweight Structures

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Abstract

Due to the producible geometric complexity, additive layer manufacturing (ALM) processes show a high potential for the production of lightweight components. Especially mesoscopic approaches, like honeycombs or lattice structures, exhibit very advantageous mechanical properties like stiffness or strength combined with low masses.

To achieve an optimum structure, a regular buildup out of equal elementary cells is not ideal. Rather, an adjustment of the course of the structure and its material filling degree has to be done.

Therefore, detailed knowledge about the material behavior of additive manufactured components is necessary. Especially for lightweight structures, these properties are affected by anisotropy and geometry dependent influences. These effects have a severe influence on the basic elements of mesoscopic patterns, like struts in case of lattice structures or the single walls of honeycombs.

In case of anisotropy this means that the material behaviour – and even the success of the build-up process – of the basic elements depend on the angle, under which the strut or honeycomb is built in relation to the building direction.

In case of geometry dependency, this means that the material behavior is influenced by several geometric attributes. For lattice structures, this can be the lengths or the cross section of the struts. In the field of honeycombs, the height and broadness as well as the thickness of the walls can be mentioned.

While there are already numerous analyses concerning the orientation dependent anisotropy, the influences of the geometric properties have not been researched, yet.

To achieve best possible mesoscopic structures in lightweight components, these influences have to be taken into account.

Therefore, a material model for struts in lattice structures, including the corresponding experimental results, will be introduced in this paper. This model takes anisotropic and geometry-dependent aspects into account and therefore provides a basis for a successful calculation and optimization of lattice structures.

Motivation and state of the art

Additive layer manufacturing (ALM) shows a high potential for the production of parts in small and medium lot sizes [1, 2]. Especially in case of the manufacturing of complex parts, ALM-processes show some very advantageous properties, like the possible geometrical freedom. Therefore, these methods are very well suited for the production of lightweight design parts.

Common lightweight design approaches can be classified in three categories, depending on their geometrical dimensions:

- macroscopic lightweight design;
- mesoscopic lightweight design;
- microscopic lightweight design [3].

Mesoscopic approaches, which are the research focus in this paper, deal with the replacement of part areas with massive material concentration by complex structures like lattice structures or honeycombs (see Figure 1).

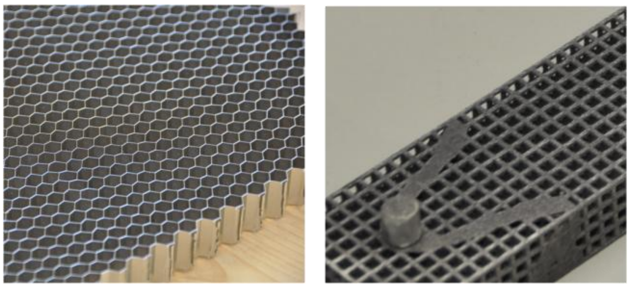

Figure 1: mesoscopic structures: left: honeycomb structure; right: lattice structure

The presented project concentrates on the optimization of lattice structures. Therefore, two main approaches have to be considered. On the one hand, the kind of stress, which appears inside the single struts, has to be optimized.

To reach the best possible mechanical properties, only push and pull forces should appear in the struts. Analyses have shown, that this state can be reached if the struts are oriented along the main stress tensors inside a given design space [4].

Furthermore, as known from macroscopic lightweight design, the absolute value of the effective stress should be as uniformly distributed as possible inside the whole part. This principle of equal stresses can be transferred to lattice structures. Here, the effective stress inside the single struts should be equal all over the structure. This can be reached by an optimization of the struts' diameters [4].

To perform this adaption of the cross sectional areas, the loads on the single struts as well as the material properties have to be known very well.

Thereby, it has to be taken into account, that generative manufactured material shows an anisotropic behavior. This has already been analyzed in literature.

Meier and Haberland [5] executed first stability examinations on the additive manufactured material 316L (1.444). The work deals with the correlation of layer thickness and anisotropic properties. The results have shown that thicker layers lead to a severe reduction of the tensile strength and ultimate strain.

Further extensive examinations on 316L have been carried out by Rehme [6]. He explains the anisotropy with the laminar microstructure of the material, which is caused by the layerwise build-up process. Rehme deals with the influence of process parameters on the material behavior. Beyond that, Sehrt [7] describes the influence of the surface condition on mechanical properties. The results show anisotropic, respectively transversal isotropic behavior. Thereby, specimens, which were built parallel to the building platform, show the highest stability.

All of these works deal with regular tensile specimen. However, the influence of geometrical attributes is not taken into account. Especially for lattice structures, where we can mainly find filigree beams, an influence of for example strut length or diameter cannot be spaced out.

For this reason, further examinations will be presented in the following sections, which identify the influences of the orientation, as well as the length and diameter of filigree struts on their material properties.

The results have to be implemented into a computer based material model, to make them usable for calculation and optimization tools.

Experimental procedure

To determine the anisotropic, geometry-dependent material properties, an extensive series of tensile specimen has been built up. The manufacturing was executed on the ALM-machine SLM 250HL. The material which has been used was AlSi12. Similar to the struts in lattice structures, no subsequent machining was carried out after the buildup process.

It is recognizable, that in many cases for horizontal orientations, the struts cannot be produced or show severe geometrical failures.

The tensile specimen used can be seen in Figure 2. It has two fixing points, which are designed analogue to standardized flat test pieces. The testing geometry is placed between these fixing points.

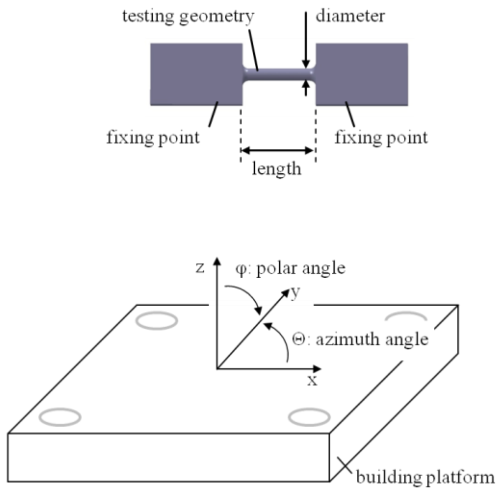

Figure 2: top: tensile specimen, bottom: azimuth and polar angle on building platform

The variable parameters are the strut's diameter and length, as well as the polar and azimuth angle (see Figure 2).

The constant boundary conditions are the alloy of the material, the used ALM-machine, the process parameters and strategy, a circular cross section of the strut and the surrounding temperature.

In the examination of the specimen, geometrical failures caused by the building process are influencing the result. These failures do for example appear for big polar angles near 90° (see Figure 7). The fact that these failures are included in the tensile testing is very advantageous for the development of the material model, because the same failures will also appear in the lattice structures for the respective parameter values. Hence, the model will not be a pure material model, but a model which combines material properties and dimensional accuracy.

Before the actual examinations start, the influence of the powder manufacturer has to be clarified. Therefore, preliminary investigations with material of two different distributers have been executed. For that purpose, tensile tests with a strut length of 5 mm and a diameter of 2 mm have been carried out for different polar and azimuth angles. Thereby it has shown that the powder of one manufacturer possesses a higher Young's modulus, while the other one has higher strength values. Because the second one also exhibits less anisotropy it is used in the following analyses.

Furthermore, the dependency of the material properties from the position of the specimen on the building platform has to be analyzed. For this reason, the job in Figure 3 has been built and the mechanical properties for the different positions have been determined.

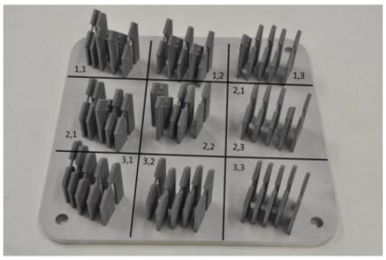

Figure 3: Influence of the specimen position on the building platform

In this experiment, no variation of the respective values can be observed. This leads to the conclusion, that the position on the platform does not have any influence on the mechanical properties.

Based on this fact, an examination plan gets developed. The tests start with a reference specimen, which has a strut length of 10 mm, a diameter of 2 mm and a polar and azimuth angle of 45°. These parameters are getting varied in the following and the dependencies of the mechanical properties are interpreted.

It is known from literature, that additive manufactured material shows anisotropic behavior, which depends on the polar angle and which does not depend on the azimuth angle [6, 7]. If this can be confirmed for the filigree struts of lattice structures, the azimuth angle will not be considered in the following experimental series (see Figure 4).

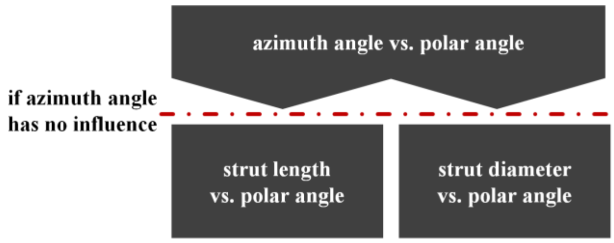

Figure 4: Procedure for the examination of the material behavior

In the following tests, the strut length and the strut diameter will be tested in combination with the polar angle.

The examined values for the single parameters are:

- azimuth angle: 0°; 22,5°; 45°; 67,5°; 90°
- polar angle: 0°; 22,5°; 45°; 67,5°; 90°
- strut length: 5 mm; 10 mm; 15 mm; 20 mm
- strut diameter; 1,5 mm; 2 mm; 3 mm

For each of the combinations depicted in Figure 4, 5 specimens are built up and tested. This leads to a total number of 300 tensile tests.

Results

The tensile tests were executed on a testing machine of the type Zwick/Roell Z100, whereat the strain was measured by a non-contact camera system.

Thereby, the mechanical properties

- Young's modulus (E),
- shear modulus (G),
- limit of elasticity ($R_{p0,2}$),
- tensile strength (R_m), and
- ultimate strain

have been determined.

Below, the results are illustrated at the example of the Young's modulus and the tensile strength, because these two parameters are very advantageous for the examination of complex lattice structures.

In the following graphs, the arithmetical means of five tensile specimen of each variant are used.

At first, the orientation dependent anisotropy is analyzed. For this, the influence of the azimuth and polar angle on the mechanical properties is determined. Analogue to spherical coordinate systems, the azimuth orientation is chosen as the rotation of the specimen on the building platform and the polar angle is determined as the angle compared to the z-axis of the ALM-machine (see Figure 2).

Figure 5 shows the tensile strength of the specimen for different polar angles as a function of the azimuth angle.

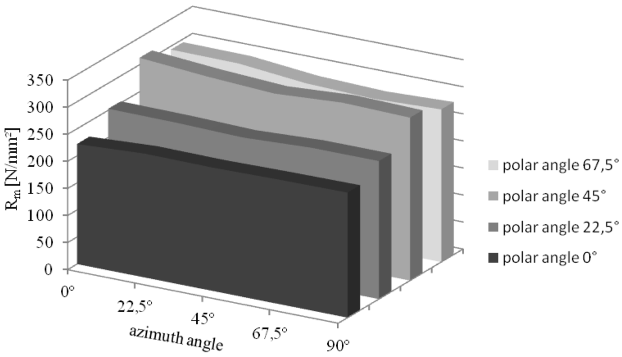

Figure 5: Tensile strength as a function of azimuth angle and polar angle

It is recognizable, that the polar angle has a significant influence on the tensile strength, while the azimuth angle shows no considerable dependency.

As noticeable, a polar angle of 90° is not contained since this orientation is not buildable for the present geometry.

The results for the limit of elasticity are qualitatively similar. In case of the Young's modulus, minor dependencies compared to the azimuth angle can be noticed, but these are not considered further due to the severe dominance of the polar angle.

These orientation dependent results for filigree struts in lattice structures are in agreement with the extensive examination on standardized tensile tests, performed by Sehrt [7].

Thus, the examined specimens show a transversal anisotropy with constant mechanical properties for an azimuthal rotation. Based on these findings, the influence of the azimuth angle is not considered in the following analyses.

Beyond the anisotropic, orientation-dependent material behavior of filigree struts in lattice structures, the influence of geometric attributes gets analyzed. Thereby, one aspect is the length of the strut in the tensile specimen. For this series, the polar angle is varied for different strut lengths. The results for the Young's modulus can be seen in Figure 6.

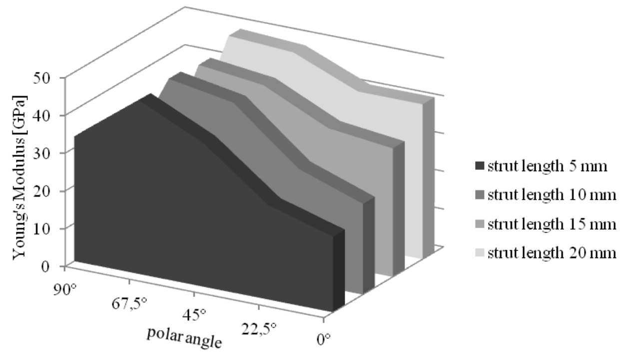

Figure 6: Young's modulus as a function of polar angle and strut length

As before, a severe dependency of the Young's modulus with respect to the polar angle is observable. For horizontal struts with angles of about 90°, a clear drop is observable, because these specimens are not buildable or show massive geometrical defects (see Figure 7 (a)), which lowers the mechanical performance.

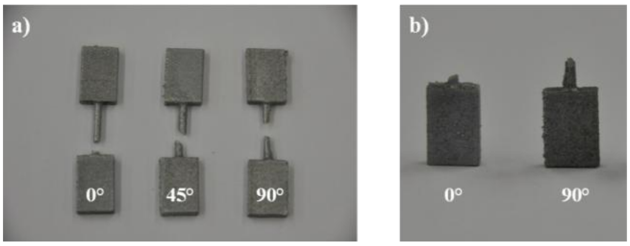

Figure 7: Geometrical defects (a) and notches (b)

Because of the better buildability, short struts show better values here. For lower polar angles, a descend of the graphs can be observed, which correlates with the results in [7]. This is explained with the worse metallurgic cohesion between the single layers compared to the stability within one layer, as well as with the appearance of notches between the single layers.

Beyond that, Figure 7 (b) shows additional notches between the fixing point and the actual strut in case of steep specimen, due to the appearing overhang in the fixing point. For short struts, these specimen sections have more influence on the overall behaviour then for long ones.

It is assumable, that this effect does not appear in whole lattice structures that much, because there are no fixing points with overhang. For this reason, additional examinations have to be executed with specimen geometries, which represent the behavior in whole structures better.

Thereby, it is due that for lower angles no influence of the struts length will appear, as it can be seen for 67,5°, were no notches do appear, too.

The correlation of the tensile strength with the strut length and the polar angle can be seen in Figure 8.

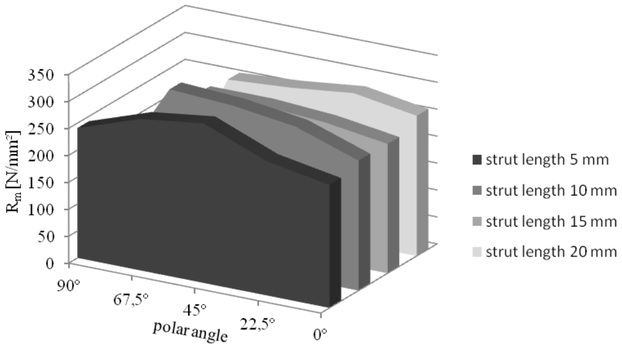

Figure 8: Tensile strength as a function of polar angle and strut length

As in case of the Young's modulus, a better behavior of short struts is observable for horizontal specimen. For steeper struts, no tendency concerning the correlation of length and tensile strength is observable.

Hence, it is assumable, that (except for horizontal struts) the length does not have any influence on the mechanical properties of struts in lattice structures. Although, there are additional examinations necessary to prove this assumption for the Young's modulus when no notches appear in the fixing points.

Another geometric parameter is the diameter of the circular cross section of the struts.

The Young's modulus for different diameters as a function of the polar angle can be seen in Figure 9.

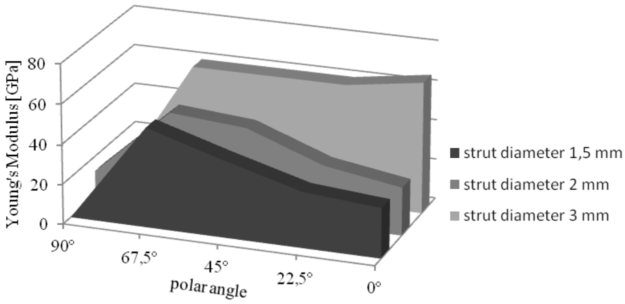

Figure 9: Young's modulus as a function of polar angle and strut diameter

As can be seen, the Young's modulus for thin struts is severely below the one for thick struts. From a diameter of 3 mm, the Young's modulus has reached a value which is similar to standardized tensile specimens (approx. 60 GPa) and has therefore reached its maximum.

This dependency can again be explained with the appearance of notches on the struts surface. At a higher surface to volume ratio (as in case of small diameters), these notches have a greater influence on the material properties of the whole strut and worsen its behavior.

The analogue results for the tensile strength can be seen in Figure 10.

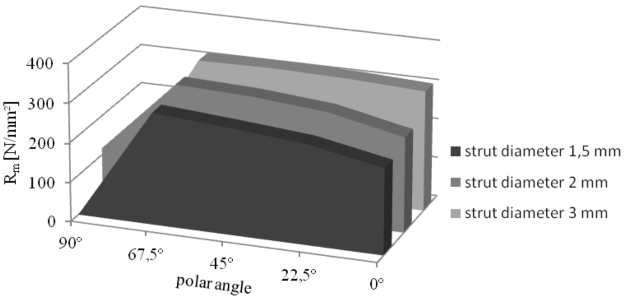

Figure 10: Tensile strength as a function of polar angle and strut diameter

As in case of the Young's modulus, an influence of the struts diameter can clearly be recognized. Here, the worse mechanical properties for bigger polar angles due to the buildability of horizontal struts can be seen again.

In summary, it can be stated that the anisotropy known from other examinations, like in [6] or [7], can be transferred to filigree struts for lattice structures. In addition, it has been shown that the mechanical properties depend on the specimen's cross section for small diameters. At current time, it is assumed that the length of the strut does not have any influence on its material behavior if no notch stresses at the fixing points appear. To prove this, additional examinations have to be undertaken.

Implementation into a calculation tool

The results presented before are to be used for the determination of the mechanical properties of lattice structures. Thereby, arbitrary structures with a complex buildup have to be calculated. Thus, very different angles and diameters appear within one structure. Hence, many unequal mechanical properties have to be used for the single struts (see Figure 11).

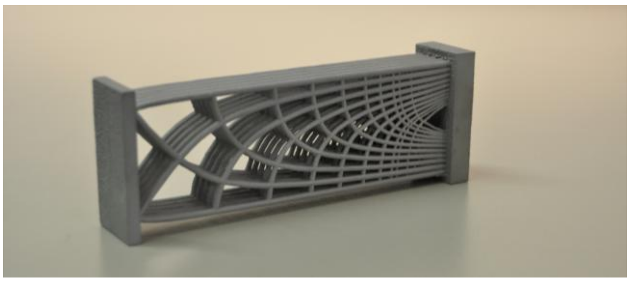

Figure 11: Complex lattice structure with different strut angles and diameters

Therefore, a software based material model gets implemented, which helps the user to determine the mechanical properties of each strut from its diameter and the coordinates of its starting and ending points.

For this purpose, mathematical functions are determined from the measurement data, which represent the respective correlations. As an example, the graph of the function for the tensile strength is depicted in Figure 12. It can be seen, that the mathematical function is in very good agreement with the measured values.

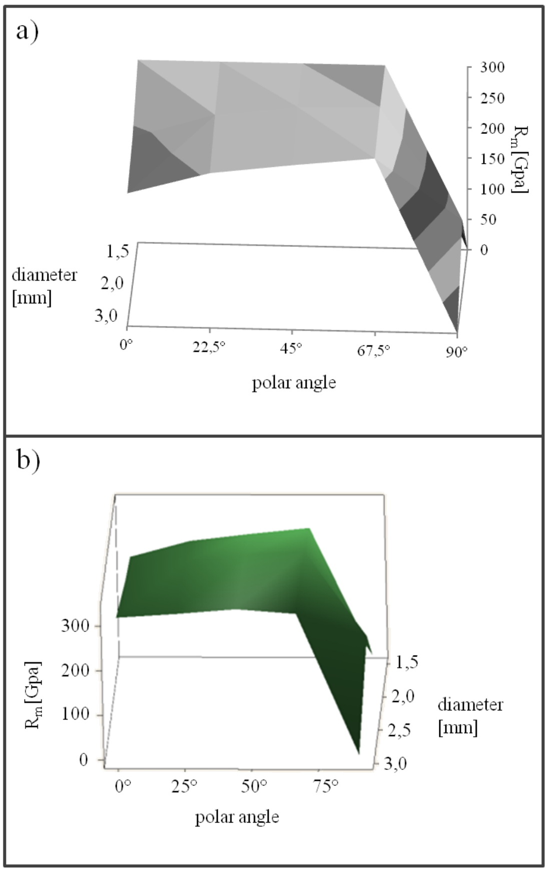

Figure 12: Experimental determined values (a) and mathematical representation (b) of R_m

Thereby, the specific material functions do only work for the respective boundary condition like the material alloy, the ALM-Machine, the process parameters etc, under which the specimen have been built.

If for example additional subsequent work is conducted, the examinations presented before have to be repeated and a new material model has to be derived.

The functions for the different mechanical properties are getting implemented in MATLAB.

The mechanical properties from this material model are used to calculate the local stiffness matrix for each strut (theoretical background, see e.g. [8, 9, 10]). This local matrices are transformed into a global coordinate system and summed up to a stiffness matrix for the whole lattice structure (theoretical background, see e.g. [11]).

Out of this, relative and absolute stiffnesses of single nodes can be determined and external forces and constraints can be applied on the calculation model.

Hence, analogue to the Finite-Elements-Analysis (FEA), displacements, forces and stresses can be calculated (theoretical background, see e.g. [12]).

This enables the dimensioning and optimization of the whole structure with respect to its mechanical properties like stiffness or strength.

Conclusions

The potential of Additive Layer Manufacturing (ALM) processes for the production of complex parts, especially in case of lightweight design, has been illustrated.

In case of mesoscopic structures, an adaption of the structure to the respective geometry is necessary to achieve best possible stiffness and strength at low masses.

For that, a suitable material model has to be developed, which determines the mechanical material properties as a function of different influencing factors. On the one hand, the behavior is defined by anisotropy. Here, it has been shown that the already published results for standardized specimen can be transferred to filigree struts in lattice structures.

On the other hand, new correlations concerning the influence of geometrical properties have been analyzed. It can be assumed, that the struts length does not have any influence on its material properties. Its diameter, in contrast, does show a severe effect on the stiffness and strength.

The achieved results were implemented into a computer based material model. This model enables the implementation of the correlations into a calculation tool. Thereby, a successful calculation and optimization of lattice structures gets possible.

In future works, further examinations, especially for polar angles near 90°, have to be done. Besides that, a bigger number of specimens for each geometry variant has to be tested, to get a better statistical coverage.

Furthermore, material models for further materials can be developed, to expand the applicability.

Acknowledgments

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