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A DESIGN METHOD FOR RESTRICTION ORIENTED LIGHTWEIGHT DESIGN BY USING SELECTIVE LASER MELTING

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Abstract

This paper describes the implementation of internal structures for mechanically loaded components to save material, and thus for a lightweight design, by using selective laser melting. Based on the analysis of structures inspired by nature and technical analogies, a design approach for the substitution of solid geometries by internal structures is investigated. Concerning a demonstrator, a stress- and manufacturing-oriented design for the integration of internal structures is analyzed. By the consideration of design guidelines and the application of Finite Element Methods, various model generations are built up iteratively and evaluated in comparison to the initial model. For the simulation, a material database is defined to involve the anisotropic material properties. The optimized model is manufactured by using AISi10Mg powder. The deviations of the physical model from the digital model are evaluated and considered by adapting the component design according to the design approach. The final model generation enables new lightweight potentials compared to conventionally manufactured models and corresponds to the possibilities of selective laser melting.

Keywords: Additive Manufacturing, Design for Additive Manufacturing (DfAM), Design methods, Design engineering, Computer Aided Design (CAD)

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1 INTRODUCTION

Additive Manufacturing is used for the production of prototypes and tools in industry (Gebhardt, 2013) (Gibson, Rosen and Stucker, 2015). Direct manufacturing, meaning the additive fabrication of end products to use or assemble directly, also becomes increasingly more important (Gartner, 2014) (VDI, 2014). Due to the excellent mechanical properties of the components, selective laser melting may be used as both a substitute for and a supplement to conventional manufacturing methods (Poprawe et al., 2015) (Lachmayer, Lippert and Fahlbusch, 2016).
A key factor for an economically and technically useful application to produce (near) net shape components with selective laser melting is the lightweight potential (Ohlsen et al., 2015) (Emmelmann et al., 2011). Thereby, one of the main factors is the given design freedom, because almost any geometries, undercuts or cavities can be produced with it (Hague, Mansour and Saleg, 2002). In comparison to conventionally manufactured components, a weight reduction of about 10% can be achieved (Lindemann et al., 2013) (Chen, Fritz and Shea, 2015).
In order to reduce the weight of a component further, the application of internal structures as a unique selling proposition towards conventional manufacturing methods becomes increasingly more important (Teufelhart, 2012). Internal structures are defined as "repeatable elements for the substitution of solid volumes with the objective to vary the material arrangement on a macroscopic level without affecting the material properties" (Lippert and Lachmayer, 2016). The main challenge lies within the integration of load optimized internal structures in order to reduce the component weight without influencing the mechanical properties. For example, a significant increase of stresses has to be avoided, so that the life expectancy is not influenced (Smith, Guan and Cantwell, 2013). In industry, different applications for conventionally manufactured internal structures are available, for example in prosthetics. Here, the objective is to maximize the surface of a component, so that an adequate adhesion of the bone with the prosthesis is possible. Another approach is the application of sandwich structures to increase the stiffness of planar geometries. The use of these becomes apparent in the automotive and aerospace industry as well as in the application of wind turbines (Kopp et al., 2009). The production of complex structures using conventional methods has limitations (Diehl et al., 2010). Thus, the question, which amount of weight saving can be achieved effectively using internal structures - considering homogeneous stress distributions and maintaining manufacturability - is investigated.

2 DESIGN METHOD FOR A RESTRICTION ORIENTED DESIGN

The following part describes a design method for weight reduction using internal structures for selective laser melting. As shown in Figure 1, the approach is divided into three sequential sections, which are characterized by an iterative arrangement.

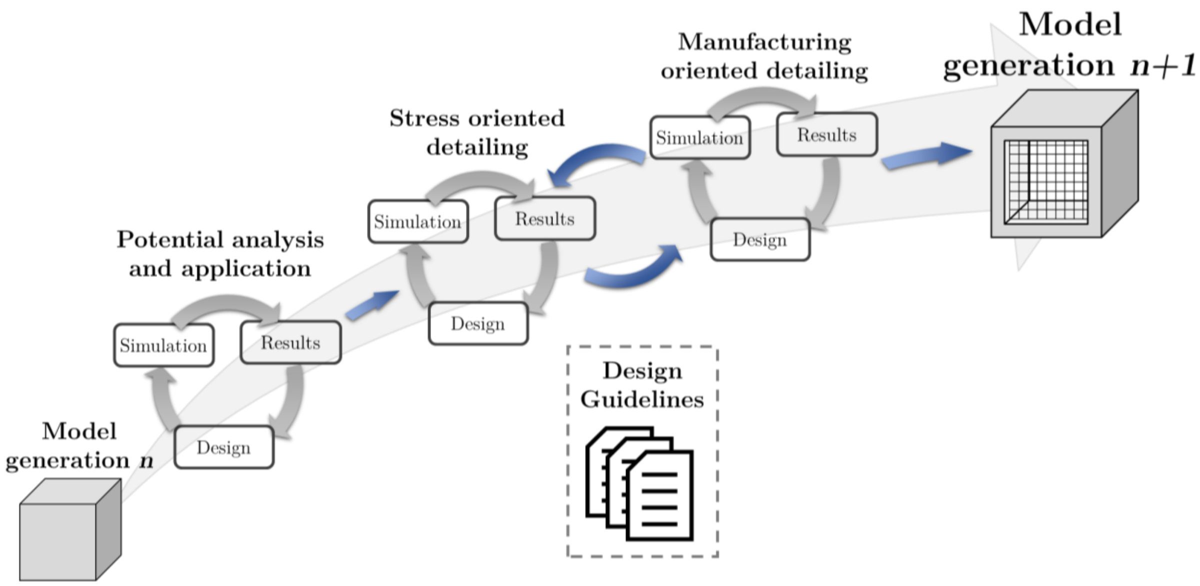
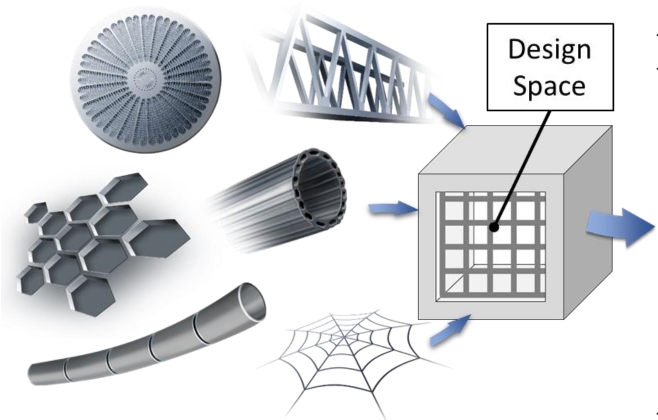


Figure 1. Design method to implement internal structures in technical systems

The initial model generation n, which is produced conventionally, has to be analysed at the beginning. Therefore, information about force application points, the amount of the load vectors as well as the stress state of the component has to be figured out. This information can be recirculated from the life cycle information in form of maximum loads or critical load cases (Gottwald, 2016). Based on the knowledge of internal stresses, a physical design space has to be defined. This includes the definition of connection and installation points as well as relevant effective areas, for example those concerning clamping in the post-process. Based on the stress state of the mechanically loaded component, internal structures are selected and transferred into the physical design space. The optimization of internal stresses and the verification of the manufacturability result in the model generation n+1.

2.1 Potential analysis and application

In order to select a suitable structure for a predefined load case, information about the structural behaviour (stress, strain or deformation) for different internal structures in response to mechanical loads has to be gathered. For basic knowledge, Lippert and Lachmayer (2016) describe investigations of digital specimens with internal structures. Accordingly analogies from nature and technology are modelled as digital specimens (basic geometries, e.g. cube or cylinder with internal structure) and analysed with a structure mechanical simulation. As a part of this, the structures undergo a basic sizing. This includes an optimization by avoiding stress peaks as well as a homogenization of the stress distribution. The sizing is limited by design guidelines, which define required parameters such as minimum wall thickness or hole diameter (Lippert 2017).
The final simulation results provide information about the optimal load type (bending, compression, tension, torsion or shear) as well as the optimal orientation of a structure. Furthermore, the results enable the selection of suitable internal structures when the load case is predefined. Figure 2 shows a number of internal structures with suitable fields of application.



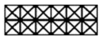
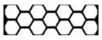
Structure	Shape	Fields of application
Bamboo		Bending, torsion
Lattice structures		Bending, compression
Truss		Bending
Truss, stiffened		Bending, tension, compression
Cobweb		Torsion
Honeycomb		Bending, compression
Honeycomb, stiffened		Bending, compression

Figure 2. Analogies for structures from nature and technology with exemplary applications

2.2 Stress oriented detailing

The selected internal structure is transferred into the component context. Within the physical design space, a load adapted orientation of the structure takes place. Through an iterative validation in a simulation environment, the transition regions between the internal structure and the relevant effective areas are designed. The objective is the homogenization of stresses and the reduction of maximum peaks in order to fulfil the permitted material properties.

2.3 Manufacturing oriented detailing

The stress optimized model generation is evaluated in terms of manufacturability with selective laser melting. Hence, the model is verified based on design guidelines, which represent the possibilities of the used parameters given by the machine and the material. These include strategies to avoid support structures by maximum overhangs or the equipping of cleaning openings to remove non-melded powder from cavities. Through the iterative application of simulation and design tools, a continuous analysis of the design impact towards the stress, strength and stiffness of the technical system is done.

3 INFLUENCE FACTORS FOR DESIGNING INTERNAL STRUCTURES

3.1 Relevant Design Guidelines

Analogous to conventional manufacturing methods, design guidelines, rules or recommendations (following named design guidelines) are partially available for selective laser melting (Vayre et al., 2012) (Wartzack et al., 2010) (VDI, 2015). In form of knowledge storage, such as checklists or design catalogs, this guideline provides standard values to ensure the manufacturability of the component in the early development phases. For example, limit values for a minimum wall thickness or a minimum diameter, depending on the building direction of a component, are hereby defined (Zimmer and Adam, 2012) (Kranz, Herzog and Emmelmann, 2015). These values are partially available for different parameter sets, which describe a specific machine and material. Furthermore, general statements are available, such as the optimum orientation, arrangement or positioning of a component in the process chamber or the necessity for cleaning openings (VDI, 2015).

The consideration of such guidelines for designing internal structures using selective laser melting is essential. Figure 3 shows exemplary guidelines for designing a lattice structure. Consequently, the geometry has to be evaluated regarding maximum overhangs or maximum angle in order to avoid support structures and thus reduce the post-process effort. Additionally, a minimum wall thickness as well as minimal hole diameter has to be considered, so that the scale of structural elements is limited. In case of internal support structures, which occur in cavities, support strategies have to be provided. Furthermore, cleaning openings to remove non-melded powder are necessary. Thereby, design guidelines limit the minimum diameter for such an opening.

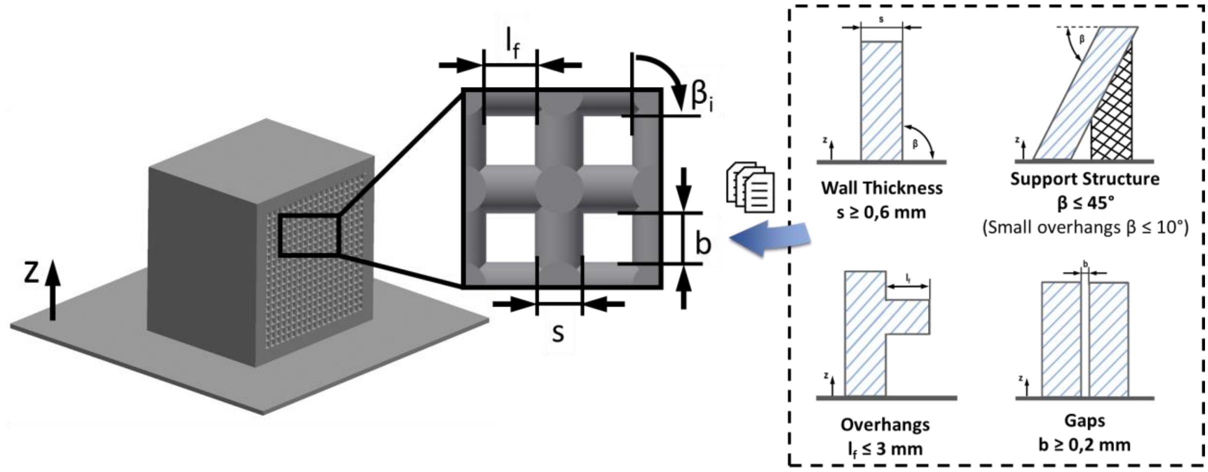


Figure 3. Schematical illustration of relevant design guidelines for a lattice structure

3.2 Setting a Material Database

To ensure a comparability of the results, a computer-aided simulation environment is set up, which is used for all computer-based steps. Hereby, a database to specify the anisotropic behaviour of a selective laser melting component is defined. The use of this material database makes the consideration of the building direction possible.

Analogous to conventional manufacturing methods, powder alloys for selective laser melting are characterized by various material properties depending on the post-process, meaning that the properties after the building process and after a post-heat treatment are different. In practice, selective laser melting components are predominantly used after a heat treatment, because internal stresses are reduced and the material properties are homogenized. Based on the example of the aluminium alloy AlSi10Mg - which is used in this paper for the validation - the material characteristics after heat treatment (300° C for 2 h) are listed in Figure 4 (EOS, 2014). These values can be used for calculating the static properties of a mechanical loaded component. Beside the static properties, the Stress-Cycle (S-N) curve for calculating the fatigue properties can also be set (Tang and Pistorius, 2016), (Brandl et al., 2016), (Kempen et al., 2012), (Anyalebechi, 2011), (Humbeeck and Thijs, 2013).

	x-direction	y-direction	z-direction
Modulus of elasticity [kN/mm²]	70	70	60
Density [g/cm³]	2,67	2,67	2,67
Poisson's ratio	0,3	0,3	0,3
Tensile strength [kN/mm²]	345	345	350
Yield strength $R_{p\,0,2}$ [kN/mm²]	245	245	245
Elongation at fracture [%]	12	12	11
Shear modulus [kN/mm²]	2,436 (yz/ xz)	2,436 (yz/ xz)	2,6315 (xy)

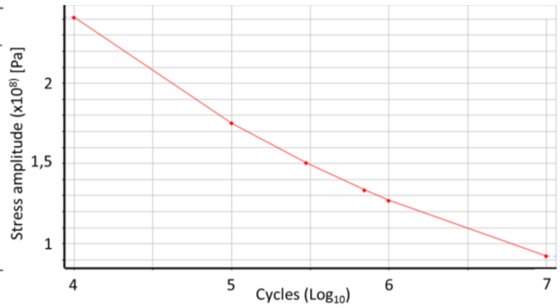


Figure 4. Material database and S-N curve for AlSi10Mg after heat treatment

4 RESTRICTION ORIENTED DESIGN OF A DEMONSTRATOR

In order to validate the design method, the integration of internal structures in a demonstrator is described. After analysing the initial model in terms of relevant load cases and the stress state, the definition of a physical design space is made. Based on the knowledge of predominating load cases, adapted model generations are built up (using Autodesk Inventor 2017) and analysed with a structure mechanical simulation (using Ansys Workbench 17.0). Stress peaks are reduced iteratively by homogenizing the stress distribution in consideration of a maximum weight reduction. The results are developed iteratively. Intermediate results are not presented entirely.

4.1 Definition of a Design Space

A pedal crank of a bicycle is used as the demonstrator, which is made of the alloy AlSi10Mg with an initial weight m = 217.5 g. As shown in Figure 5, different load cases occur in response to the rotational movement. The rotational angle α_i defines the position of the pedal crank in relation to the initial position α_1 = 0°. Within α_{max} = 360°, three predominant load cases (tension, compression and bending) occur. The pedal crank is assumed as an idealized model, which is why the marginal torsion component - as a fourth load case - is not considered in this paper. To figure out the maximum stresses, the load is subjected to an amount of F_{max} = 2250 N, which results from the occurring force while driving accelerated uphill with an added safety factor (Sullivan and Chris, 2013). As depicted in Figure 5, a bending load results in the maximum von Mises stresses. Consequently, bending as the critical load case has to be considered for dimensioning the new model generation.

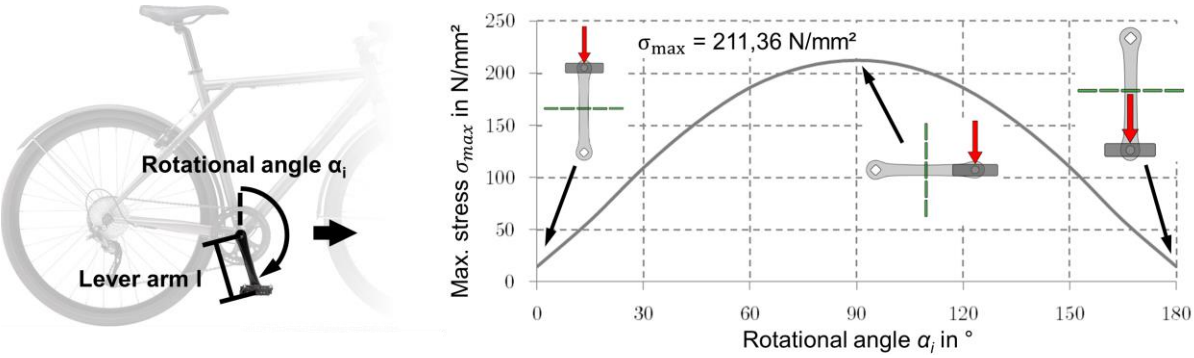


Figure 5. Maximum stress σ_{max} of a pedal crank depending on the rotation angle α_i

For the determination of the physical design space, preliminary investigations are carried out. The objective for designing a structural component is the material arrangement in the areas of maximum stresses. Referring to Figure 6, the pedal crank has to be reinforced in the two outer surfaces. Based on the theory of the bending beam, design strategies to define the physical design space are modelled in several forms. In addition to a conventional design strategy of an I-profile (1), forms with internal structures are illustrated. Forms (2) and (3) describe an unclosed surface of the internal structure. In contrast, forms (4) and (5) show the complete covering. Figure 6 depicts the simulation results for the different forms - according to the simulation environment of the initial model. The results are defined as a function of the stress and component weight. The graphical curves of the different forms describe the variation of the wall thickness x for each model. Furthermore, the stress/ weight ratio of the initial model as well as the allowable stresses σ_{all} of the aluminium alloy AlSi10Mg are illustrated.

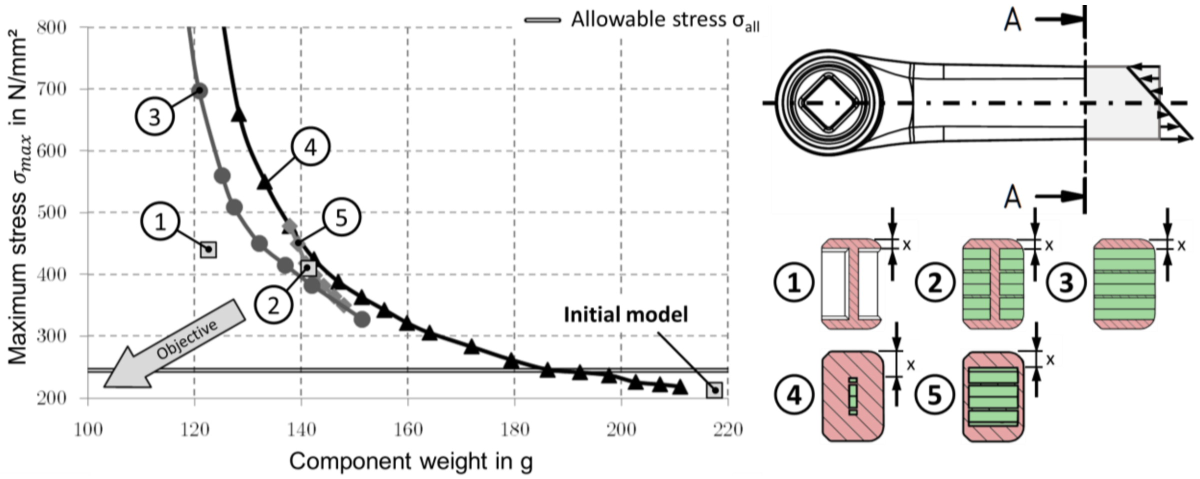


Figure 6. Determining the physical design space as a function of the cross section

It can be seen, that an increase in wall thickness x results in a reduction of the maximum stresses induced and in a rising component weight. Based on the simulation results, the physical design space is determined by design form (3). Beside the limitation of the two outer surfaces, the bearing locations of the pedal and the bottom bracket have to be considered.

4.2 Potential Analysis and Application

Using the findings about the load type, appropriate internal structures for transmission in the physical design space are selected. Based on the applications in section 2.1, six different structures with a high eligibility for bending load are chosen and transferred towards new model generations with comparable parameter sets (same number of structural elements, equal wall thickness, etc.).

Figure 7 depicts the physical design space as well as the chosen structures. The stress/ weight ratio can be used for the selection of an internal structure, which can be optimized to reduce stress peaks and to homogenize the stress distribution. It can be seen, that the transmission of a structure in the component context has a non-negligible influence for the stresses. Thus, each structure has to be examined in order to neglect local stress peaks that are due to an increased notch effect.

The simulation results show that the structures (1) and (2) have significant maximum stresses despite the reduction of local stress peaks. These structures are not suitable for the stress oriented detailing and thus also not adequate for a new model generation. Furthermore, the structures (3), (8), (9) and (10) show reduced stresses with a marginal weight advantage. Because the component weight can probably not be significantly reduced in the further optimization, these structures are also not considered. Structures (4), (5), (6) and (7) have a potential for further optimization because they represent a synthesis of weight and stress. Nevertheless, the induced stresses in the present models are still too high. With the objective to reduce the induced stress towards the allowable stress, structure (7) is analysed further.

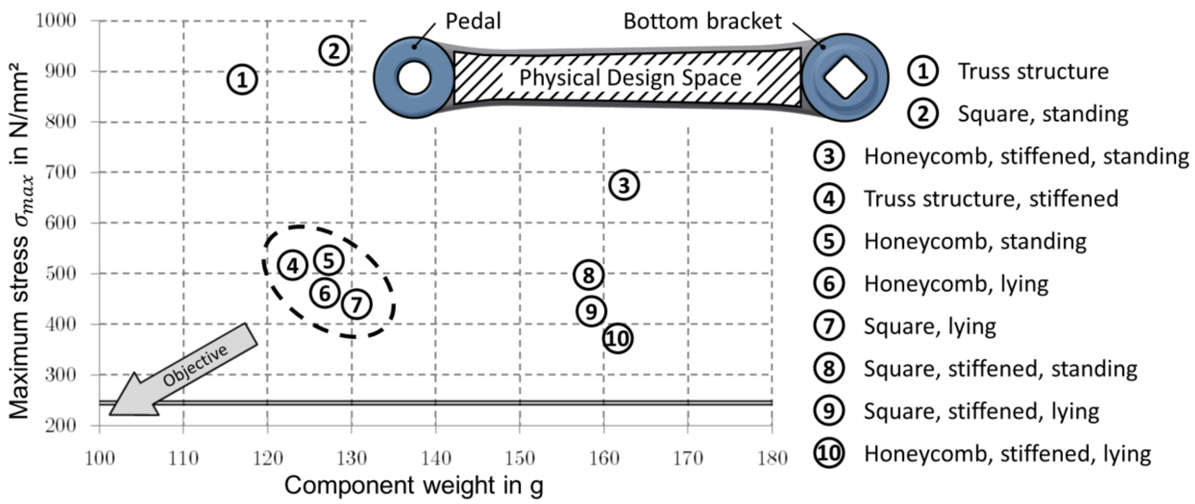


Figure 7. Potential analysis for internal structures within a pedal crank

4.3 Stress oriented Detailing

Based on the selected internal structure (7), two optimization approaches to reduce stress peaks as well as to homogenize the stress distribution are accomplished. On one hand, the element size is gradually refined as shown in Figure 8. In the areas with a high stress, detailed structures to densify the material arrangement are implemented. Through a subdivision within a square, the element size is halved in three steps a_i to a_{iii}. With regard to the design guidelines for a minimal gap, a fourth refinement level is not implemented but rather modelled as a solid material. It can be seen, that the maximum stresses could be reduced, so that the allowable stress is not exceeded. The second approach is the variation of the physical design space. By adjusting the helix angle β_i, the design space is varied iteratively in the fields of increased stresses. The variation of the design space also provides a maximum stress $\sigma_{max} \leq \sigma_{all}$. In addition, the stress distribution is homogenized by not affecting local peaks. Due to the lower weight, the model generation, which could be achieved by varying the physical design space, is further considered for the manufacturing oriented detailing.

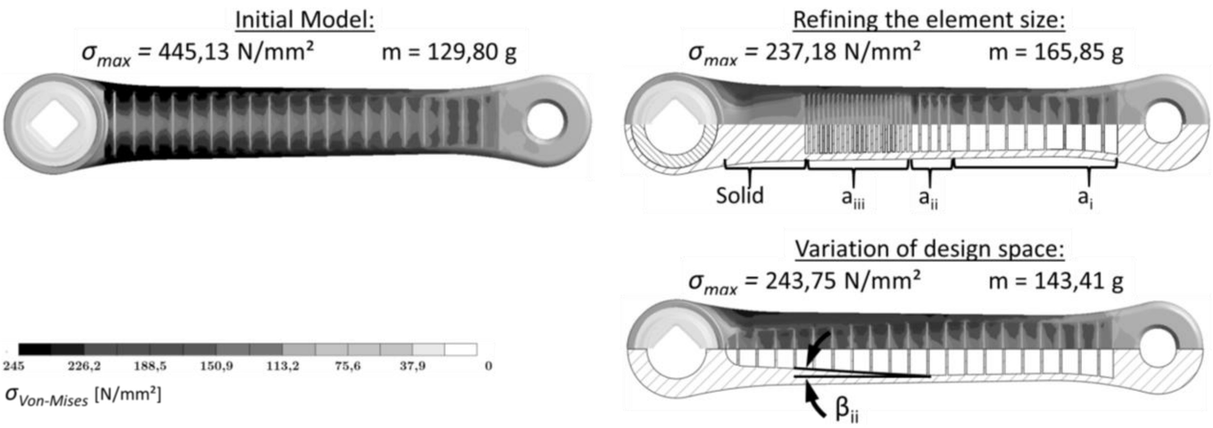


Figure 8. Optimization strategies for stress oriented detailing

4.4 Manufacturing oriented Detailing

The idealized model is verified for manufacturability in the next step. A basic dimensioning taking into account the design guidelines as described in chapter 3.1 is already done during the potential analysis and the transfer into the component context. Here, the parameters of the structure have been selected for manufacturability in selective laser melting.

In the next step, cleaning openings are intended to remove non-melted aluminium powder after the building process. The cleaning openings are provided for each inner square and are mounted onto the less loaded outer surfaces. Further forms of cleaning openings, such as connecting the cavities in the component inside or elliptical openings, were not effective and are not considered further. As shown in Figure 9, a cleaning opening causes an increase of the maximum stresses σ_{max}. Accordingly, the opening has to be strengthened to achieve the allowable stress σ_{all}. Through this approach, a reduction towards σ_{max} = 244.31 N/mm² ≤ σ_{all} is possible. As shown in Figure 9, the maximum stresses of the notches can be moved in the direction of the outer surfaces.

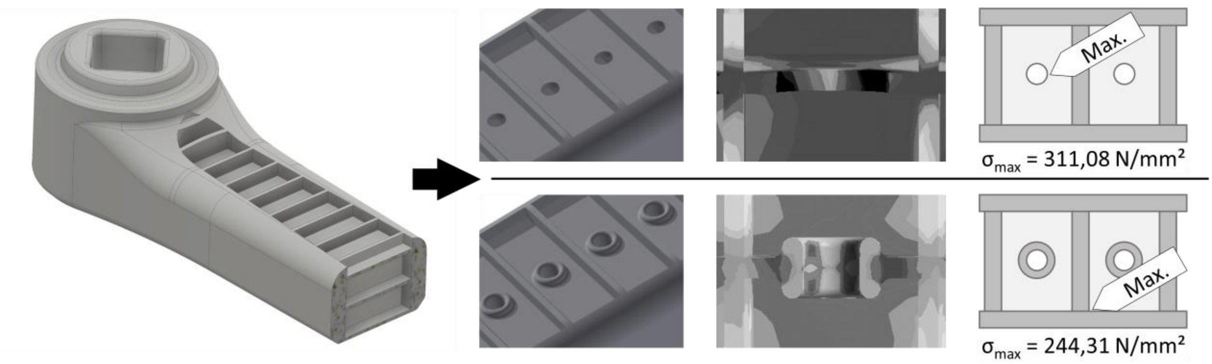


Figure 9. Optimization strategies for stress oriented detailing

The new model generation is analysed in terms of necessary support structures. Therefore, the position, orientation and arrangement in the process chamber has to be defined. For the presented case, the pedal crank is intended to have a horizontal orientation during manufacturing, so that a minimum height is given and manufacturing time can be reduced. Furthermore, a high accuracy of the bearing points can be achieved, thereby allowing for a reduction of the post process effort. Due to the horizontal orientation, various down skin surfaces - normal vector is negative in respect to the direction z (VDI, 2015) - with a parallel arrangement to the construction platform arise as depicted in Figure 10. These surfaces occur in the component cavities, so that a mechanical removal of the necessary support structures is not feasible in a post process. Accordingly, geometries for avoiding support structures have to be designed.

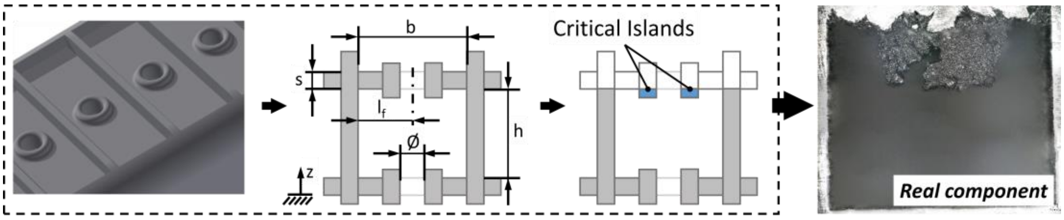


Figure 10. Critical Islands, b = 6 mm, h = 6 mm, l_f = 3 mm, s = 0.7 mm, Ø = 2 mm

A relevant parameter for designing the internal structures is the maximum overhang $l_f \leq 3$ mm. This value describes the width of a geometry, which can be produced in a 90° angle without the necessity of support structures. For the design of the pedal crank, the overhang is supported from both sides, so that the upper limit b = $2 * l_f$ is achieved. In combination with the height h = 6 mm, a marginal sinking of the overhang in the non-melted powder during the construction process will take place. However, due to the horizontal down skin surface a high roughness is expected.
In addition, Figure 10 depicts critical islands on the strengthened cleaning openings. In contrast to an overhang, these geometries are not connected with the residual component. The sinking into the negative z-direction during the process and a resulting non-defined surface cannot be avoided. Thus, support strategies are defined. First, pillars are designed to support the critical islands. These are dimensioned with a minimum diameter $Ø_s$ = 0.7 mm according to the design guidelines, so that the flowability of the powder is not affected. However, damage to the pillars during the building process occurs as a result of the coating movement. Concerning the second strategy, bevels are provided below the cleaning openings. Due to the small overhang, the helix angle is set iterative from β = 30° - 45°. As shown in Figure 11, an angle of β = 45° prevents the sinking of the critical islands and shows an appropriate dimensional accuracy for the down skin surfaces.

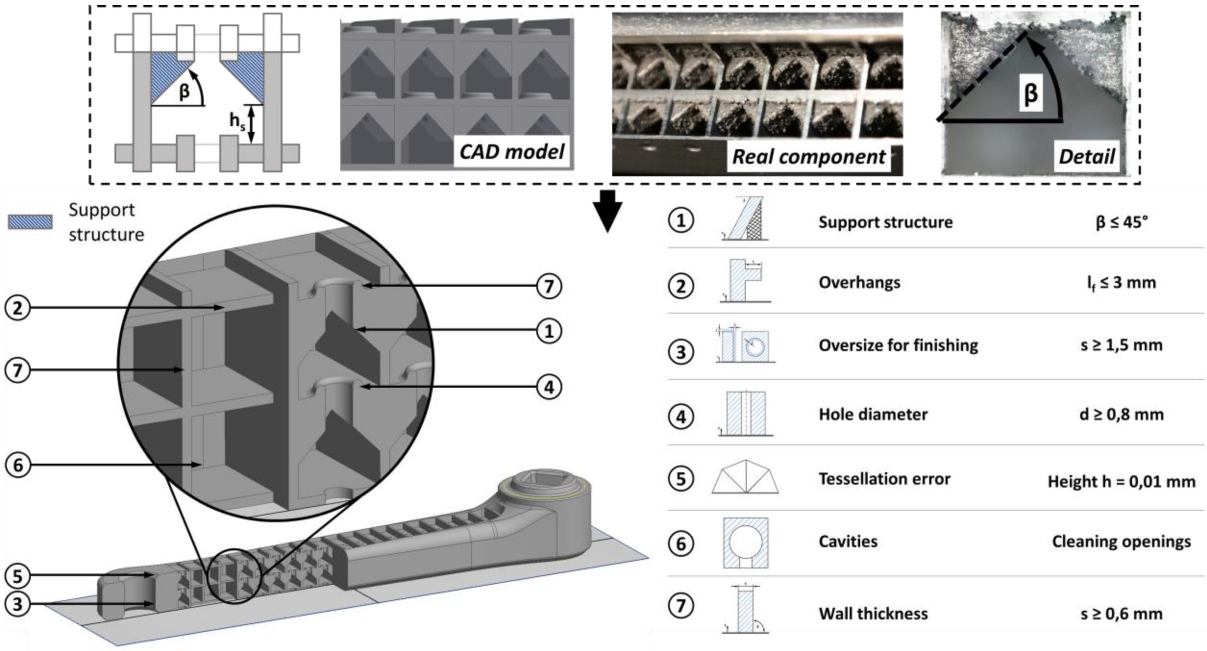


Figure 11. Restriction oriented design of the new pedal crank generation

Based on the optimized support strategy, Figure 11 illustrates an overview of relevant design guidelines, which have a significant influence for designing internal structures in the demonstrator. The new pedal crank generation n + 1 has a maximum stress σ_{max} = 242.46 N/mm². After introducing the support structures underneath the cleaning openings, the component weight is m = 148.92 g (without support m = 143.85 g). Compared to the initial model, with the weight m = 217.45 g, the application of internal structures offers new lightweight potentials. The result is a geometry which cannot be manufactured using conventional manufacturing methods.

5 CONCLUSION

Based on the theoretical design method, the integration and restriction oriented design of load optimized internal structures can be described. As shown in Figure 12, the total weight of the new model generation is reduced by 32 %. However, the weight reduction has to be set in relation to the potential of optimizing the initial model for conventional manufacturing methods. In addition to the weight reduction, the maximum stress σ_{max} is increased by approximately 15 %. By referring to the properties of the aluminium alloy AlSi10Mg, the maximum allowable stress σ_{all} is complied with. Due to the assumed force, a safety factor is also taken into account. In a next step, the physical models need to be analysed with a test bench. Beside the analysis of static forces to validate the FEM simulation, the dynamic properties for life tests has to be determined.

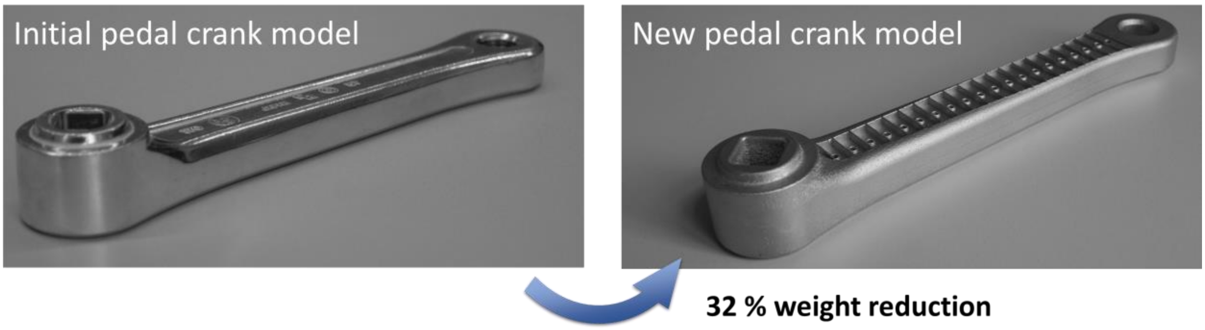


Figure 12. Comparison of the initial model and the new model generation

For further optimization, the conditions of the pedal crank can be varied. On one hand, a superimposed bending and torsional load can be set. On the other, a variation of the physical design space through breaking from the conventional shape is significant. However, especially three restrictions have to be considered. The shape is defined by mounting restrictions of the pedal, the bottom bracket and the distance l = 170 mm between the bearing points. Considering these restrictions, the shape can be enlarged by a simultaneous application of more filigree structures. By varying the physical design space, an increased bending stiffness could result.

The sequential approach of the design method requires an iterative evaluation of the stress state and the manufacturing oriented design regarding the weight reduction. In order to achieve a significant reduction of the optimization effort, a mathematical algorithm, which varies the macroscopic material arrangement on the basis of the maximum stresses, will be developed. Thus, the proportion of solid material in critical stress areas can be increased. As a part of this, design guidelines like minimum wall thickness, maximum overhang or necessary bevels have to be considered independently.

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