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Design guidelines for a software-supported adaptation of additively manufactured components with regard to a robust production

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Abstract

The design of additively manufactured components requires a rethinking in the design process. This is inhibited by a lack of knowledge about additive manufacturing technologies. For this reason, a large number of design guidelines have been developed in recent years. In their present form the design guidelines are not suitable for processing in a software algorithm, since the guidelines have a certain redundancy and partly influence each other. This paper describes several steps to consolidate the existing guidelines and to prepare them in a way that they can be used in a software algorithm for a design check. Therefore, existing guidelines are collected, prioritized and quantified with regard to their relevance for a robust production. To quantify the guidelines, test specimens are developed, produced and evaluated in order to obtain a limit value for the geometric properties. With these limit values, quantifiable design guidelines can be applied to designers and software tools.

Introduction

Additive manufacturing (AM) processes are increasingly used in the production of components and structures in industrial practice. The term additive manufacturing refers to processes in which a component is manufactured in layers and without forming tools [Tho09, Geb07, VDI3405, LQM+17, LAS+16]. The potentials of the layered design is visible from an economic and technical point of view. In particular, the freedom in the geometric design of components enables to produce structures that cannot be produced using conventional manufacturing processes such as turning or milling. Complex structures, such as lattice structures or bionic and topologically optimized structures can be produced. However, additive manufacturing technology is also subject to some restrictions. The challenge of this relatively new technology is to exploit the potential mentioned, taking into account the process-specific restrictions. New design processes and possibilities in component design require a rethinking, especially in the design process. This rethinking is made more difficult by a lack of knowledge of additive manufacturing technology [HHD06, WC15].

In order to make efficient use of AM, design recommendations have been made in recent years [Ada15, KHE15, Tho09, VDI3405-3]. These design recommendations support the design for production and thereby the minimizing of geometric deviations during the design process in order to enable a robust manufacturing. Since the development has resulted in a large number of recommendations, which contain different quantitative information, it is increasingly difficult to maintain an overview and to identify the most important recommendations concerning a robust production.

Therefore the present study focuses on an automated, software-based design check for additively manufactured components with laser beam melting (LBM) with regard to manufacturability, minimal post-processing by removing support material and the best possible compliance with geometric requirements. An automated, software-based design check should support the conception and design of AM components. Furthermore, it is possible to test lattice structures and topologically optimized components for a robust production. For this reason, existing design recommendations have to be reviewed and prioritized according to their relevance for the AM process and component quality. The aim is to identify a reduced number of recommendations that include all process-specific restrictions. These recommendations should then be prepared and experimentally tested in order to obtain relevant design guidelines for the respective case, which can be used in an automated software-based design check.

State of the art: Design recommendations

The scientific literature contains numerous papers containing recommendations for the design of AM components suitable for production. Some work dealing with the laser beam melting process will be presented below.

In his work on various component geometries, THOMAS [Tho09] carries out experimental parameter studies with the material 316L and analyses these with regard to production-related restrictions. The results of the analysis form the basis for the preparation of design recommendations. For this purpose, sample geometries are developed to specifically evoke previously observed effects. Through targeted variation of geometric dimensions, THOMAS determines how a geometric property is to be designed in order to produce it reliably using laser beam melting processes. His recommendations refer in particular to the design of overhangs, gaps, bores and the need for support structures.

ADAM [Ada15] develops design recommendations for fused deposition modeling, laser sintering and laser beam melting. He considers so-called geometric standard elements, which are used repeatedly in component design. Based on these standard elements, he develops specimen geometries that reflect the properties of these standard elements. By varying the geometric properties, he identifies conditions in which robust production can be guaranteed no longer. ADAM records the findings of its investigation in recommendations that describe a fact quantitatively or qualitatively.

KRANZ, HERZOG and EMMELMANN [KHE15] carry out experimental investigations with the material TiAl6V4. The aim of the work is to define design recommendations for lightweight components so that they can be manufactured and used reliably. Typical elements that are frequently recurring in lightweight design are considered, such as beam elements and cavities. The results are classified in tabular form and supplemented by qualitative and quantitative data.

Some of the literature contains recommendations describing the same facts. However, the quantitative data often differ due to different materials, machines and their parameter settings. Furthermore, some of the work contains recommendations whose essence can also be applied to other recommendations and geometries.

For this reason, existing design guidelines need to be consolidated and prioritized to reduce their number for a software-based design check. Furthermore, they need to be mathematically describable so that they can be processed in a software. This poses a particular challenge for design recommendations with qualitative data, which have to be transformed into quantitative data.

Priorization of design recommendations

The knowledge about a production-ready design of AM components is manifold and influenced by many factors. Most publications on design recommendations for AM processes are often comparatively abstract and therefore less qualified for the generation of quantitative indications. In order to make these recommendations manageable for a software based design check, a procedure is developed, which provides a compact overview of relevant design recommendations and quantifies characteristic values. In the course of this, the design recommendations mentioned above [Ada15, KHE15, Tho09] are arranged in a tabular overview. Despite diverging boundary conditions in the derivation of design recommendations, agreement can be found among the different authors. By prioritizing these nearly 100 design recommendations, relevant guidelines for robust production can be identified. The design recommendations are allocated to four priority levels according to Table 1.

Table 1: Prioritization scheme of the design recommendations

Priority level	**Description**	**Exemplary design recommendations**
1	Violation of the design recommendation endangers the manufacturability or functionality of the component.	Adherence to the minimum wall thickness to ensure the design of a wall. [KHE15]
2	Violation of the design recommendation deteriorates the component properties (surface quality, geometric properties). These deteriorations can be corrected by post-processing.	Provision of surfaces oriented perpendicular to the building platform in order to avoid the stair step effect, as this worsens the component surface [Ada15].
3	Design recommendations enable users to determine the dimensions or positions of the components themselves without setting a specified limit value. They have no significant influence on component quality.	The user can freely select the component position in the building chamber. [Ada15]
4	Design recommendations are also taken into account in other design recommendations.	Overhanging sections with an angle of <50° must be supported [KHE15]. This recommendation is already included in the recommendation to orientate surfaces 45° to the building platform. [Ada15]

The recommendations classified in priority level 1 and 2 are most important for use in a software for production-oriented design checking and have a direct influence on a robust production, component functionality and component quality. Due to their relevance for automated, software-based design verification, these recommendations will be called design guidelines in the following. These are described in Tabels 2-9 where they are categorized in eight superior categories. They are prepared graphically by listing the essential effects. These are shown in the second and the third column, respectively, by an example suitable for production and an example not suitable for production. Each guideline is also listed in written form in the first column. Backgrounds are explained in the surrounding text.

<u>Surface orientation</u>

The guideline category for surface orientation contains four effects, that occur when the orientation angle $\delta_{O,lim}$ falls below a limit value:

- the surface quality is reduced by the need for support.
- a production-related oversize is introduced by the surfaces orientated obliquely to the building platform, because of powder adheres due to the laser penetration depth beyond a component layer

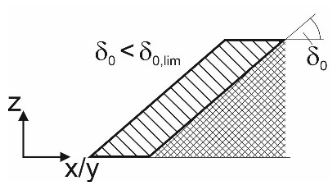
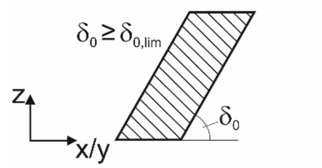
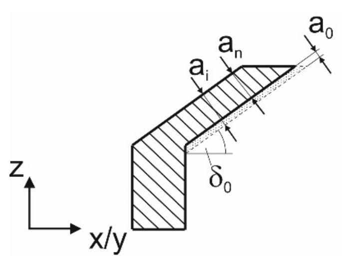
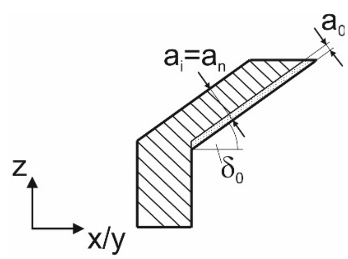
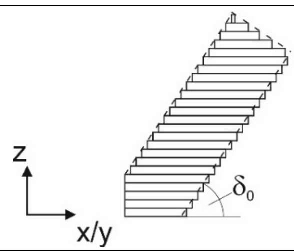
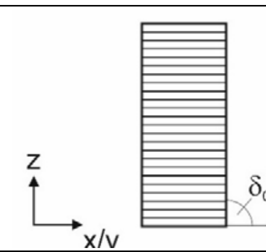
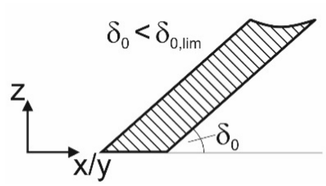
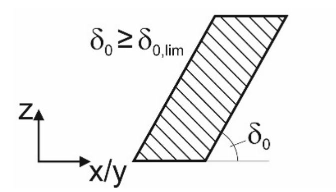
- the stair step effect, which results from the layered construction and the approximation of the component contour through rectangular layers which also leads to a poorer surface quality at low surface orientation angles.

These effects are mapped to priority level 2.

- a robust production is endangered if the surface orientation angle of unsupported surfaces falls below a limit value.

This effect has to be allocated to priority level 1

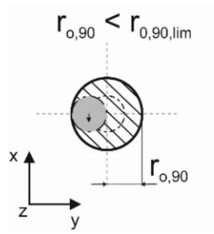
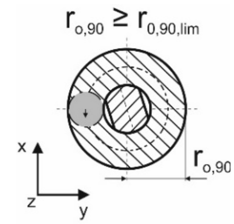
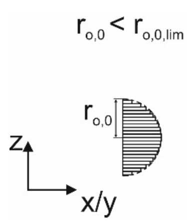
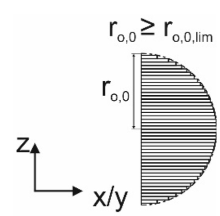
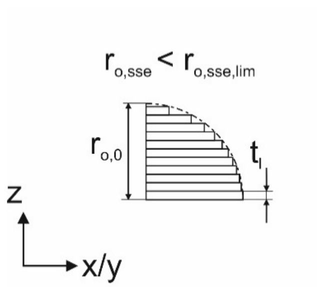
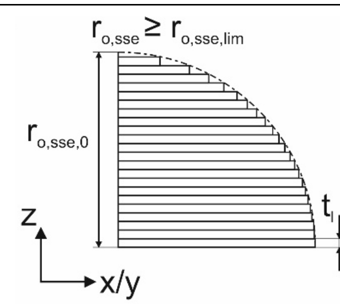
Table 2: Guideline "Surface orientiation"

	Not suitable for production	**Suitable for production**
1 Surface orientation		
1.1 Support: Angled surfaces must not fall below the angle $\delta_{O,lim}$ relative to the building platform to avoid support		
1.2 Powder adherence: Unintentional powder buildup with a thickness a_O occurs on the surfaces facing downwards, which cannot be prevented. The dimension a_O must be taken into account in the design so that the actual dimension a_i complies with the nominal dimension a_n.		
1.3 Stair step effect: If possible, large surfaces should be aligned orthogonally to the building plane (δ_O = 90°).		
1.4 Unsupported surfaces: Unsupported surfaces should not fall below a limit value for δ_O to ensure a robust production		

<u>Outer radius</u>

The minimum possible outer radius is limited depending on the orientation in the building chamber. Thus, the radius in 90° to the building platform is dependent on the formation of a contour path and an inner grid, which only occurs at a limit value for the radius $r_{o,90,lim}$. The cross-section is also limited in 0° orientation and should not fall below a limit value to allow the component to detach from the building platform. These guidelines are allocated to priority level 1. Furthermore, the stair step effect occurs in rounded component areas at a limit value for the radius. These guideline is mapped to level 2.

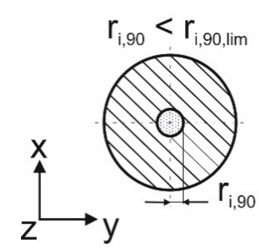
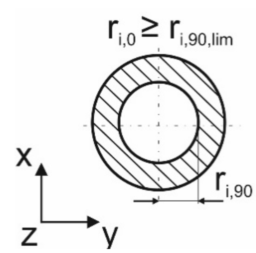
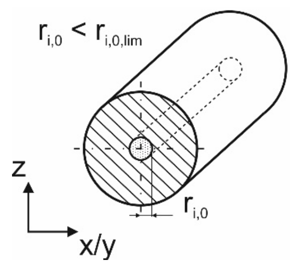
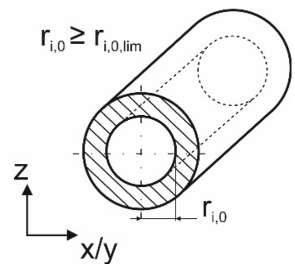
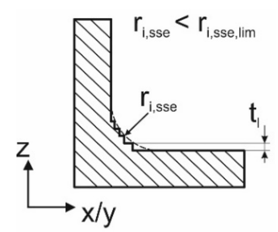
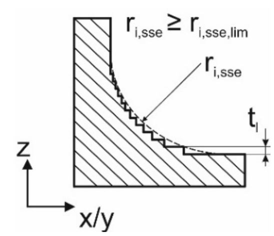
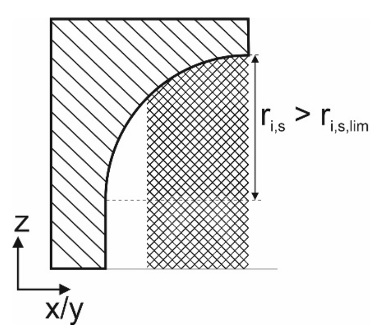
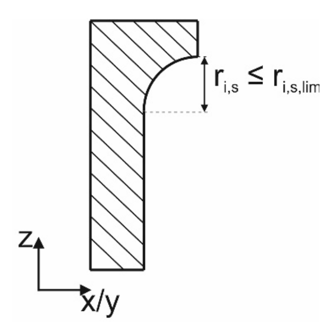
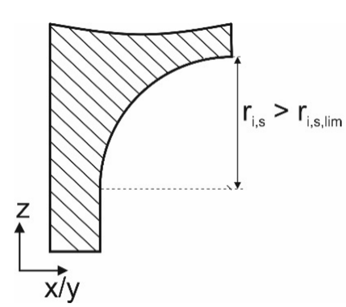
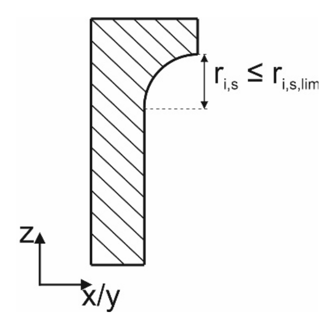
Table 3: Guideline ”Outer radius“

	Not suitable for production	**Suitable for production**
2 Outer radius		
2.1 Minimum 90°: The outer radius $r_{o,90}$ of cylindrical components must be greater than or equal to the permissible outer radius $r_{o,90,lim}$.		
2.2 Minimum 0°: The outer radius $r_{o,0}$ of cylindrical elements must be greater than or equal to the permissible outer radius $r_{o,0,lim}$.		
2.3 Stair step effect: The outer radius $r_{o,sse}$ should exceed the permissible outer radius $r_{o,sse,lim}$.		

<u>Inner radius</u>

The inner radius cannot be formed with very small radii, as powder adhesion results in radii that are below the limit value $r_{i,90,lim}$. This effect occurs both in the 90° and in the 0° orientation. Moreover unsupported surfaces can only be build until a limit radius. These three effects are allocated to level 1. In addition, rounded surfaces are approximated by rectangular surfaces, which lead to a deterioration of the surface quality due to the stair step effect. The deterioration of the surface can be increased by the need for support above a limit value for the radius. Because of its relevance for robust production, this guideline is are mapped to priority level 1.

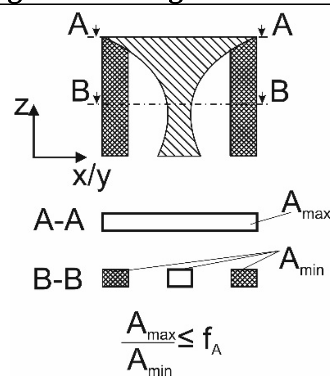
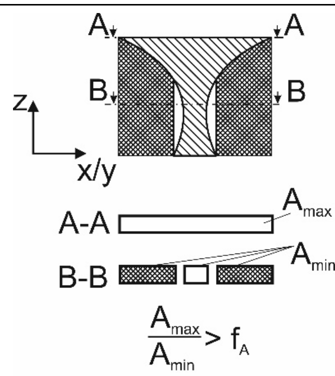
Table 4: Guideline "Inner radius"

	Not suitable for production	**Suitable for production**
3 Inner radius		
3.1 Minimum 90°: Cylindrical cavities oriented perpendicular to the building platform need an inner radius of $r_{i,90,lim}$.		
3.2 Minimum 0°: Cylindrical cavities, which are not oriented perpendicular to the building platform need an inner radius of $r_{i,0,lim}$.		
3.3 Stair step effect: The inner radius $r_{i,sse}$ should be larger than the permissible inner radius $r_{i,sse,lim}$.		
3.4 Support: To produce a cavity or an overhang with the inner radius $r_{i,s}$ without support structures, the radius $r_{i,s}$ of the downward facing surface must be selected smaller than or equal to the permissible inner radius $r_{i,s,lim}$.		
3.5 Unsupported Surfaces: Unsupported surfaces should not increase over a limit value to ensure a robust production without support		

<u>Cross-sectional area change in building direction</u>

While building components in layers, it must be ensured that the ratio of the maximum cross-sectional area A_{max} and the minimum cross-sectional area A_{min} is less than or equal to the factor f_A, especially for branched components. This applies in the case that A_{max} is in a higher layer than A_{min}. When determining the cross-sectional areas A_{min} and A_{max}, not only the cross-sectional area of the solid component but also the cross-sectional areas of solid support structures are added up. This guideline is to be assigned to priority level 1, as non-compliance will lead to a endangering of the build job.

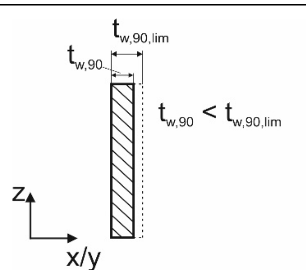
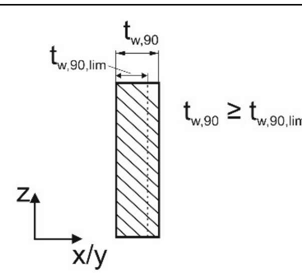
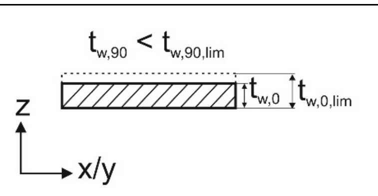
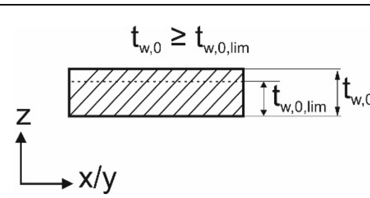
Table 5: Guideline ”Cross-sectional area change in building direction“

	Not suitable for production	**Suitable for production**
4 Cross-sectional area change in building direction		
The ratio of the cross-sectional area of A_{max} to A_{min} should not exceed the factor f_A over the overall height z.		

<u>Wall thickness</u>

These guidelines are mapped to priority level 1, as violation leads to walls not being built up either in 0° or 90° orientation. This is on the one hand due to the lack of contour and grid paths in the 90° orientation. And on the other hand to the fact that walls in the 0°orientation under a limit wall thickness cannot be detached from the support and have holes in the surface.

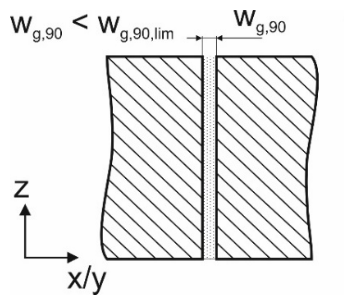
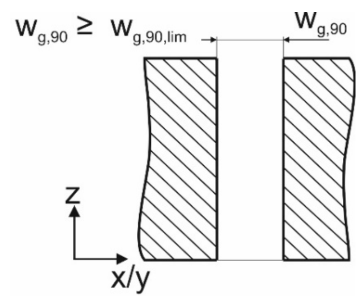
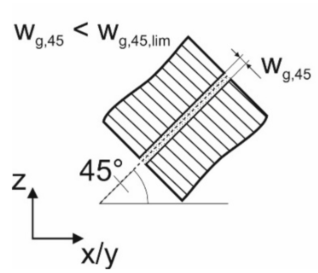
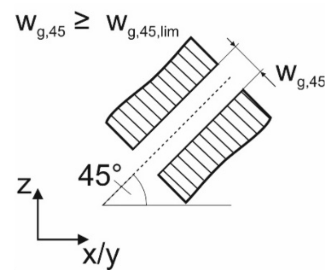
Table 6: Guideline “Wall thickness“

	Not suitable for production	**Suitable for production**
5 Wall thickness		
5.1 Minimum 90°: The wall thickness $t_{w,90}$ must not be less than the minimum wall thickness $t_{w,90,lim}$.		
5.2 Minimum 0°: The wall thickness $t_{w,0}$ must not be less than a minimum wall thickness $t_{w,0,lim}$.		

Gap width

Gaps are not formed below a minimal gap width, as the gap is closed by powder adhesion. Violation of the rule therefore leads to a loss of function. For this reason, the rule must be assigned to priority level 1.

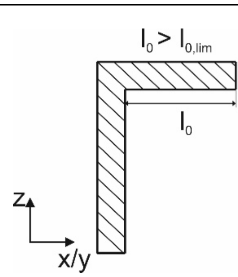
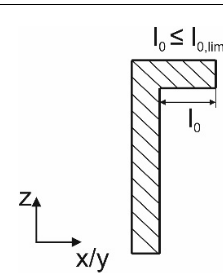
Table 7: Guideline “Gap width“

	Not suitable for production	Suitable for production
6 Gap width		
6.1 Minimum 90°: Gaps arranged perpendicular to the building platform or x/y-plane must have at least a gap width $w_{g,90}$ of $w_{g,90,lim}$.		
6.2 Minimum 45°: Gaps arranged at an angle to the building platform must have at least a gap width $w_{g,45}$ of $w_{g,45,lim}$		

Overhang

Long overhangs increase the area where heat penetrates the component without creating additional space for heat transport to the building platform. This can lead to heat accumulation, which leads to shrinking processes in the component. The resulting internal stresses can lead to plastic deformation of the component and termination of the build job. For this reason, the guideline has to be mapped to priority level 1.

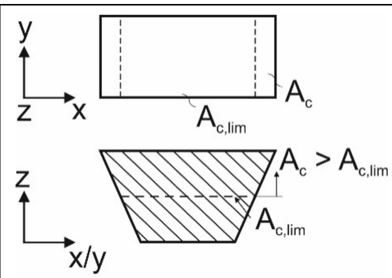
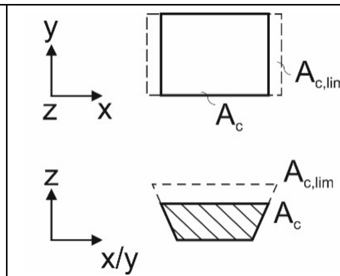
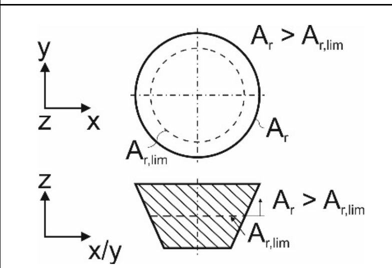
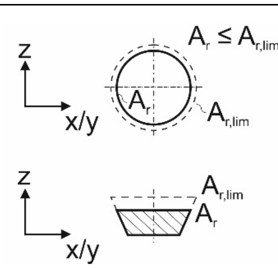
Table 8: Guideline “Overhang“

	Not suitable for production	Suitable for production
7 Overhang		
7.1 Support: The length of an overhang in the xy-plane must not exceed $l_{0,lim}$ without the use of support material.		

Cross-section area

Cross-sectional areas in a component layer should not exceed a limit value, since the layerwise melting of powders results in locally different temperature gradients. This can lead to residual stresses and therefore to deformations and endanger the build job. For this reason, these guidelines are allocated to priority level 1.

Table 9: Guideline "Cross section area"

	Not suitable for production	**Suitable for production**
8 Cross-section area		
8.1 Maximum (cubic): The continuous rectangular cross-sectional area A_c in the x-y-plane must not exceed the critical area $A_{c,lim}$.		
8.2 Maximum (round): The continuous round cross-sectional area A_r in the x-y-plane must not exceed the critical area $A_{r,lim}$.		

Quantification of design rules

To quantify the guidelines, test specimens were developed for each guideline category. The test specimens allow the verification of the respective attributes, which are considered in the corresponding guidelines. For this purpose, the test specimens were produced under different machine-, material-, and production parameter combinations.

Further on the permissible limit value for the attribute was determined. The test specimens were divided into two specimen build jobs, which are referred as test specimen build job 1 and 2. Test specimen build job 1 contains test specimens that have to be sorted as critical with regard to a robust production. These test specimens can lead to an abort of the build job. A successful or unsuccessful production of the test specimens can be used as an evaluation criterion. Specimen build job 2 contains specimens that can be manufactured robustly. These specimens can be measured optically or tactilely after production [LTM+18, TL18].

The test specimens were manufactured for all guidelines with 316L stainless steel (1.4404) and AlSi10Mg aluminium alloy on a SLM 250 HL and SLM 280 HL systems. For each machine-material combination, the test specimens were produced for two common parameter sets. A total of eight build jobs with different boundary condition combinations (machine, material, parameter set) were produced. These eight build jobs were each produced in triplicate, resulting in a total number of 24 build jobs. The parameter sets (PS) used, are listed in Table 10.

Table 10: Parameter set for the production of the specimens.

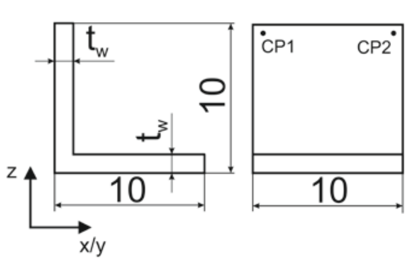
Machine	Material	Parameter set
SLM 250 HL	316L	PS1: 316L_S09-02A16-312V3_30
		PS2: 316L_S32-14A18-506V1_50
	AlSi10Mg	PS1: AlSi10Mg_S32-14A20-514V4_30
		PS2: AlSi10Mg_S32-14A18-512V5_50
SLM 280 HL	316L	PS1: 316L_SLM_BP2.1_V5104_30
		PS2: 316L_SLM_BP2.1_V5104_50
	AlSi10Mg	PS1: Al_SLM_BP2.1_V5102_30
		PS2: Al_SLM_BP2.1_V5102_30

The buildjob preparation was carried out with Materialise Magics V21.1. In case of the 250 HL Autofab 1.8 was used for the slicing process. After production, the test specimens were separated from the building platform with a band saw. The subsequent measurement is explained exemplary for the test specimens for guidelines 5 (wall thickness) and 6 (gap width). The corresponding test specimens and determined limit values for different boundary condition combinations are listed in the tables 11 and 12. The limit values and test specimens of the remaining design guidelines are listed in the appendix.

For the test specimen of guideline 5 the minimum wall thickness shall be determined from which a robust manufacturing of the wall is possible. The wall thickness $t_{w,90}$ and $t_{w,0}$ is varied in the range of 0.1mm to 1.0mm in 0.1mm steps. The wall surfaces are then subjected to a visual inspection and evaluated with a view to robust production. Surfaces that are perforated or walls that have not been formed out are declared as not possible to manufacture. The maximum wall thickness which enables such a declaration must at least be maintained in order to be able to manufacture a wall.

In addition, the target wall thickness $t_{w,90}$ was measured at the upper two corner points (CP1, CP2) of the vertical walls using an outside micrometer to detect geometric deviations. The measured values on the triple specimens are recorded in tabular form and averaged for the different boundary conditions to determine the corresponding limit values. The limit values are shown in Table 11. Both machines used for the production show the same limit values for 316L. AlSi10 Mg diverge from this results and show a higher limit value. This is due to the greater thermal conductivity of the aluminium and the associated greater heat input into the powder bed, which leads to the melting of powder particles onto the component contour. Besides this is caused by bigger adhesions related to different powder particle size of AlSi10Mg.

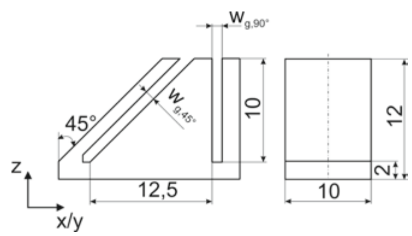
Table 11: Specimen and limit values for t_w in design guideline 5 “Wall thickness”



	Machine	Parameter-set	Material	
			316L	**AlSi10Mg**
	SLM 250	**PS1**	≥0,4 mm	≥0,3 mm
		PS2	≥0,4 mm	≥0,4 mm
	SLM 280	**PS1**	≥0,4 mm	≥0,4 mm
		PS2	≥0,4 mm	≥0,3 mm

The test specimens for guideline 6 shall be used to determine the permissible gap width perpendicular to the building platform ($w_{g,90}$) and at an angle of 45° ($w_{g,45}$) to the building platform (see Table 12). The gap width was varied in steps of 0.05mm from 0.05mm to 0.3 mm. In this case, the measurement is carried out with a feeler gauge. It is checked whether the complete gap is free by pushing the largest possible feeler gauge into the gap. The feeler gauge must be inserted completely into the gap. The maximum possible insertable thickness of the feeler gauge is recorded as the permissible limit value. The determined limit values are listed in Table 12. It is recognizable, that the SLM 280 parameters allow a smaller minimum gap width of 0.15mm for both materials. This is due to the different process parameters of the machines.

Table 12: Specimen and limit values for wg in design guideline 6 "Gap width".



Machine	Parameter -set	Material 316L	AlSi10Mg
SLM 250	PS1	≥0,15 mm	≥0,2 mm
	PS2	≥0,3 mm	≥0,3 mm
SLM 280	PS1	≥0,15 mm	≥0,3 mm
	PS2	≥0,3 mm	≥0,3 mm

Summary / Outlook

In order to be able to integrate the existing design recommendations into a software, a systematic review and prioritization of these is required. Approximately 100 design guidelines were examined. These were evaluated with a view to robust production. Overlapping and similar design guidelines were summarized. This reduced the number of design guidelines most important for a software-based design check to eight. These guidelines are described in detail and discussed using sample graphical illustrations.

Test specimens were developed to determine permissible quantifiable limit values for the attributes of the design guideline. For this purpose, the test specimens were manufactured and examined as well as the permissible limit values determined. These limits values represent the basis for a software-based design check. These were produced for different boundary conditions (machine, materials, parameter sets) to enable applicability. The procedure for determining limit values was described in detail as well to enable the user to determine limit values for his own boundary conditions.

In the future, limit values for further boundary condition combinations should be determined in order to enable a broad application of the design guidelines. In addition, these limits are to be used for software-supported design testing and implemented in a software tool. Furthermore, guidelines for a post-processing, load-fair and cost-fair design are to be determined and implemented in a design checking software.

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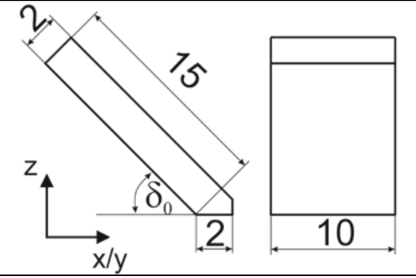
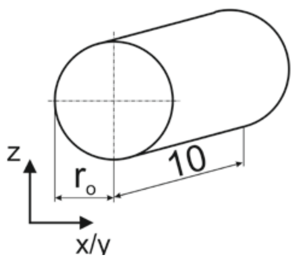
Appendix

Table 13: Specimen and limit values for design guideline 1 "Surface orientiation".



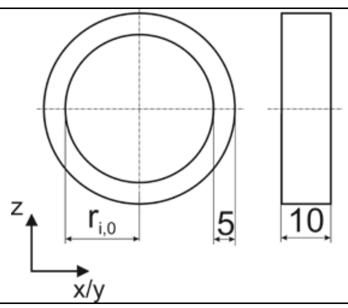
Machine	Parameter-set	Material 316L	Material AlSi10Mg
SLM 250	PS1	≥40°	≥25°
	PS2	≥35°	≥25°
SLM 280	PS1	≥25°	≥25°
	PS2	≥25°	≥25°

Table 14: Specimen and limit values for r_o in design guideline 2 "Outer radius".



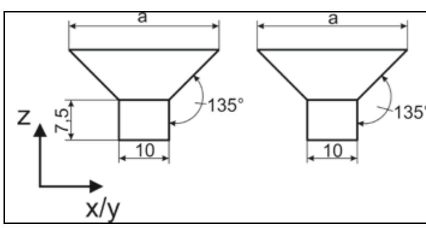
Machine	Parameter-set	Material 316L	Material AlSi10Mg
SLM 250	PS1	≥1,2 mm	≥1,2 mm
	PS2	≥1,0 mm	≥1,2 mm
SLM 280	PS1	≥1,2 mm	≥0,8 mm
	PS2	≥1,2 mm	≥0,8 mm

Table 15: Specimen and limit values for r_i in design guideline 3 "Inner radius"



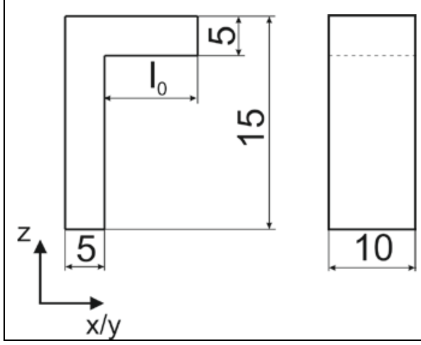
Machine	Parameter-set	Material 316L	Material AlSi10Mg
SLM 250	PS1	≥0,4 mm	≥0,8 mm
	PS2	≥0,8 mm	≥0,8 mm
SLM 280	PS1	≥0,6 mm	≥0,6 mm
	PS2	≥0,6 mm	≥0,8 mm

Table 16: Specimen and limit values for design guideline 4 "Cross-sectional area change in building direction".



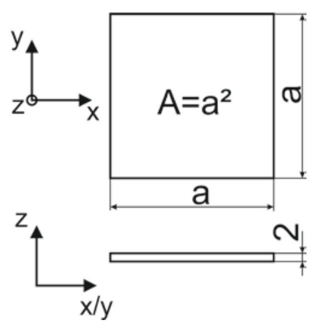
Machine	Parameter-set	Material 316L	Material AlSi10Mg
SLM 280	PS1	7,5 mm	15 mm
	PS2	7,5 mm	15 mm

Table 17: Specimen and limit values for l_0 in design guideline 7 “Overhang”.



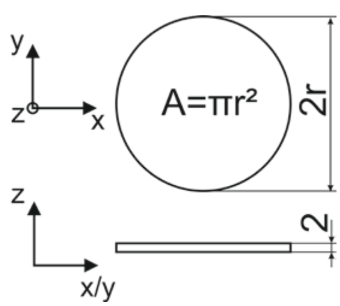
Machine	Parameter -set	Material	
		316L	**AlSi10Mg**
SLM 250	**PS1**	≤2 mm	≤2,5 mm
	PS2	≤2,5 mm	≤5 mm
SLM 280	**PS1**	≤2,5 mm	≤2 mm
	PS2	≤3 mm	≤5 mm

Table 18: Specimen and limit values for design guideline 8 ”Cross section area – cubic”



Machine	Parameter -set	Material	
		316L	**AlSi10Mg**
SLM 250	**PS1**	≤576 mm^2	≤676 mm^2
	PS2	≤676 mm^2	≤784 mm^2
SLM 280	**PS1**	≤676 mm^2	≤676 mm^2
	PS2	≤784 mm^2	≤784 mm^2

Table 19: Specimen and limit values for design guideline 8 ”Cross section area –round“.



Machine	Parameter -set	Material	
		316L	**AlSi10Mg**
SLM 250	**PS1**	≤676 mm^2	≤676 mm^2
	PS2	≤784 mm^2	≤784 mm^2
SLM 280	**PS1**	≤676 mm^2	≤784 mm^2
	PS2	≤784 mm^2	≤784 mm^2