Solid Freeform Fabrication 2021: Proceedings of the 32nd Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Geometrical Deviations In Additive Manufacturing – Influences On The Manufacturing Accuracy

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Abstract

The advantages of Additive Manufacturing (AM) highlight the capability to become an inherent part within the product development process. However, process specific challenges harm its further currency for industrial applications, for instance the high geometrical deviations. Different process factors influence the manufacturing accuracy and lead to large dimensional, form and positional deviations. Published research relative to deviations is difficult to compare, because it is based on several specimens that were manufactured with different processes, materials and machine settings. This fact emphasizes that reliable tolerance values for AM are hard to define in standards. Within this investigation, a universally applicable method was developed to examine geometrical deviations for AM processes. The main aim is the derivation of achievable tolerance values considering important influencing factors. Furthermore, due to the locally varying surface roughness of additively manufactured parts several tactile measurements were compared.

Introduction

Additive Manufacturing (AM) has been known since the 1980s. The development of the AM processes illustrates that the technology has high technical and economical potentials that become more and more visible due to the increased market volume in the last decades. Apart from the current challenges the COVID-19 pandemic can cause an expected decrease between 10% and 39% in 2021 [1]. However, ongoing machine, material and research developments will enable a further growth in the market. AM processes produce components and assemblies by joining single volumes, usually expressed as layers. They do not require molding tools and the layer-by-layer manufacturing breaks down complex three-dimensional challenges into two-dimensional, simple manufacturing situations, allowing the processes to offer enormous freedom in the areas of material science and design [2, 3].

Although the technical relevance of the processes has grown tremendously in the recent years, several process-specific challenges inhibit the increasing distribution and use of the processes for serial applications outside the leading industry sectors, such as aerospace, medical or automotive [4]. One essential drawback is the high surface roughness of additively manufactured components, which arises, for example, as a result of the stair-stepping effect. In addition to the surface roughness, the components often exhibit higher dimensional, form and positional deviations compared to components that are manufactured with conventional processes. Due to the lack of knowledge regarding the achievable manufacturing accuracy, additively manufactured components are often provided with large oversize, which causes an increase of costs in the manufacturing process and in post-processing to meet the geometrical requirements of the components.

Publications on the subject of geometrical accuracy often show a qualitative evaluation of existing processes using standard benchmark parts and do not include detailed quantification of achievable tolerance values. The main target of these investigations are the repeatability, manufacturing speed or the manufacturability of minimal geometries. Existing investigations are difficult to compare, since they refer to different machines, materials, process parameters, test specimen and measuring methods. Particularly in the area of the measurement method, specially adapted extraction strategies must be used to record deviations realistically. One reason for individual numbers and positions of measuring points is the high and inhomogeneous surface roughness on a single component.

Overall, the manufacturing accuracy in AM is insufficiently researched, although many different benchmark artifacts for the evaluation of geometric accuracy for additive manufacturing processes have been investigated. REBAIOLI and FASSI provide an intensive overview of the existing investigations in this area [34]. Nevertheless, many of these investigations neither consider Geometric Dimensioning & Tolerancing (GD&T) characteristics [35] nor a systematic selection of geometric features as well as the quantification of geometric tolerances [36, 37]. Furthermore, there are special requirements for additively manufactured components that have not yet been fully described in the state of the art or standards, for example the tolerancing of complex free-form surfaces, lattice structures or support structures [38]. In addition, measurement methods must be adapted to the AM specific challenges, such as characteristic surface texture with high surface roughness [38]. Furthermore, causal relationships between the occurring deviations and the process-specific environment are often missing, since a multitude of influencing factors must be considered. A large number of investigations are focused on optimizing process parameters and machine components for various processes that are not explicitly listed in the following, as they do not have the objective of deriving tolerance values.

In general, the research topic represents an important quality aspect for additively manufactured components. Thus, the current status of achievable geometrical accuracy must be examined and optimized in the future in order to make the serial production of components accessible to a larger number of industries.

State of the art

Geometrical deviations are unavoidable due to the physical manufacturing of parts and can generally be divided into four categories [5]. The four categories are dimensional deviations (two-point dimensions), form deviations (e.g. roundness or cylindricity), positional deviations (e.g. perpendicularity or position) and surface deviations (e.g. surface roughness). For conventional manufacturing processes the achievable manufacturing accuracy is often defined in standards, e.g. general casting tolerances. The achievable tolerance values for AM are not standardized so far. Thus, the existing literature is used to give an overview about the manufacturing accuracy for Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Laser Beam Melting (LBM) in the following.

The geometrical accuracy of the FDM process has already been investigated in various studies. IPPOLITO ET AL. found a deviation of up to +0.7 mm [6]. MAHESH ET AL. analyzed free-form surfaces and observed deviations from the nominal shape of up to +2.5 mm [7]. The machine manufacturer STRATASYS advertises achievable tolerance values of ±0.127 mm or ±0.04 mm per mm [8]. Further investigations focus on the influence of machine parameters, such as shrinkage factors [9, 10]. The outcome shows shrinkage is the dominating factor for dimensional deviations in FDM. MOHAMED ET AL. showed a summary of the current activities to improve the geometric accuracy in FDM [11]. MINETOLA ET AL. developed a benchmark part where different nominal lengths are considered according to DIN EN ISO 286-1. The results show that FDM can achieve ISO tolerance (IT) classes between 11 and 16. The investigation of the geometrical characteristics is carried out on cubes with an edge length of 10 mm. The cubes are made of explicitly specified ABS material, produced on a low-cost printer. A design of experiment (DoE) delivers optimized process parameters, e.g. smallest possible layer thickness for low dimensional deviations [12]. Another paper on dimensional accuracy in FDM was published by NANCHARAIAH ET AL. [13]. For the investigations, a test specimen with a constant dimension of 25.4 mm in length and 12.7 mm in diameter is used. The outcome of this research work demonstrates, that layer thickness and filament width affect the part accuracy significantly. HANSSEN ET AL. published a study on the achievable dimensional accuracy of the Stratasys Fortus 360mc and 400mc systems [14]. They advertise the considered systems with achievable tolerances of ±0.127 mm or ±0.0015 mm per mm depending on the nominal dimension. The investigations were executed on three Fortus 400mc machines. The test specimen had a dimension of 127 mm x 76 mm x 14 mm and was manufactured using ABS-M30 [14]. Furthermore, LIENEKE ET AL. investigated dimensional tolerances for additive manufacturing for FDM and classified the process into the IT-classes 9 to 14 according to DIN EN ISO 286-1 [15].

TANG ET AL. investigate the influence of process parameters on the accuracy of SLS. According to them, the geometric accuracy is mainly caused by the temperature distribution in the build chamber, the material shrinkage, the laser beam offset and the laser speed. After finding improved settings for the main influencing factors, the errors remain below ± 0.2 mm [16]. WEGENER and WITT [17] also demonstrate that the influence of the temperature distribution within the building chamber affects the accuracy as well as the mechanical properties. They even proclaim that the temperature distribution is the main reason for a lack of reproducibility [16]. This statement can be clarified by the in-process temperature measurement by JOSUPEIT and SCHMID [18]. Further studies deal with shrinkage modelling to reduce the occurring deviations [19, 20]. RAGHUNATH, PANDAY and YANG ET AL. tested cuboids and show relations between material shrinkage and various process parameters [19, 20]. SENTHILKUMARAN ET AL. discussed the influence of building strategies on the accuracy of laser-sintered parts [21]. SEEPERSAD ET AL. showed manufacturing limitations for SLS. The investigation deals with geometrical deviations on simple elements such as walls, holes, cylinders and complex elements such as gears [22]. However, SEEPERSAD ET AL. performed a qualitative assessment of the occurring deviation, but they did not mention numerical tolerance values. Furthermore, most of the literature references use only one nominal dimension for the executed investigations. LIENEKE ET. AL. [23] investigated the influence of the position, the alignment and the selected nominal dimension on the accuracy of the SLS on the geometric accuracy, whereby laser sintering was classified in IT classes 13 to 15 according to DIN EN ISO 286-1 under consideration of the boundary conditions [23, 24].

COOKE and SOONS deal with deviations in the range of dimension, shape and position in the field of LBM and Electron Beam Melting (EBM). Based on a test specimen with a nominal dimension of 100 mm, dimensional deviations between -0.2 mm and +0.1 mm in the x-direction and -0.2 mm and +0.05 mm in the y-direction were defined. The circularity exhibits tolerance zones between 0.094 mm and 0.156 mm, which are calculated between the minimum and maximum deviation [25]. HANUMAIAH ET AL. investigated form and location deviations and derived tolerances for Direct Metal Laser Sintering (DMLS). A straightness tolerance of 0.0372 mm is defined in this publication. The deviations for flatness are examined within a tolerance of 0.0868 mm and the circularity tolerance is estimated to be 1.5320 mm [26]. Furthermore, LIENEKE ET. AL. [27] experimentally investigated dimensional deviations in LBM for different orientations and nominal dimensions up to 80 mm and derived IT-classes between 12 and 17 according to DIN EN ISO 286-1.

Concluding, the abovementioned literature demonstrates a large variation of observed geometrical deviations on different machines, test specimens and boundary conditions, which are mostly not listed in detail. These differences can be explained by the large number of factors influencing the geometrical accuracy. Therefore, it is difficult to compare individual investigations with different processes, materials, machine settings and test specimens, if the manufacturing boundary conditions are not mentioned. This fact highlights that there is no generally known, reliable and comprehensive information about tolerances for AM processes. Thus, a uniform method needs to be developed to examine geometrical deviations and to derive realistic tolerance values. This publication is based on further results and extends an existing method [15, 23, 24, 27, 28].

Purpose of investigation

In general, proven knowledge about the achievable manufacturing accuracy should be known for each manufacturing process in order to enable a solid component design and tolerancing. Furthermore, this allows to plan and to realize the development of the respective component process chain including further process steps. This fact applies both to conventional manufacturing and to additive manufacturing processes. As already mentioned, the accuracy and achievable tolerance values are not yet comprehensively and publicly known for AM. For conventional processes, general tolerances are defined to the greatest possible extent, which express the manufacturing accuracy customary in the workshop and document it by means of a central entry on the technical drawing, e.g. DIN ISO 2768-1 and -2 for machining.

Furthermore, no cross-process method is known that allows the investigation of the manufacturing accuracy. Therefore, the main objective of this investigation is the development of a method for the investigation of geometric deviations using standard workshop process settings, geometrically defined test specimens and selected measurement strategies. The method is developed on the basis of the FDM, SLS and LBM processes. However, the method should be transferable to other additive or conventional manufacturing processes. The test specimens should cover different geometric shapes of measuring surfaces that allow the determination of geometric deviations. The classification of the geometries and their combinations is based on the definition of standard elements according to ADAM [29]. In the experimental investigations, the determination of geometric deviations and the quantification of the manufacturing accuracy by realistic tolerance values is focused. The results are described and interpreted within and across the considered processes.

Methodical approach

In the beginning of the method development, necessary requirements are defined. The following requirements should be considered:

- **Transferability:** The methodical investigation of geometrical deviations should be applicable to different additive manufacturing processes as well as to conventional processes.
- **Universality:** The method should include technically relevant geometric elements and differently shaped measuring surfaces.
- **Scalability:** During the development of the method, the focus is on the FDM, SLS and LBM processes. Nevertheless, the method should be adaptable to other manufacturing processes.

Thus, considered factors, for example the nominal dimension of test specimens, should be scalable.

- **Transparency:** The method is developed using standard workshop settings along the process and thus offers the possibility to compare process optimizations with the initial state.
- **Measurability and repeatability:** Suitable measuring strategies should be investigated for the defined test specimens to allow a repetitive execution.
- **Quantification:** The method and the included experimental investigation should enable the derivation of quantitative tolerance values.
- **Classification and comparability:** The determined tolerance values should be classified into standards and compared with conventional processes.

After the definition of the main requirements, the general structure and the step-by-step procedure of the method is shown. In the following, the *seven main steps* are described with the upcoming results.

Step 1: Definition of target values:

The aim of the method is the investigation of geometrical deviations. So, the four geometrical deviations (dimensional deviations, form deviations, positional deviations and surface deviations) are defined as the target values. In addition, profile deviations are considered.

Step 2: Identification of factors influencing the manufacturing accuracy:

A cause-effect diagram is developed for each of the processes. In Figure 1 the diagram for the LBM process is shown. In this paper, mainly factors in the area of "human" and "measurement" are considered in detail. Influences regarding the "machine", "method" as well as "material" are determined as constant in this publication, because these influences had already been considered and published by e.g. KNOOP and JOSUPEIT for FDM and SLS [30, 31].

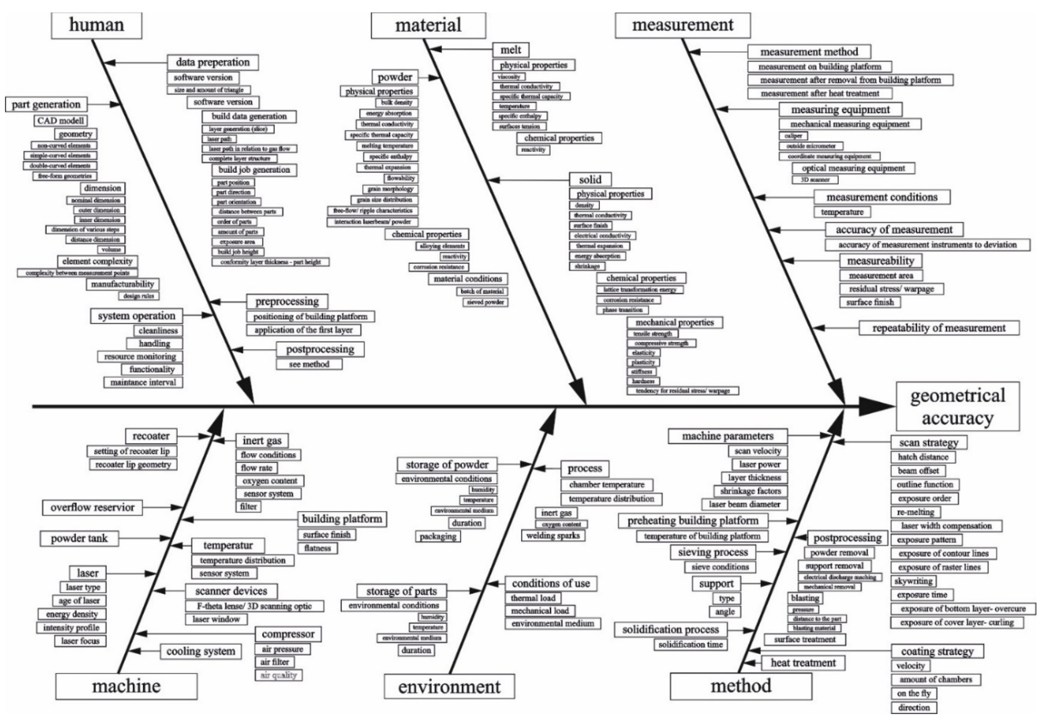


Figure 1: Cause-effect-diagram - influencing factors on the geometrical accuracy (LBM)

Step 3: Selection of relevant influencing factors

Within this paper, the following influences are considered in detail:

- “human”: geometry, dimension, part position in the build chamber, and orientation
- “measurement”: measuring equipment and measuring method (extraction strategy)

Step 4: Definition of the variation range for selected influencing factors

For each selected factor, a variation range is determined in order to investigate the influence of the factor. According to the selected factors in this publication the following ranges of variation for the experimental investigation are defined:

- “human”:
  - The *geometry* is subdivided into three main groups according to the definition of standard elements by ADAM [29]. For the experimental investigation the measuring areas of the test specimen are defined as planar, cylindrical, and spherical surfaces.

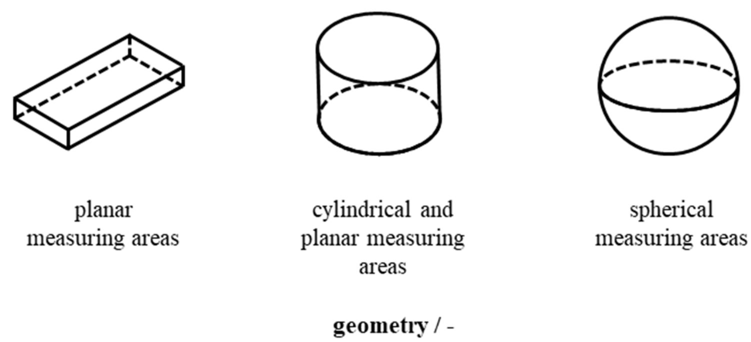


Figure 2: Classification of the geometry – planar, cylindrical and spherical areas

  - The *dimension* (e.g. length, width, height or diameter) of the different geometries and measuring areas are set according to the DIN EN ISO 286-1. The variation range of the nominal dimensions is documented in Table 1. Although the standard offers higher nominal dimensions, the value of 500 mm is defined as the maximum by the build chamber limits of the considered processes.

Table 1: Selected nominal dimension according to DIN EN ISO 286-1

Nominal dimension / mm														
3	6	10	18	30	50	80	120	180	250	315	400	500	600	⋯

  - The chosen *position in the build chamber* is an often-mentioned influencing factor in literature [29, 30, 31]. In order to analyze the possible influence on the geometrical accuracy in detail, different numbers of positions are investigated in the x-y plane depending on the nominal dimension and build chamber space. Thus, in dependence of the selected process between 81 and 225 positions are investigated for small nominal dimensions (3 to 18 mm), nine different positions for nominal dimensions up to 80 mm and three positions for nominal dimensions between 120 mm and 500 mm. Figure 3 demonstrates the nine different positions in the x-y plane that are considered up to 80 mm for all processes.

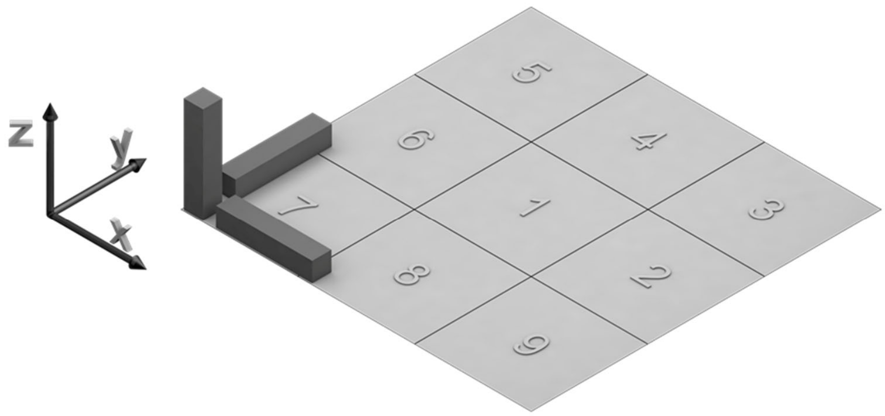


Figure 3: Schematic representation of the nine positions in the x-y plane with cuboids

- Another important influencing factor is the *orientation* of test specimen. Due to this, the factor is investigated by the following variation range depending on the target value. Dimensional deviations are recorded in x, y and z alignment in order to have the possibility to optimize the shrinkage factors along the axis. Form and positional deviations are investigated in 0°, 30°, 45°, 60° and 90° orientation. Because literature demonstrates that the scattering in the surface roughness is very high, for example in SLS [31], the measuring areas for surface deviations are orientated in 0°, 30°, 45°, 60°, 90°, 120°, 150° and 180°.

  For further influencing factors, the variation ranges were defined, but they are not pictured in this paper. For instance, for the process-specific influencing factor "layer thickness" that appears in the category "method – machine parameters" (s. Figure 1) is varied between 0.06 mm, 0.120 mm and 0.180 mm for SLS, between 0.030 mm and 0.050 mm for LBM and between 0.127 mm, 0.178 mm and 0.254 mm for FDM.

Step 5: Design and classification of test specimens

Based on "Step 4", test specimens that allow the consideration and the experimental investigation of the defined influences within the belonging ranges are designed. Due to the definition of the geometry, test specimens with planar, cylindrical and spherical measuring areas are developed and selected. Table 2 shows the classification of test specimens as well as the investigated target values on each test specimen design. Each test specimen design exists in an "outer" and an "inner" design, in order to investigate outer and inner diameters of cylinders and holes, because previous studies have shown that inner and outer dimensional deviations can vary significantly for the same nominal dimension.

Table 2: Classification of test specimen designs according to the geometry of measuring area and the targets values: dimensional (two-point measurement), form (flatness, straightness, roundness, cylindricity), profile (line and surface), positional (direction, location and run) and surface deviations

geometry/ measuring area	design of test specimen	target values: geometrical deviations				
		dimension	form	profile	positional	surface
planar	cuboid	x	x		x	x
	inner cuboid	x				
	pyramid		x		x	
	inner pyramid		x		x	
cylindrical	cylinder	x	x		x	x
	inner cylinder	x	x			
	cone			x		
	inner cone			x		
spherical	sphere	x		x		
	inner sphere	x		x		
combined	global test specimen	x	x	x	x	x
	surface test specimen					x

As an example of the above-mentioned classification and the demonstration of the variation range of influencing factors, Figure 4 demonstrates the application of the orientation for cuboids and hollow cylinders with fixed dimensions. In addition, the dimensions are varied according to the nominal dimension of DIN EN ISO 286-1 (s. Table 1).

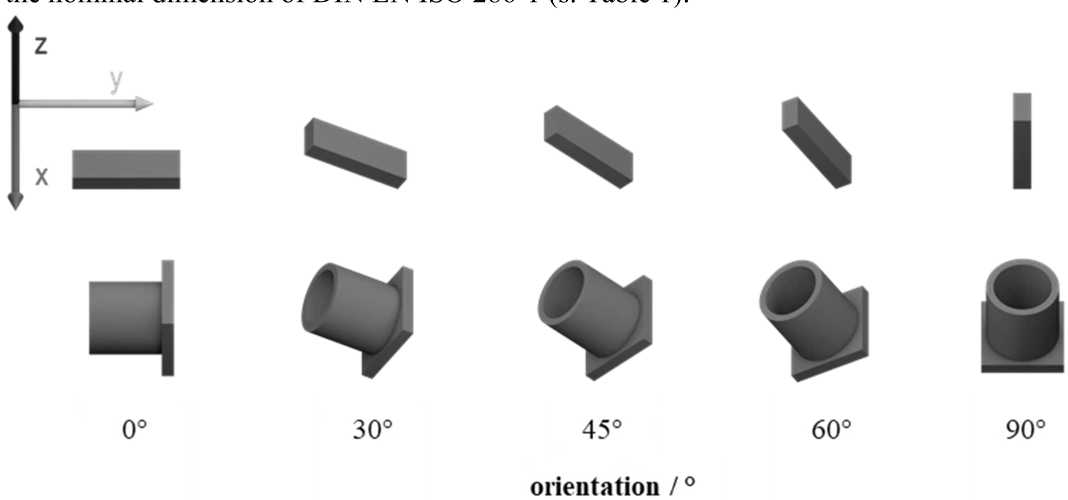


Figure 4: Representation of cuboids and hollow cylinders in five different orientations

Step 6: Definition of tactile measuring methods

After the definition of the different test specimen designs, the measuring equipment and measuring strategies are selected. The following topics belong to the point “measurement”, “measuring equipment” and “measuring method (extraction strategy)” within the cause-effect-diagram in Figure 1.

The Nikon Altera 8.7.6 coordinate measuring machine is used to record the target geometrical deviations. The tactile measuring system has a volumetric accuracy of 1.8 µm + N/400 (N: nominal dimension). For the tactile measurement a probe with 40 mm length and ruby sphere diameter of 2 mm is used.

The planning of the measurement method for each test specimen design is important to achieve realistic and meaningful results. For quality standardization and the industrial verification of conformity, DIN EN ISO 17450-1 and -2 are adopted. The standard deals with the verification of the specification of parts to be evaluated. The connection between the extraction and association of the part is covered by DIN ISO 14660. The extraction is a derivation of the real part geometry into the geometry of a grid of measuring points. The determination of the position and number of measuring points is relevant for the degree of approximation of the real geometry [33]. Thus, for each test specimen, a meaningful extraction and association strategy is selected and developed. Especially in AM, the inhomogeneous surface roughness on a single component complicates the measurement of realistic values. Because of this, different extraction strategies are experimentally analyzed and evaluated for planar, cylindrical and spherical geometries. Within this publication the experimental preliminary investigation for planar and cylindrical geometries are considered in detail.

- *Planar geometries – cuboids:* Planar surfaces are tested with three different extraction strategies. Starting from a nominal area of 10 mm by 10 mm to be examined, triangular grids, rectangular grids and the random distribution of points (by CMM software) are used. As the nominal length increases, so the number of measuring points increases proportionally. Since in preliminary studies the recommended numbers of measurement points (e.g. nine measurement points for a plane) showed non-realistic deviations, the minimum numbers of measurement points on Level 1 were defined to a value approximately twice as large. The three extraction strategies are varied in three levels of measuring points (s. Figure 5):
    - Level 1: Low number of measuring points
    - Level 2: Medium number of measuring points
    - Level 3: High number of measuring points

    The following figure demonstrates the three different extraction strategies and three different level of measuring points on the cuboid with a measuring area of 10 mm by 50 mm.

  Figure 6 shows the results for the flatness deviation on the SLS cuboid with a planar measuring area of 10 mm by 50 mm that was manufactured in 0° orientation. Each measuring strategy was performed three times on the same test specimen. In sum, each test specimen was manufactured three times. Exemplary, the diagram shows the minimum, maximum and the average value of three measurements on one test specimen. The 0° orientation was used, because this orientation causes the highest flatness deviations due to the higher exposure area in x-y plane and the resulting warpage of the test specimen.

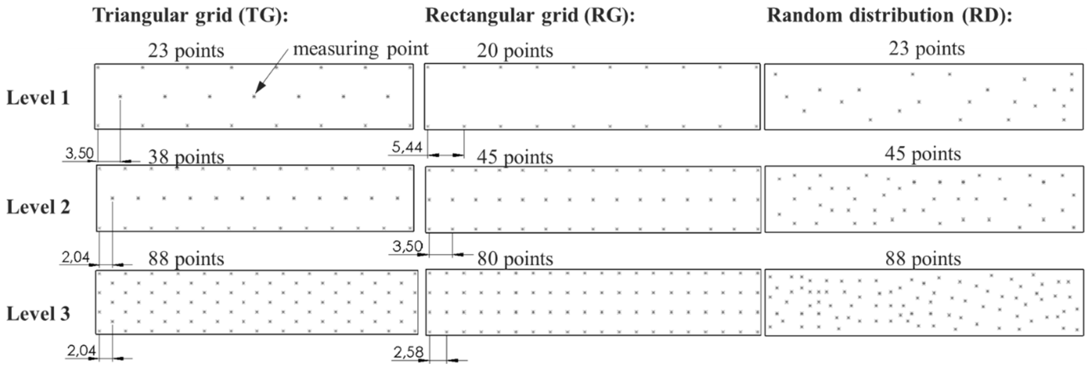


Figure 5: Extraction strategies for planar measuring areas with three different levels of points

It can be seen that the extraction strategy "random distribution of points (RD)" determines significantly smaller deviations than the other two strategies for the examined surface, regardless of the number of measuring points. With an increase in the number of measuring points, the recorded flatness deviations of the RD strategy increase. The triangular grid (TG) and rectangular grid (RG) strategies record almost equivalent flatness deviations at Level 2 (TG:38 and RG:45) and Level 3 (TG:88 and RG:80). In these ranges, the strategies are not significantly different from each other. However, in the case of the rectangular grid with a low number of measuring points (RG:20), much smaller deviations in flatness are recorded compared to the triangular grid (TG:23). The average value of the deviations for the rectangular grid is 0.068 mm and for the triangular grid it is 0.121 mm on level 1.

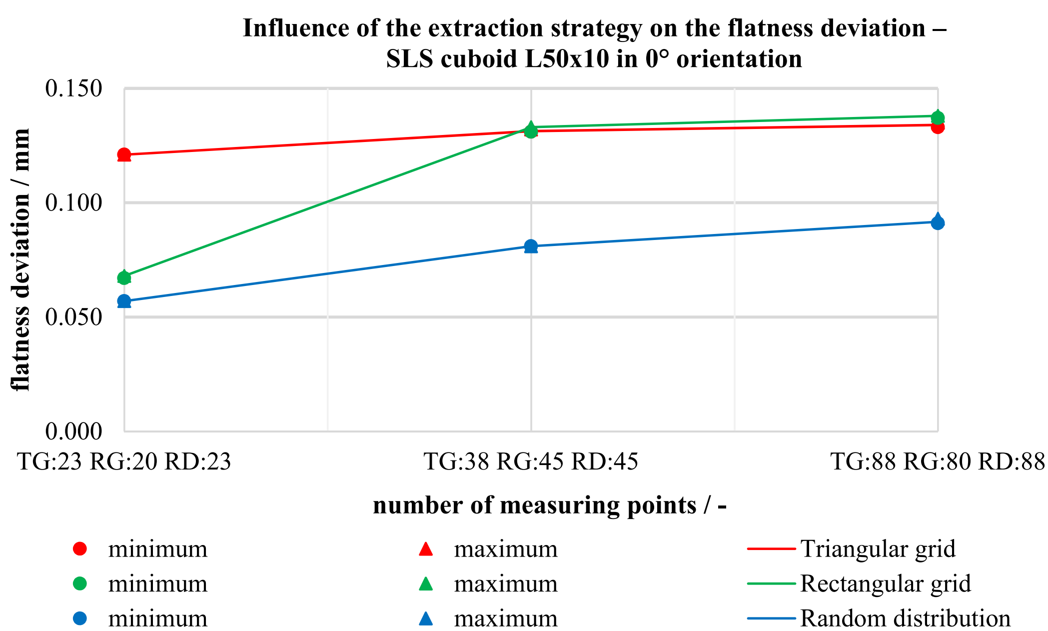


Figure 6: Influence of the extraction strategy on the measured flatness deviation

- *Cylindrical geometries – hollow cylinders:* Cylindrical surfaces are measured with two different extraction strategies. Firstly, roundness profiles (RP) and secondly, shifted roundness profiles (SRP) are examined. The two strategies are identical in the number of measurement points as well as the measuring cycles for each variation level (s. Figure 7). Only the distribution of the measurement points is changed here. In general, the number of measuring points is adjusted via the circle diameter of the cylindrical geometries.
  So, the both strategies and their four levels of measuring point numbers are demonstrated on the hollow cylinder with a nominal diameter of 30 mm and a nominal length of 30 mm (Figure 7).

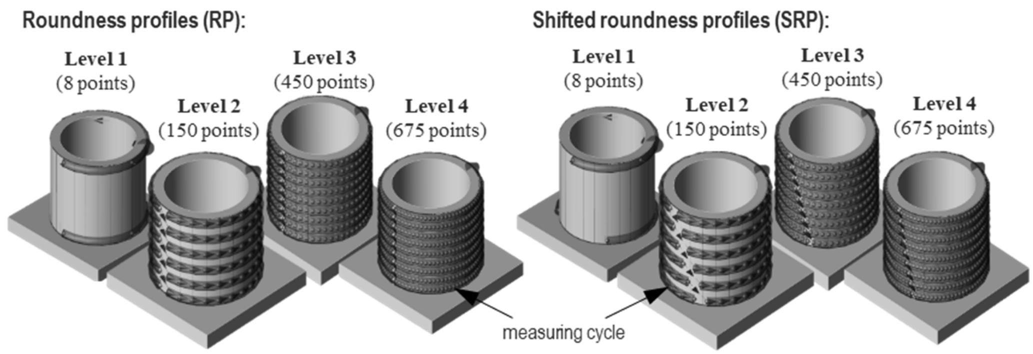


Figure 7: Extraction strategies for cylindrical measuring areas with four different levels of points

Figure 8 shows the deviation of the cylinder form of the SLS hollow cylinders with a length of 30 mm and a diameter of 30 mm (L30xD30) in 0° orientation. The average value is based on three measurements on one test specimen (Figure 8). Each test specimen was manufactured three times. The recorded average values of the cylindricity deviations is shown as a function of the extraction strategy and the number of measuring points. The red curve stands for the roundness profile strategy (RP) and green curve for the shifted roundness profile strategy (SRP). Comparing both curves, it can be clearly seen that different averaged measured values of the cylinder form deviation are achieved with a low number of measuring points.

For example, with a minimum number of measuring points (8 points), the measured value of the roundness profile is 0.048 mm and the measured value of the shifted roundness profile is 0.102 mm. As the number of measuring points increases, the recorded deviations in cylindricity also increase. The more points are used to measure the cylindricity, the closer the measured mean values are to each other. With 675 measuring points, both extraction strategies have approached a measured value of 0.268 to 0.275 mm. For all measurements it is obvious that the scattering of the three repeated measurements is very small (Figure 6 and 8).

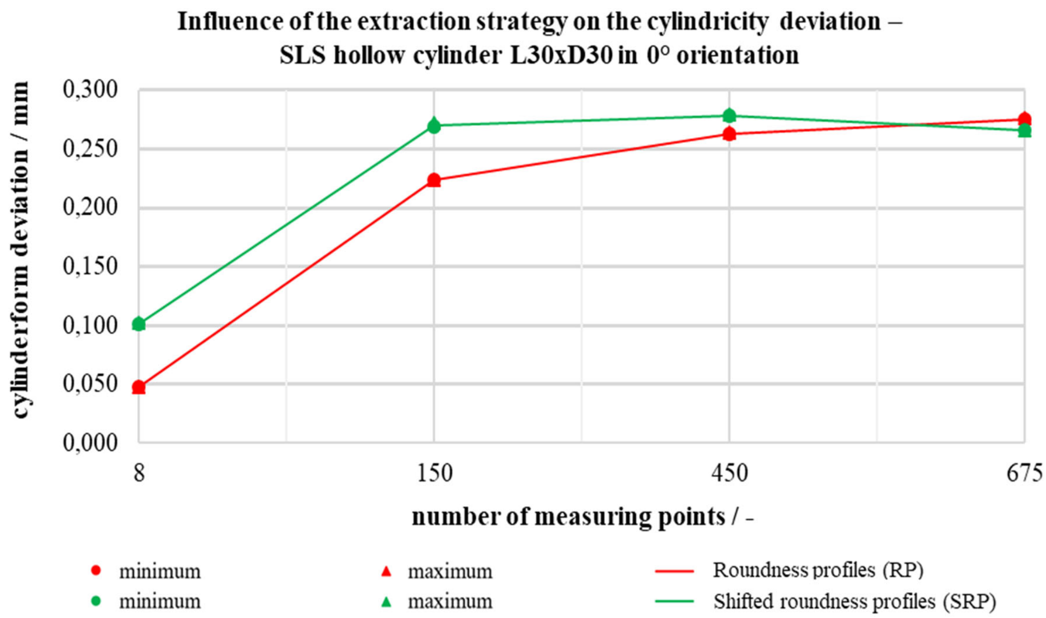


Figure 8: Influence of the extraction strategy on the measured cylinder form deviation

Based on the experimental preliminary investigation, hints for the measuring method are derived. The recommended extraction strategies strike a balance between accuracy and reliability, measurement time and economy of measurement results:

1. *Note:* Full-surface measurement point distribution and choice of a structured distribution strategy is needed.
2. *Note:* Sufficiently high number of measuring points:
    a. For planar measuring areas: Triangular grid for detection is useful. At least 3 measuring lines and 5 measuring points on a 10 mm by 10 mm surface. The number of measuring points increases proportionally to the nominal size of this surface (s. Figure 5).
    b. For cylindrical areas: Shifted roundness profiles or similar detection strategies are recommendable. Cylinders with a nominal length of 10 mm and a diameter of 6 mm should be measured with at least 3 measuring cycles and 10 measuring points per cycle. Here, the number of cycles and measuring points per cycle increases with increasing nominal dimension (s. Figure 7).
3. *Note:* Selection of a suitable probe diameter: Recommendation of small probe diameter for planar, cylindrical and spherical measuring areas.

Step 7: Definition of constant boundary conditions

In the last step of the method development, the test plan for the experimental investigation and the boundary conditions are set up. All manufactured test specimens are conditioned in standard climate according to acceptance regulations of plastic and metal components (DIN EN ISO 291). Furthermore, Table 3 lists the boundary conditions for the AM processes that are used for the manufacturing of the test specimens. These settings are defined as constant and are used as a standard during the method development and validation.

Table 3: Boundary conditions for FDM, SLS and LBM

process factor	**FDM**	**SLS**	**LBM**
machine	Stratasys Fortus 400mc	EOS EOSINT P396	SLM Solutions SLM 280 HL 1.0
Layer thickness	178 µm	120 µm	50 µm
shrink factors (x/y/z)	0.55 % 0.55 % 0.59 %	3.2 % 3.2 % 2.55 - 1.4 %	0.223 % 0.223 % 0.223 %
material	ABS M30	PA2200 (50%-50%)	316L
support	SR-30	Dispers powder	Solid block support
post-processing	Mechanical/chemical removal of the support	Glass ball blasting	-

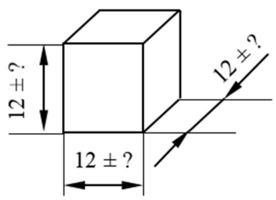
Experimental investigation

Within this publication, the results for two selected test specimens and selected influencing factors are presented. For this purpose, the above-mentioned cuboids and hollow cylinders are focused. On the basis of the cuboids, the possible influence of the position on the dimensional deviations in LBM is considered. Therefore, cuboids with a constant nominal dimension of 12 mm x 12 mm x 12 mm are used, which are manufactured on 81 positions in the build chamber. The dimensional deviations of the test specimens are measured in the x-y plane. The hollow cylinders are manufactured with different diameters and lengths and in the orientations 0°, 45° and 90°. In addition to the dimensional deviation, the cylindrical form deviation of the hollow cylinders is determined according to the defined measuring method. In the following, the two test specimens and the results are presented in more detail.

Cuboids – planar measuring areas:

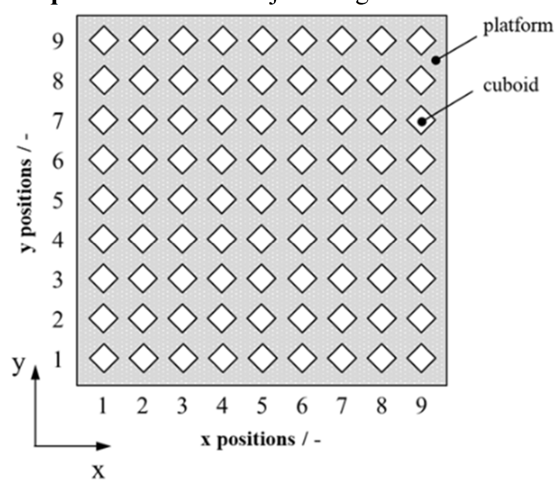
The following results are shown for LBM. Table 4 sums up the considered influencing factors and the variation range of each factor that is analyzed. The investigation focuses on the influence of the chosen position in the LBM building chamber. The dimensional deviations of the manufactured cuboids are measured in the x-y plane. The entire build job (s. Table 3) is repeated three times.

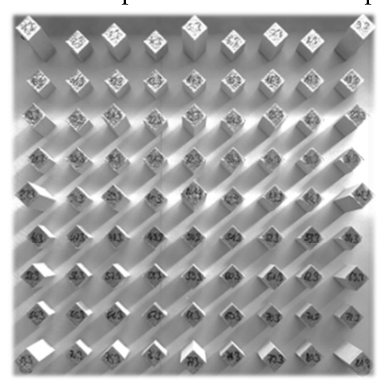
Table 4: Design of experiment for the investigation of the influence of the position in the LBM build chamber

drawing	target value	influencing factor	variation range
	dimensional deviation	test specimen	cuboids
		geometry	planar
		nominal dimension	12 mm
		position in build chamber	81 positions
		orientation	90°

measuring method: coordinate measuring machine – triangular grid (TG) – level 3

schematic representation: build job design and the manufactured test specimens on the build platform





After the measurement of all cuboids, the dimensional deviation is calculated for each position. The results are shown in Figure 9. The diagram presents the mean values of three build jobs. The occurring dimensions emphasize that the measured dimensions increase in the outer areas of the build platform, especially in the corners. It is obvious, that the extreme positions in the four corners show the highest actual dimensions and so the highest dimensional deviations. The actual dimensions vary in the corners between 12,11 and 12,16 mm. The middle position shows an actual dimension of 12,05 mm. In contrast to further investigations [29], the chosen position shows an influence on the geometrical accuracy. Similar results had already been shown for the SLS process [23, 24, 30]. However, in SLS the deviations occur due to the inhomogeneous thermal situation in the build chamber during and after the building process [30]. Such a high influence due to the temperature in LBM is not expected. Because of this, some feasible explanations are pointed out hereafter.

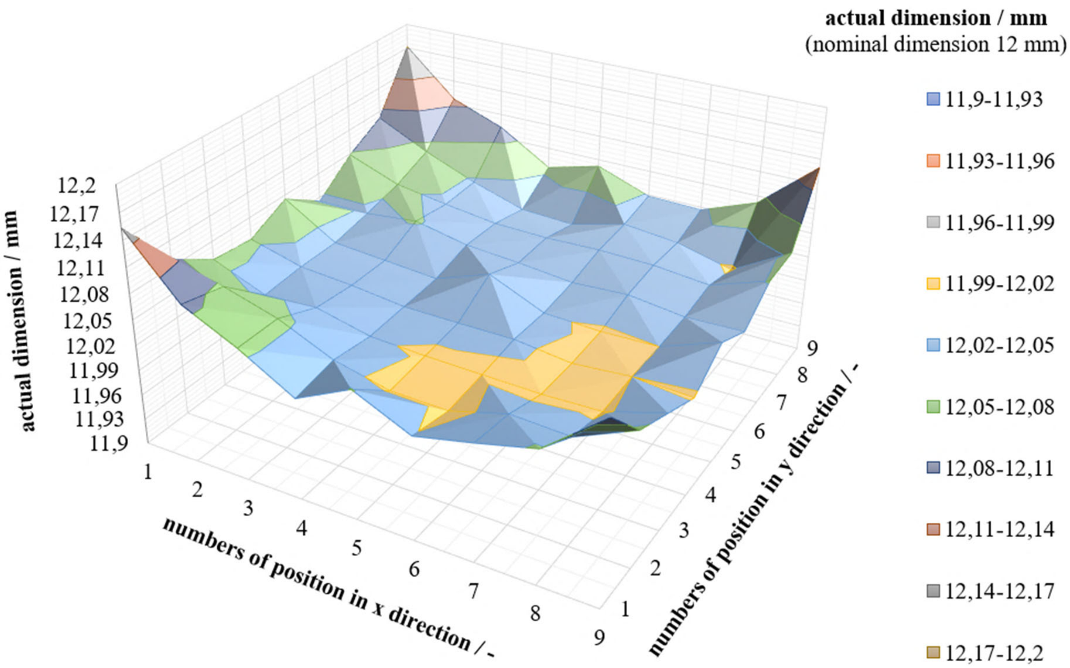


Figure 9: Dependence of the occurring dimensions as a result of the selected position in LBM

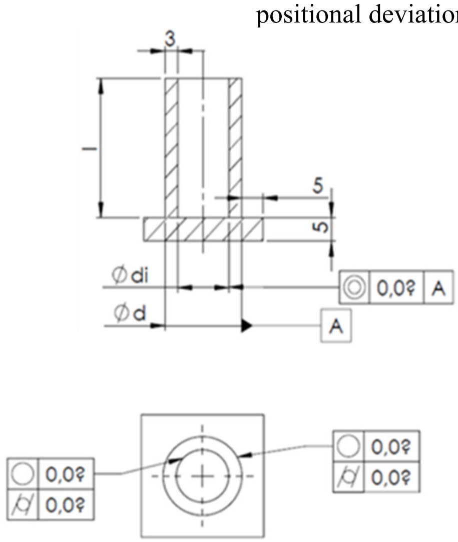
The cause of these position-specific deviations cannot be fully explained. It seems unlikely that thermal effects such as in the SLS process, where the different temperature distribution in the build chamber causes the plastic components to shrink inhomogeneously, are the main influence. A possible explanation for the increased deviations in the corners of the LBM chamber could be the laser beam guidance. By deflecting the laser beam into the corners, an elliptical change in the laser spot occurs without the usage of any correction systems. However, this change is prevented by F-theta lenses or dynamic systems as standard in LBM machines. So, one reason could be an improperly calibrated component in the beam guidance. Furthermore, it is conceivable that there is an increased influence on the gas flow in the corners, for example due to the position of the recoater. An insufficient gas flow velocity could not be removed possible welding spatter that could lead to increased dimensional deviations. Last, the left-hand side of the build chamber (s. Figure 9) also shows slightly increased actual dimensions in contrast to the right-hand side, which could be possible due to an increased weld spatter density in this area.

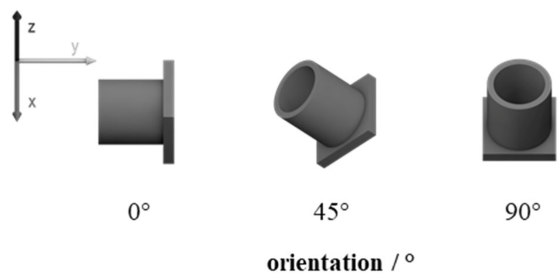
Hollow cylinder – cylindrical measuring areas:

The investigation of hollow cylinders is shown in the following for LBM. Table 5 summarizes the influencing factors and the variation range of each investigated factor. The investigation considers on the geometrical deviations on cylindrical measuring areas. The focus here is on the dimensional and form deviations on the outer diameter of the test specimen. Further considered deviations are not presented in this paper. The hollow cylinders are built in each influencing factor variation three times. Due to solid support material, the measuring method need to be adapted locally [28]. Measuring points were omitted at surfaces with solid support material appearing in 0° and 45° orientation.

Table 5 Design of experiment for the investigation of geometrical deviations in LBM using hollow cylinders

drawing / target values	influencing factor	variation range
dimensional, form and positional deviations	test specimen	hollow cylinder
	geometry	cylindrical
	nominal outer diameter d	10, 18, 30, 50 mm
	nominal length l	10, 18, 30, 50 mm
	position in build chamber	freely chosen
	orientation	0°, 45°, 90°





measuring method: coordinate measuring machine – shifted roundness profiles (SRP) – level 4

schematic representation: build job design and real test specimens in 45° and 90° orientation

The hollow cylinders are measured with the coordinate measuring machine using the above-mentioned measuring method. In 0° and 45° orientation some surfaces need solid support material in order to guarantee a robust manufacturing process (s. Table 5). Those areas are left out during the measurement. This emphasizes that especially for LBM the defined measuring method needs to be adapted locally. However, it is obvious that surfaces with solid support material need to be machined for the support removal. The results for the occurring dimensional deviations are shown in Figure 10. The diagram presents the mean, maximum and minimum values of the dimensional deviations. Both the chosen orientation and the dimension in diameter and length show a significant influence on the dimensional accuracy. In general, the occurring deviation increases with increasing nominal length and diameter independent of the selected orientation. For higher dimensions, for example L50xD50, the influence of the chosen orientation is strengthened. On average, the 90° orientation shows the smallest dimensional deviations and also the scattering of the measured values is the smallest. In contrast, the 0° orientation mostly indicates the largest deviations. In particular, larger nominal diameters show a larger undersize and the highest scattering values in this orientation.

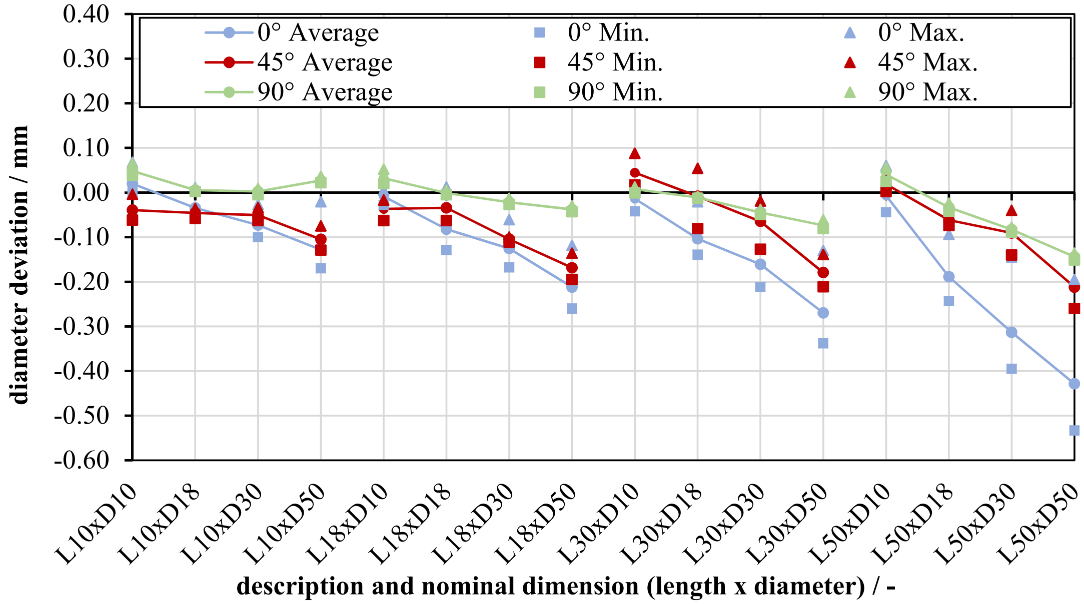


Figure 10: Dimensional deviations of the outer diameter in dependence of the dimension and orientation

The explanation on dimensional deviations can also be transferred to the cylindricity of the outer surface of the cylinders. The results in Figure 11 show that the cylinder form deviations on 90° orientated cylinders is the smallest in average. Similar to the dimensional deviations, cylinders in 0° and 45° orientation show the highest cylinder shape deviations. This distinction becomes clearer when the diameter and the length of the cylinder increase. Furthermore, the scattering of the measured values predominantly raises with a decreasing orientation.

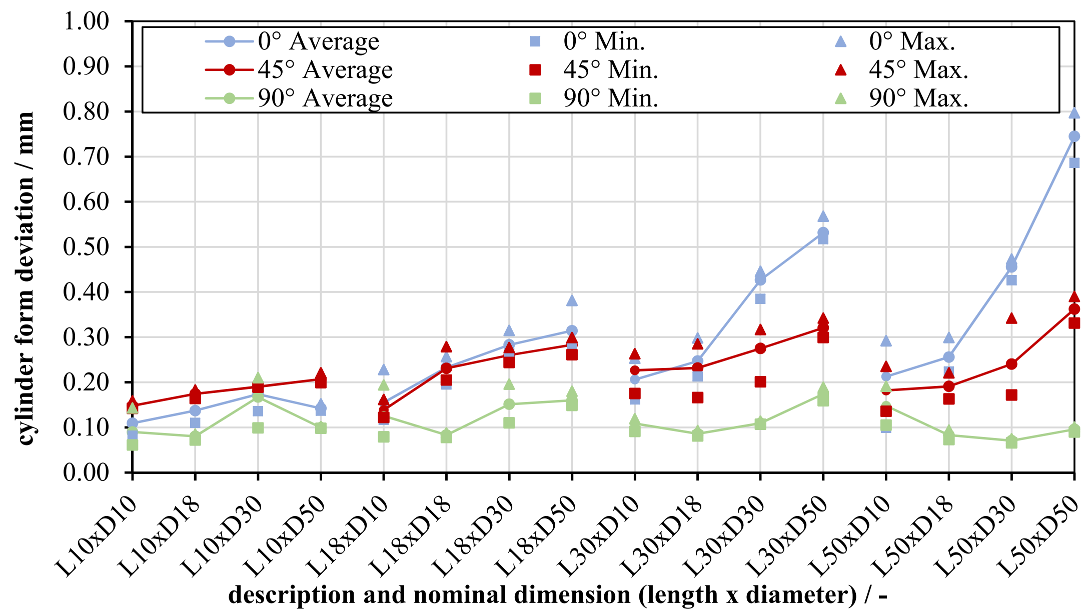


Figure 11: Cylinder form deviation of the outer diameter in dependence of the dimension and orientation

The resulting deviation can be explained on the one hand by the scaling of the components with standard shrinkage factors independent on the actual dimension of the test specimen and on the other hand by the induced residual stresses, which are induced significantly higher in the cylindrical measuring surface in the orientations 0° and 45°. The orientation 90° shows the lowest deviations because the respective layers are manufactured exactly on top of each other, which means that no free overhangs have to be built into the powder bed. In addition, test specimens in 90° orientation are not influenced by the stair-stepping effect.

Summarizing it can be said that the selected influencing factors and their variation ranges are fitting so far. Furthermore, it was necessary to carry out preliminary investigations in terms of suitable measurement methods in order to ensure a realistic representation of the occurring deviations. Relative to the geometric influencing factors, significant dependencies on the position in the build chamber, the orientation and on the dimension of the test specimens could be demonstrated. In addition to the test specimens and deviations shown here, all test specimens shown in Table 2 were investigated experimentally for the FDM, SLS and LBM processes using adapted measurement methods.

Conclusion and outlook

Additive manufacturing provides new technical and economical capabilities for the product development by contrast to established manufacturing processes. However, many process specific challenges hamper the usage of AM for serial production. One of the biggest challenges is the insufficient geometrical accuracy. Since the achievable manufacturing accuracy of the processes is often unknown, a successful post-processing is also difficult to consider before manufacturing. The present publication provides a contribution to the systematic investigation of the geometrical accuracy in AM. On the basis of relevant influencing factors and variation ranges, test specimens and suitable measuring methods were systematically developed and evaluated. The resulting method was tested by experimental investigations. The defined influencing factors and their variations could be considered as suitable. The defined measurement method, which describes in particular the extraction strategy, was also considered as sufficient. Besides tactile measuring methods with a high number of points, optical measuring methods offer a clear advantage in order to investigate the local geometrical deviations and their causes in detail. Especially due to local warpage and varying surface roughness on a single test specimen, a sufficient number of measuring points has to be provided. In addition, the number of points and the strategy are dependent on the geometry of the measuring area. The results illustrate an influence of the position, orientation and the selected nominal dimensions on the dimensional and form deviations of additively manufactured parts quantitative. The reasons for the occurring deviations could not yet be fully clarified within this work. In addition to geometric influences, process-related influences and machine components must also be taken into account in more detail in the upcoming steps. These influences enable to improve the geometric accuracy of the different processes. An optimized and quantifiable geometric accuracy can simplify the design process and make it more plannable. This minimizes costs in production and post-processing and avoids unnecessary rejects of components as well. By disseminating such knowledge in the future, the serial production of components can be made increasingly accessible to further industrial sectors.

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