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Manufacturing Accuracy In Additive Manufacturing: A Method To Determine Geometrical Tolerances

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Abstract
Additive Manufacturing (AM) processes generate plastic or metal parts layer-by-layer without using formative tools. The resulting advantages highlight the capability of AM to become an inherent part within the product development. However, process specific challenges such as a high surface roughness, the stair-stepping effect or geometrical deviations inhibit the industrial establishment. Thus, additively manufactured parts often need to be post-processed using established manufacturing processes. Many process parameters and geometrical factors influence the manufacturing accuracy in AM which can lead to large deviations and high scatterings. Published results concerning these deviations are also difficult to compare, because they are based on several geometries that are manufactured using different processes, materials and machine settings. It is emphasized that reliable tolerances for AM are difficult to define in standards. Within this investigation, a uniform method was developed regarding relevant test specimens to examine geometrical deviations for Laser Beam Melting (LBM), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) in order to derive geometrical tolerance values. The manufactured test specimens were measured using tactile and optical systems to examine the occurring geometrical deviations. The results show possible geometrical tolerance values that were classified according to the international standard DIN EN ISO 286-1.

Additive Manufacturing, accuracy, tolerances, method development, Laser Beam Melting, Selective Laser Sintering, Fused Deposition Modeling

1. Motivation and objective

The geometric and material freedom is one of the most significant advantages achieved by the layer-by-layer manufacturing in Additive Manufacturing (AM). Due to this principle, AM reduces 3D complexities in producible 2D layers, whereby almost any geometry is realizable. The parts are created by an addition of material so that compared to established subtractive technologies no formative tools are required [1]. Despite these benefits, the usage of AM for end-use part production purposes is still limited [2]. The reason is that AM involves different process-specific challenges such as rough surfaces as a result of the stair-stepping effect [3] which prevent the industrial establishment. Furthermore, the end-use part production requires an accurate knowledge and understanding of all restrictions and possibilities [4]. Therefore, the geometrical accuracy constitutes an important quality characteristic and a great challenge for the further determination and improvement of AM [5, 6].

Published results concerning geometrical deviations are also difficult to compare, because they are based on several geometries that are manufactured using different processes, materials and machine settings. It is emphasized that reliable tolerances for AM are hard to define in standards. Within this investigation, a uniform method is developed to examine geometrical deviations for Laser Beam Melting (LBM), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) in order to derive realistic tolerance values.

2. State of the art

In the following sections, the basics of geometric deviations as well as literature references to geometric accuracy for AM are presented.

2.1 Geometrical deviations and tolerances

Geometrical deviations are unavoidable due to the physical manufacturing of parts and can generally be divided into four categories [7]. The four categories are dimensional deviations (two-point dimensions), form deviations (e.g. roundness or cylindricity), location deviations (e.g. perpendicularity) and surface deviations (e.g. surface roughness). The first and fourth category were investigated for AM in further studies by the "Direct Manufacturing Research Center" of Paderborn University [8-11]. However, a description of the geometry with dimensional and surface tolerances is not sufficient. Thus, this paper focuses on form and location deviations in AM. Form and location tolerances serve to tolerate the geometry of parts in the context of assembly and functionality. These deviations result in fourteen types of tolerances according to ISO 1101 [13].

2.2 Geometrical accuracy in AM

Literature demonstrates a variety of research activities of benchmarking the geometrical accuracy for several prominent processes. These studies focus on aspects such as repeatability, building speed or feasibility of minimum feature size to compare available processes and machines [12-16]. Beside these studies, process-specific investigations on occurring geometrical deviations and concepts to optimize the accuracy are known and presented in the following.

2.2.1 Fused Deposition Modeling (FDM)

The manufacturing accuracy of FDM parts has already been addressed in previous contributions. The studies deal with the influence of individual process parameters on the resulting dimensional deviations. Sood *et al.* used a design of experiments (DoE) with the Taguchi method for improving the dimensional accuracy [17, 18]. The outcome shows shrinkage is the dominating factor for dimensional deviations in FDM. However, these investigations only focused on FDM and were done with the material ABS P400 on an older FDM machine. Minetola *et al.* developed a benchmark part where different nominal lengths are considered according to DIN EN ISO 286-1 [19]. The results show that FDM can achieve IT-classes between 11 and 16 with occurring deviations up to +2.5 mm. 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 DoE delivers optimized process parameters, e.g. smallest possible layer thickness for low dimensional deviations. Another paper on dimensional accuracy in FDM was published by Nancharaiah *et al.* [20]. 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 strand 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 [21]. They advertise the considered systems with achievable tolerances of ± 0.127 mm or ± 0.0015 mm/mm depending on the nominal dimension. The investigations were executed on three Fortus 400mc machines. The test specimen had a dimension of 127 x 76 x 14 mm and was manufactured using ABS-M30.

2.2.2 Selective Laser Sintering (SLS)

Tang *et al.* investigated the accuracy of SLS and mentioned the influence of several parameters. According to Tang *et al.*, the geometrical accuracy of laser-sintered parts is mainly influenced by the temperature distribution, material shrinkage, laser beam offset and laser scanning [22]. After finding improved settings for the main influencing factors, the errors remain below ± 0.2 mm [22]. Wegener and Witt [23] also demonstrate that the influence of the temperature distribution within the building chamber affects the accuracy as well as mechanical properties. They even proclaim that the temperature distribution is the main reason for a lack of reproducibility [23]. This statement can be clarified by the in-process temperature measurement of Josupeit and Schmid [24]. Further studies deal with shrinkage modelling to reduce the occurring deviations [25, 26]. Raghunath and Panday tested cuboids and show relations between material shrinkage and various process parameters [25]. Senthilkumaran *et al.* discussed the influence of building strategies on the accuracy of laser-sintered parts [27]. 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 [28]. However, Seepersad *et al.* only performed a qualitative assessment of the occurring deviation and did not mention any numerical tolerance values. Furthermore, most of the literature references use only one nominal dimension for the executed investigations.

2.2.3 Laser Beam Melting (LBM)

Cooke and Soons investigated deviations of dimension, form and location for LBM and Electron Beam Melting (EBM) [29]. Based on one test specimen, they analysed the influence of different heat treatments on the occurring deviations. For instance, the tested nominal dimension of 100 mm along the x- and y-axes shows 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. The circularity exhibits tolerance zones between 0.094 mm and 0.156 mm, which are calculated between the minimum and maximum deviation [29]. Hanumaiah investigated form and location deviations and derived tolerances for Direct Metal Laser Sintering (DMLS). A straightness tolerance of 0.0372 mm is defined. The deviations for flatness are examined within a tolerance of 0.0868 mm and the circularity tolerance is estimated to be 1.5320 mm [30].

Concluding, the abovementioned literature demonstrates a large variation of observed geometrical deviations on different machines, test specimens and boundary conditions. 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. 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 contribution is based on further results and extends an existing method for the examination of dimensional tolerance by adding investigations on form and location deviations. The finalized method shall be universally applicable to AM processes.

3. Method development

For the purpose of determining geometrical tolerances for AM, the “Direct Manufacturing Research Center” (DMRC) and the “Chair of Design and Drive Technology” (KAt) of Paderborn University started to explore dimensional tolerances in a first step. The developed method for dimensional tolerances was already published [8-11, 31]. Within this contribution, this method is extended to form and location deviations. Based on the initial results, achievable geometrical tolerances shall be systematically determined. For the systematical examination of dimensional deviations, a method is required that considers important aspects in determining tolerance values. Besides the identification of relevant factors influencing the geometrical accuracy, variation steps for each factor, different test specimens and suitable measurement methods are defined.

3.1. Influencing geometrical factors

The geometrical factors describe the shape and spatial position of parts within the AM build chamber [8-11]. The selected factors are applicable to all AM processes, whereby the method can be applied to every AM process, potentially with little process-specific adaptions. In the following, the geometrical factors and their variation steps are presented.

Nominal dimension (N):

A dimension is generally defined as the distance between two opposite points [7]. The investigated nominal dimensions are derived from DIN EN ISO 286-1 between 3 mm and 500 mm. The standard allows the cross-process comparison of the geometrical accuracy between plastic and metal AM processes.

Dimension group:

The dimension group includes four different types of dimensions: external, internal, distance dimensions and dimensions of various steps [7], whereby the underlying paper focuses on external and internal geometries, for instance, the roundness of inner or outer cylinders.

Element geometry:

The element geometry is an important factor. Adam developed a classification of geometrical elements, where basic elements are divided into non-curved (i.e. cuboids), simplecurved (i.e. cylinders) and double-curved elements (i.e. spheres) [32]. The classification is extended by element transitions and aggregated structures to develop design rules for AM [32]. This definition of elements is also applied to the examination of geometrical deviations in the present contribution.

Orientation and alignment:

Due to the layer-by-layer manufacturing, the spatial alignment of parts shows a major influence on the geometrical accuracy [8-11]. In the studies on the examination of dimensional tolerances, the test specimens were aligned along the x-, y- and z-axes of the build chamber in order to investigate the influence of the shrinkage factors within AM processes. For the investigation of form and location deviations, finer orientations (0°, 30°, 45°, 60° and 90°) are selected to investigate their influence on the occurring deviations in more detail.

Position in the AM build chamber:

AM machines use different heating systems and temperature controllers trying to generate a homogeneous temperature distribution during and after the manufacturing. However, the machine environment generates different temperature areas and gradients within the machine, whereby geometrical deviations can occur. This fact was already represented in [31] on nine different positions in the x-y-plane. The results show that it is difficult to deduce a clear correlation between the chosen position and occurring deviations. However, an influence is obvious.

In the next step, the above described influential factors are considered to design suitable test specimens.

3.2. Test specimens

In the context of the defined influencing factors, their variation steps and the relevant geometrical deviations, several test specimen are developed to investigate the manufacturing accuracy in AM. Therefore, non-, simple- and double-curved elements and their combinations are used to design test specimens. In sum, several test specimens were evaluated according to selected criteria, for instance the manufacturability or the technical relevance. Besides simple plates for measuring the flatness accuracy, cylinders and holes for measuring the roundness, cylindricity and coaxiality are designed. Furthermore, combinations of plates are defined to measure the achievable rectangularity or parallelism. Figure 1 exemplarily shows test specimen designs in different orientations. The following steps in the method development and experimental investigations are shown for test specimen number 2 which represents a hollow cylinder.

Beside the orientation of the hollow cylinder, the cylinder length and diameter are varied. Within this contribution, only a few of the considered nominal dimensions can be mentioned. Table 1 lists investigated cylinder lengths, diameters and orientations.

Table 1. Test specimen no. 2: Hollow cylinder with variation steps

Test specimen No.	Diameter D	Length L	Orientation O
No. 2:	Ø 10 mm	10 mm	0°
"hollow	Ø 18 mm	18 mm	45°
cylinder"	Ø 30 mm	30 mm	90°

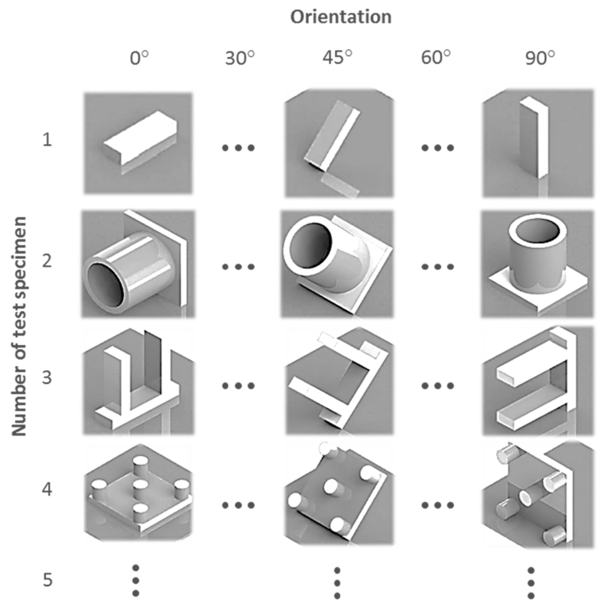

Figure 1. Examples for test specimens in different orientation

3.3. Measuring method

In measurement technology, the planning of the measurement method is important to achieve 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 association and extraction of the part is covered by DIN ISO 14660.

The extraction of the part is a derivation of the real geometry of the part 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 extraction to the real geometry [33]. Thus, for each test specimen, a meaningful extraction and association strategy is selected and developed.

In case of the hollow cylinder, different extraction strategies (Figure 2) are analyzed and evaluated. With regard to the target deviations and the high surface roughness at additively manufactured parts, cycles in three different levels along the length of the cylinder are defined.

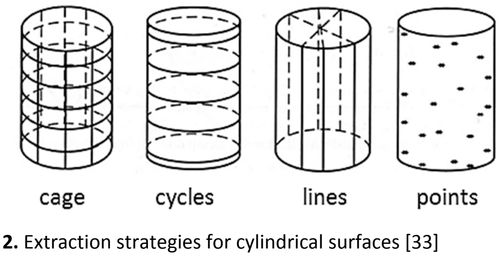

Figure 2. Extraction strategies for cylindrical surfaces [33]

In a next step, the number of measuring points on each cycle or roundness profile is set. The minimum number of measuring points recommended by Weckenmann for circles is nine [33]. As the number of measuring points must be increased to maintain the resolution as the circle diameters increase, it makes sense to adjust the number of measuring points over the circle diameter. The arc length formula is used to identify and calculate a relationship between diameter and number of points. The smallest cylinder diameter of 6 mm is measured with 10 measuring points per cycle. The resulting distance between two adjacent points is held constant for larger diameters. So, for instance a single cycles at a diameter of 30 mm contains 50 points. Concluding that a complete cylinder with an outer diameter of 30 mm is measured tactile on three cycles with a total of 150 points. This high number of points is justified by the varied surface roughness on a single test specimen. This fact is emphasized by the results of an optical measurement in section 4 "Experimental investigation".

Due to process specific support material in LBM, the extraction strategy for cylinders in 0° orientation need to be adapted. Thus, surfaces that are in contact with support material are omitted within the measurement. Figure 3 schematically shows the support material in LBM as well as the adapted measurement points for outer cylinders.

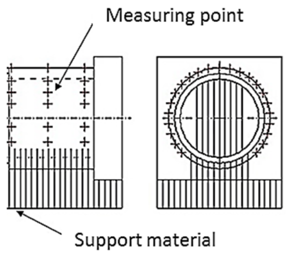

Figure 3. Adaption of extraction and measurement points due to the unavoidable support material in LBM

The Nikon Altera 8.7.6 coordinate measuring machine is used to record geometrical deviations. The tactile measuring system has a volumetric accuracy of 1.8 µm + N/400. Furthermore, the optical scanner Nikon LC15Dx is used for a detailed extraction. The results of the optical measurements are used to emphasize the occurring deviations and to identify their causes in more detail.

3.4. Boundary conditions for FDM, SLS and LBM

Table 2 shows the boundary conditions during and after the manufacturing process. The developed test specimens are manufactured with the processes FDM, SLS and LBM in order to test the developed method for the determination of geometrical tolerances.

Table 2. Boundary conditions for FDM, SLS and LBM

Process factor	**FDM**	**SLS**	**LBM**
Machine	Stratasys Fortus 400mc	EOSINT P396	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	316L
Support	SR-30	Dispers powder	Solid block support

4. Experimental investigations

The following results focus on the experimental investigation of FDM, SLS and LBM. Each test specimen is manufactured three times in each variation step. The diagram in Figure 4 shows the mean values of the roundness deviations in SLS depending on the chosen orientation and nominal dimension of the hollow cylinder. Different nominal diameters of the cylinder are characterized by three line types. For all nominal dimensions, the SLS hollow cylinders show the trend towards larger average deviations as the orientation angle decreases. This means that the smallest roundness deviations can be achieved with an orientation of 90° (see Figure 1). As the cylinder diameter increases, the mean value of the roundness deviations also increases. This observation becomes more significant considering the orientation of 0°. This is caused by the layer-by-layer manufacturing and the larger powder adhesions at downsizing surfaces in SLS. At downsizing surfaces a huge amount of the laser energy is dissipated into the non-melted powder bed resulting in additional powder adhesions [32].

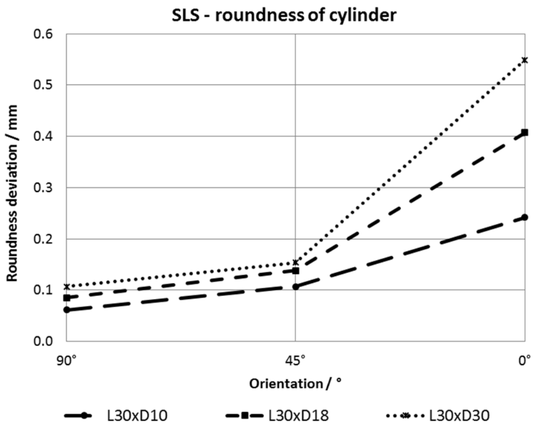

Figure 4. Roundness deviations depending on nominal diameter and orientation for SLS

LBM shows quite the same trends as SLS. However, the influence of the solid support material is special. Because of this, the extraction strategy needs to be adapted (see Figure 3). As distinguished from SLS, solid support material in LBM is used to dissipate the thermal heat from the current manufacturing layer and to reduce residual stresses and thus warpage of parts. Hence, areas of a part that are in contact with solid support material show smaller deviations. This fact can be highlighted by the tactile as well as by the optically measured outer cylinder in 0° orientation (see Figure 5). Especially the optical measurement emphasizes the need and importance of a high number of tactile measurement points and the influence of solid support material as well as the smaller deviations in these areas.

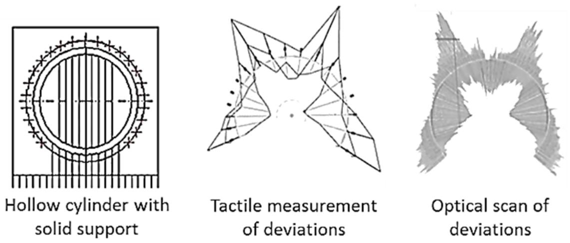

Figure 5. Demonstration of the influence of solid support material on the occurring deviations for LBM measured with tactile and optical systems (Hollow cylinder in 0° orientation)

5. Achievable tolerance values in AM

Based on the experimental results, tolerances are derived according to DIN EN ISO 286-1. For this, the maximum deviations are used to show the worst manufacturing accuracy. In the case of achievable roundness accuracy, the 0° orientation shows the maximum of deviations and therefore the limitation of manufacturing accuracy. The following table shows the achievable roundness tolerance values and ISO tolerance classes for SLS and FDM. The tolerance values highlight that FDM achieves smaller IT classes compared to SLS.

Table 3. Roundness tolerance values and IT classes for FDM and SLS

Nominal dimensions	Process	Roundness tolerance	ISO tolerance class
6 - 10 mm	SLS	0,336 mm	IT14
	FDM	0,089 mm	IT11
10 - 18 mm	SLS	0,477 mm	IT15
	FDM	0,111 mm	IT12
18 - 30 mm	SLS	0,612 mm	IT15
	FDM	0,157 mm	IT12

6. Summary and outlook

AM provides new possibilities for the product development process and technical benefits in contrast to established manufacturing processes. However, many process specific challenges impair the usage of AM for serial production. One of the biggest challenges is the insufficient geometrical accuracy. Thus, additively manufactured parts need to be post-processed by established manufacturing processes to meet the geometrical requirements. Since the achievable manufacturing accuracy of the processes is often unknown, a successful post-processing is also difficult to consider before manufacturing. Furthermore, data on geometric accuracy in references has often been determined individually without a transparent procedure, which makes general transferability and comparability difficult.

The present publication provides a contribution to the systematic investigation of geometric accuracy in AM processes. Based on an existing method for the analysis of dimensional deviations, this contribution shows an extension for the investigation of form and location deviations. On the basis of relevant influencing factors, necessary test specimens were developed and evaluated in a target-oriented manner. The resulting method was tested in experimental investigations. The defined influencing factors and their variations could be classified as suitable. The defined measurement method, which describes in particular the extraction and association strategy, was also considered sufficient. Occasionally, besides tactile measuring methods with a high number of points, optical measuring methods offer a clear advantage in order to be able 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. The results illustrate, by way of example, an influence of orientation and the selected nominal dimension on the roundness of additively manufactured parts quantitatively. The derived tolerance values for the roundness of cylindrical test specimen were classified in IT classes between 11 and 15 for the plastic processes SLS and FDM.

In the following, the reproducibility and process-related characteristics of the individual processes must be examined more closely, e.g. the reduction of warpage due to different solid support material structures in LBM. This also includes the identification of the causes and possible measures to improve geometric accuracy through design or process-related factors.

7. Acknowledgement

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