SYSTEMATICAL DETERMINATION OF TOLERANCES FOR ADDITIVE MANUFACTURING BY MEASURING LINEAR DIMENSIONS

T. Lieneke[1,2], G. A. O. Adam[1,2], S. Leuders[1,3], F. Knoop[1,4], S. Josupeit[1,5], P. Delfs[1,5], N. Funke[1,5], and D. Zimmer[1,2]

[1]Direct Manufacturing Research Center (DMRC), University of Paderborn, D-33098 Paderborn, Germany
[2]Design and Drive Technology (KAt), University of Paderborn, D-33098 Paderborn, Germany
[3]Automotive Lightweight Constructions (LiA), University of Paderborn, D-33098 Paderborn, Germany
[4]Polymer Engineering (KTP), University of Paderborn, D-33098 Paderborn, Germany
[5]Particle Technology Group (PVT), University of Paderborn, D-33098 Paderborn, Germany

REVIEWED

Abstract

Additive manufacturing offers many technical and economical benefits. In order to profit from these benefits, it is necessary to consider the manufacturing limits and restrictions. This applies in particular to the geometrical accuracy. Therefore, the achievable geometrical accuracy needs to be investigated, which enables the determination of realistic tolerances. Thus, two different aims are considered. The first aim is the determination of dimensional tolerances that can be stated if additive manufacturing is used under normal workshop conditions. Within the second aim, relevant process parameters and manufacturing influences will be optimized in order to reduce dimensional deviations. To achieve both aims a method was developed first. This method identifies relevant influential factors on the geometrical accuracy for the processes Fused Deposition Modeling (FDM), Laser Sintering (LS) and Laser Melting (LM). Factors were selected that are expected to affect the geometrical accuracy mainly. The first investigations deal with measuring linear dimensions on a designed test specimen and the derivation of achievable dimensional tolerances. This paper will present both, the developed method and the first results of the experimental investigations.

Introduction

Additive manufacturing

Additive manufacturing produces components by a repetitive manufacturing and assembly of layers [1]. Thereby the shaping of the layers occurs in the building plane (x-y plane); assembled layers in z-direction create the third dimension [2]. The processes Laser Sintering (LS), Laser Melting (LM), and Fused Deposition Modeling (FDM) are considered within the present publication. The processes differ in the manufacturing of layers and in the used materials. The LS and LM processes use plastic or metal powder, which is locally melted by a laser exposure [2]. On the contrary to LS and LM, the FDM process is an extrusion process. Thereby a plastic strand material is melted and deposited by a heated nozzle on the substrate [2, 3, 4].

State of the art

Through the layer-by-layer manufacturing without using formative tools, additive manufacturing offers great benefits compared to established manufacturing processes. Especially, great design freedoms provide new possibilities for the part design, such as helical cooling channels or complex lattice structures. In economic terms, the decoupling of the manufacturing costs from the component complexity is achievable [5]. The application of the processes is carried out in Rapid Prototyping, Rapid Manufacturing, and Rapid Tooling [2]. Nevertheless, various reasons, such as large geometrical deviations, inhibit the use of additive manufacturing in Rapid Manufacturing and Rapid Tooling. Such deviations are insufficiently researched [6, 7]. However, the literature demonstrates that various research was performed to classify the geometrical accuracy of additive manufacturing [8 - 33]. Most of the references evaluate the geometrical accuracy with standard benchmark parts. However, the geometrical accuracy is influenced by many geometrical factors, which need to be considered. Additionally, the derivation of tolerances is often lacking. Moreover, reasons for the occurrence of dimensional deviations are often unknown. As a result, there is a knowledge gap regarding achievable tolerance values for the realistic limitation of geometrical deviations [6, 7]. Additionally, the influence of process parameters on the geometrical accuracy is considered superficially so far. Within this work, dimensional tolerances are investigated with two objectives: the systematic development of dimensional tolerances for additive manufacturing processes and the optimization of machine parameters and manufacturing influences to minimize dimensional deviations.

Method Development

In order to allow a systematical determination and minimization of dimensional deviations, a method is required. The method development is executed in two steps:

- First, a method is developed that enables a systematical development of dimensional tolerances under normal workshop conditions for the additive manufacturing processes. Normal workshop conditions describe the use of frequently applied parameters, materials and machine settings.
- Second, the method development deals with the minimization of dimensional deviations by finding optimized process parameters and manufacturing influences.

Within the method, different important aspects in determining tolerances were considered. The method development started with the identification of influential factors on the geometrical accuracy of additive manufactured parts by a literature research [8 - 33] and by a workshop with technology experts from science and industry. In addition to the identification of important factors, a test specimen was designed, which enables the consideration of all selected factors. For the reproducible determination of dimensional deviations, a suitable measurement method was developed. In the following sections, the results of the method development are presented.

Influential Factors

Due to the manufacturing principles of additive manufacturing, new influential factors and effects on the geometrical accuracy must be taken into account. In the present publication, focus is on the influential factors of Laser Sintering. Some of the identified factors are shown in terms of an Ishikawa diagram in Figure 1.

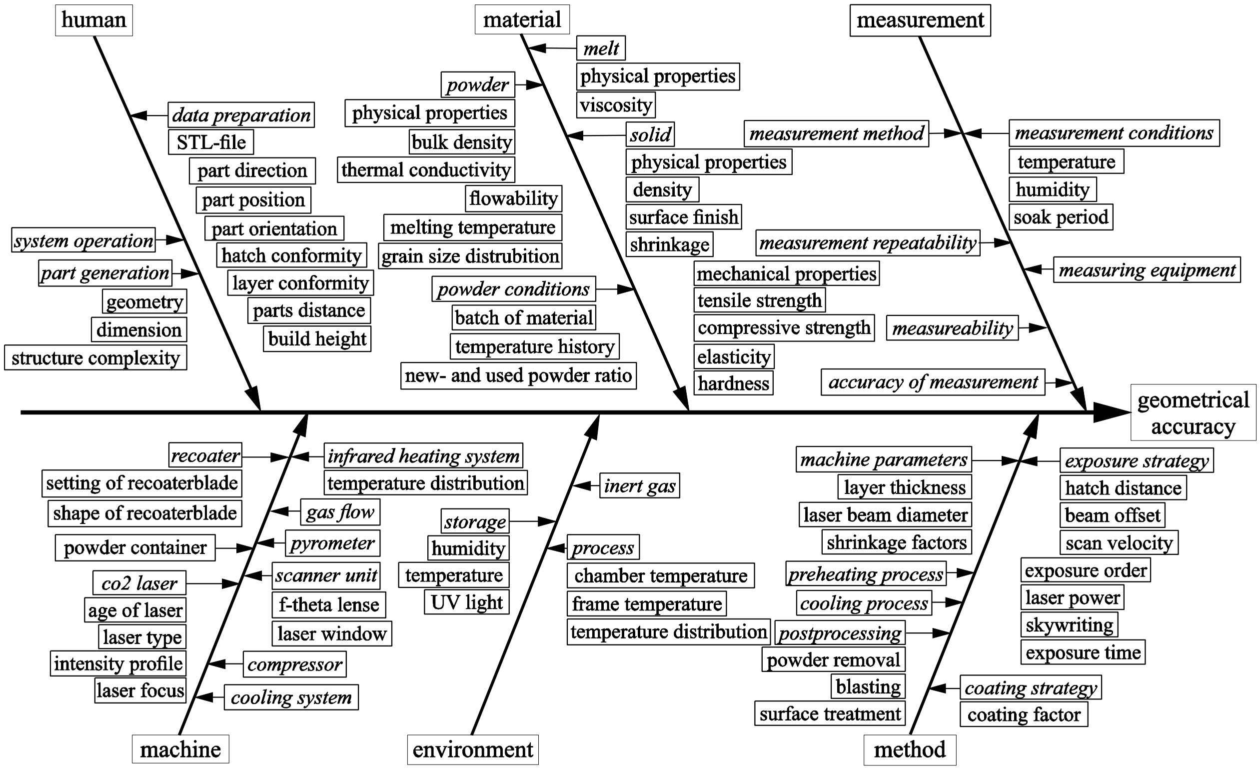

Figure 1: Ishikawa diagram for Laser Sintering

Due to the large amount of factors, a selection of the most relevant influences for the experimental investigation was performed. Technology experts, from both science and industry defined the selection of relevant influences and the determination of variation boundaries. The selected factors for the experimental test are shown in Figure 2. The remaining factors can be subdivided into geometrical factors, process parameters and measurement influences. The impacts of material, machine and environment are kept as constant as possible. For instance, the laser-sintered test specimens are made from one batch of material. The materials for the considered processes are listed in Table 1. Additionally, no changes of the mechanical and electronic components of the machine are planned.

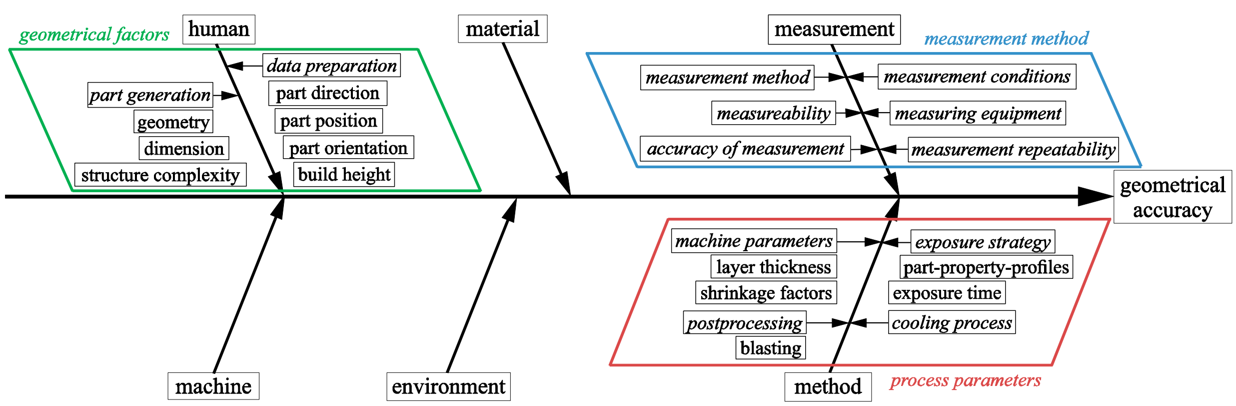

Figure 2: Selected influential factors for the experimental investigation of Laser Sintering

Table 1: Materials for the investigation of occurring dimensional deviations

Process	Fused Deposition Modeling	Laser Sintering	Laser Melting
Material	ABS-M30	PA2200	Stainless steel 316L

In the following section, the influential factors are described in more detail. Geometrical factors describe the shape and the spatial position of components in the build chamber. These factors apply for all considered processes. For each factor variation boundaries and steps were defined. Because the first investigations focus on dimensional deviations, four **dimension groups** – external, internal, step and distance dimension (Figure 3) – need to be considered. The first experimental investigations focus on external dimensions.

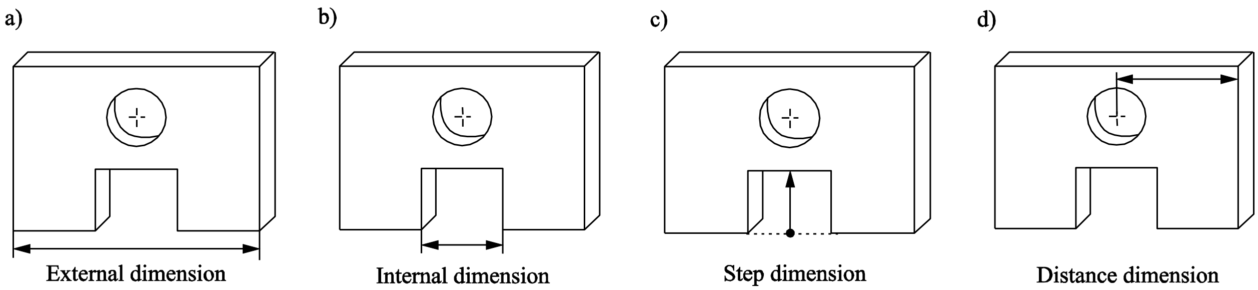

Figure 3: External (a), internal (b), step (c) and distance dimension (d) [34]

In this case, a dimension is defined as the distance between two opposite points and a dimensional tolerance is checked by a two-point measurement [34]. The examination of dimensional deviations requires the investigation of various **nominal dimensions**. For this purpose, the nominal dimensions are derived from the DIN EN ISO 286-1 [35]. This German standard describes the ISO code system for tolerance on linear dimensions and defines fundamentals of tolerances, deviations and fits. The DIN EN ISO 286-1 also allows the comparison between different manufacturing processes subject to their achievable tolerances.

Although the definition is geometry-independent, different **geometries** need to be considered. According to ADAM, geometrical basic elements are divided into non-, simple- and double-curved elements [36]. These definitions describe for instance cuboids, cylinders and spheres. This classification is expedient to apply for the determination of dimensional deviations as well. Additionally, the **structure complexity** causes an impact on the geometrical accuracy. The complexities vary between simple full material geometries, e.g. cuboids and high complex geometries, e.g. lattice structures. Within the first investigations, simple full material and non-curved elements are manufactured.

Apart from the shape of the component, also the spatial position of components in the build chamber influences the geometrical accuracy. Because different temperature gradients and temperature areas result within the powder cake [37], the components **position** have an influence on the geometrical accuracy in Laser Sintering [35]. Thus, a consideration of the position in x-y plane as well as in the direction of the z-axis is indispensable. Therefore, nine different position in x-y plane and three positions along the z-axis were defined (Figure 4a). In x-y plane, the middle (M), four side (S) and the four edge (E) positions have been selected. Along the z-axis the positions between 0 – 200 mm, 200 – 400 mm and 400 – 600 mm are investigated in Laser Sintering.

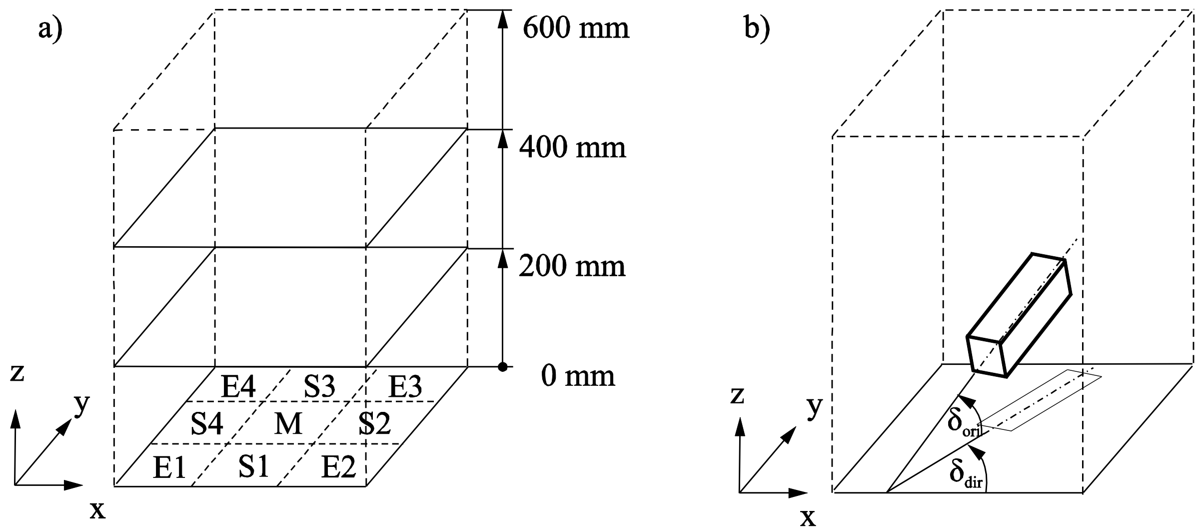

Figure 4: Defined spatial positions for Laser Sintering (a) and schematic representation of orientation and direction (b)

In addition, literature attributes importance on **orientation and direction** of components regarding the occurring deviations [38, 39]. Therefore, these geometrical factors must be taken into account as well. According to ADAM, the orientation is defined as the polar angle (δ_{ori}) between the surface of the component and the x-y plane. In order to achieve a clear description for the spatial alignment of components, a further definition for the direction is necessary. The direction is determined as the azimuth angle (δ_{dir}) between the projection of the component on the x-y plane and the x-axis (Figure 4b) [36]. For the experimental investigations, combinations of orientation and direction were chosen for which the nominal dimensions run parallel to the x-, y-, z-axis, as illustrated in Figure 5.

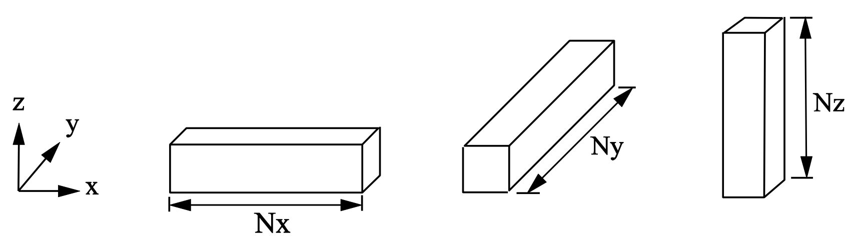

Figure 5: Spatial alignment – Nominal dimensions along the x, y and z-axis

Furthermore, process parameters and manufacturing influences for Laser Sintering, Fused Deposition Modeling and Laser Melting need to be considered in order to minimize the geometrical deviations. For Laser Sintering different layer thicknesses, shrinkage factors, packing densities, cooling times within the machine, removal chamber temperatures and sand blasting strategies were selected. The experimental investigations will identify their influence on the geometrical accuracy. These experimental tests are currently ongoing and are not presented in this publication.

Test specimen and Measurement

For the establishment of tolerances for additive manufacturing, the occurring deviations must be examined first. In addition, the investigations should identify the causes and effects of dimensional deviations. For this purpose, simple full material cuboids with a constant cross sectional area of 10 by 10 mm and different nominal dimensions (Table 2) were manufactured to investigate external dimensions. The nominal dimensions were aligned along the x-, y- and z-axis (Figure 5). Within the first experimental investigations, three specimens were built for each nominal dimension, alignment and position. Afterwards, a successive change of the geometrical factors dimension group, geometry and structure complexity is envisaged.

Table 2: Nominal dimensions derived from DIN EN ISO 286-1 [35]

Nominal dimension [mm]												
3	6	10	18	30	50	80	120	180	250	315	400	500

To enable a uniform and reproducible determination of the occurring deviations, a measurement method was set up. The actual dimension is measured by a micrometer screw with a ratchet stop. The measurement instrument accords to the German standard DIN 863-1 and has an accuracy of 0.01 mm. In this case, three local two-point measurements are recorded diagonally at the ends of the test specimen (Figure 6a). The location of the measurement points were defined for each alignment to allow a repeatability of the measurement. From these measured values, a global dimension is evaluated as maximal dimension for external dimension of each specimen (Figure 6b). After this step, the dimensional deviation is calculated as the difference between the actual global dimension and the nominal dimension.

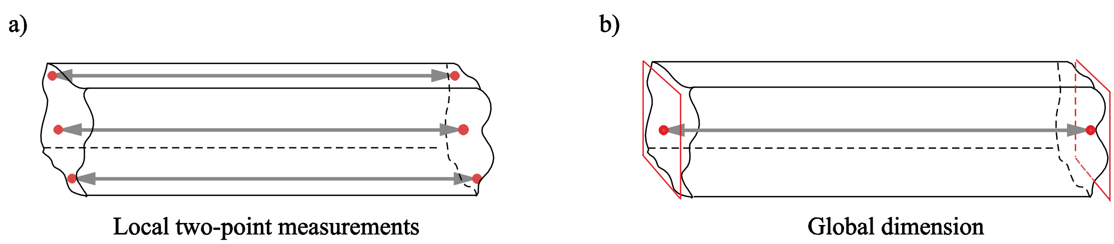

Figure 6: Measuring of test specimens – Local two-point measurements (a) and evaluated global dimension (b)

Experimental results and Discussion

The experimental investigations were carried out for Fused Deposition Modeling, Laser Sintering and Laser Melting. The test specimens were manufactured with fixed standard process parameters, which are given by the machine manufacturers. The boundary conditions are shown in Table 3. The laser-sintered test specimens were blasted after manufacturing to remove the non-melted powder. The glass bead blasting was performed with a pressure of 4.0 bar and a distance of circa 300 mm between blasting nozzle and specimen. The duration of blasting took 300 seconds. A side cutter removed the solid support material at FDM and LM mechanically as far as possible.

Table 3: Boundary conditions during the manufacturing for FDM, LS and LM

Boundary condition	FDM (Insight 9.1)	LS (PPP Balance)	LM (Standard)
Machine	Fortus 400mc	EOSINT P396	SLM 280^{HL}
Material	ABS-M30	PA2200	Stainless steel 316L
Layer thickness	0.178 mm	0.120 mm	0.050 mm
Shrinkage factors (x/y/z)	0.55/ 0.55/ 0.59 %	3.2/ 3.2/ 2.2-1.6 %	0.223/ 0.223/ 0.223 %

The diagrams in Figure 7 show the average deviation in combination with the occurring standard deviation dependent on nominal dimension and alignment for the considered processes. The results are averaged over the investigated positions. Regarding the occurring deviations, it is important to note the different axis scales for the considered processes.

For the FDM process, it becomes apparent that all test specimens show an oversize independent from their spatial alignment. In x-alignment, the positive deviation arises with increasing nominal dimension. In contrast to this, the positive deviation in y-alignment decreases. Test specimens, which are aligned along the z-axis, show an erratic curve depending on the nominal dimension.

In Laser Sintering, an oversize for small nominal dimensions was determined independently from the spatial alignment. All alignments show a decreasing dimensional deviation with increasing nominal dimension. The average deviation of the test specimen with a nominal dimension of 80.0 mm is negative. In this case, a large standard deviation is noticed for the nominal dimensions 50.0 and 80.0 mm. This large standard deviation is caused by the strong position impact of laser-sintered components. This influence becomes obvious in Figure 8. Additional other influences must be taken into account to justify the appearing deviations. For instance, the shrinkage factors have a huge importance of the occurring deviations. Those factors are usually determined for an average nominal dimension [40] and can also be responsible for the positive and negative deviations dependent on the nominal dimension.

Laser-melted test specimens in x-alignment show small deviations. The y-specimens display a constant positive deviation of circa 0.15 mm. In particular, the z-specimens show a large positive deviation of circa 0.7 mm. The support residues on the measurement areas mainly causes this oversize in z-orientation. Additionally, the melting bath penetrates deeper into the powder bed than one layer while creating a part layer. On the one hand, it is useful for the most part layers to guarantee a bond between the actual part layer and the layer below. On the other hand, the first layer of a component has no other layer below, thus the melting bath bonds undefined powder particles. Thereby an oversize results [36].

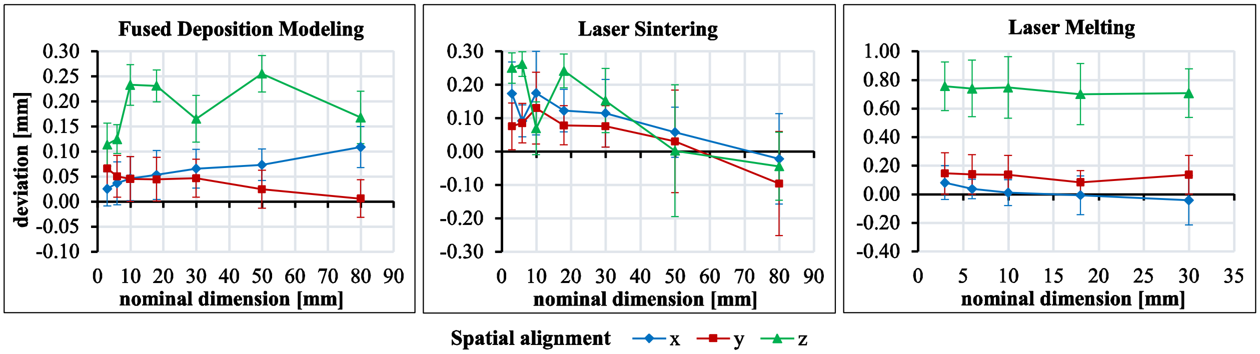

Figure 7: Average dimensional deviations in relation to selected nominal dimension and alignment of the test specimens

As already mentioned, the position of test specimens has a large influence on the geometrical accuracy. In this context, nine different positions (Figure 4) in the x-y plane were investigated. The first experimental test were executed within z-positions between 0.0 mm and 200.0 mm for Laser Sintering. The results are presented in Figure 8. It is obvious that the selected position influences the dimensional deviation. However, no clear regularity between position and occurring deviation is evident. This is consistent with representations made by ADAM [36]. The results for z-alignment shows a characteristic erratic curve. These curves are caused by the resolution of different nominal dimensions along the z-axis. Especially, nominal dimensions, which are not a multiple of the layer thickness, include larger deviations. In general, the middle position (Figure 4) shows the best average geometrical accuracy.

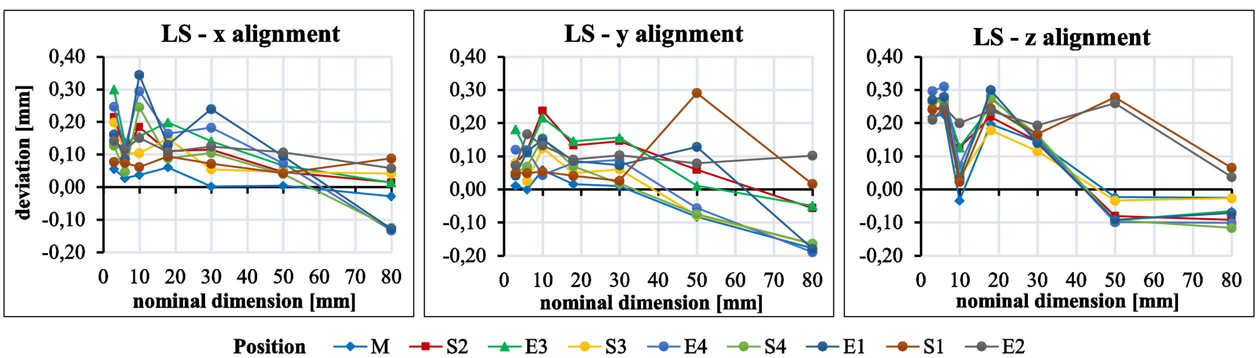

Figure 8: Average dimensional deviation in relation to the alignment, position and nominal dimension of the test specimens

The second aim is the investigation of machine parameters and manufacturing influences. For instance, the position in x-y-plane was investigated with a finer position matrix (Figure 9a) to identify the influence of different temperature areas in x-y plane according to the occurring deviations. Within the x-y plane, 224 cubes (Figure 9c) with a nominal dimension of 10 x 10 x 10 mm were manufactured on three different z-positions in near of the build platform (Figure 9a/b). The experimental investigation was executed on a EOSINT P396 with the same boundary conditions as mentioned in Table 3. After manufacturing, the actual global dimension of each cube along the x-, y- and z-axis was measured with a micrometer screw.

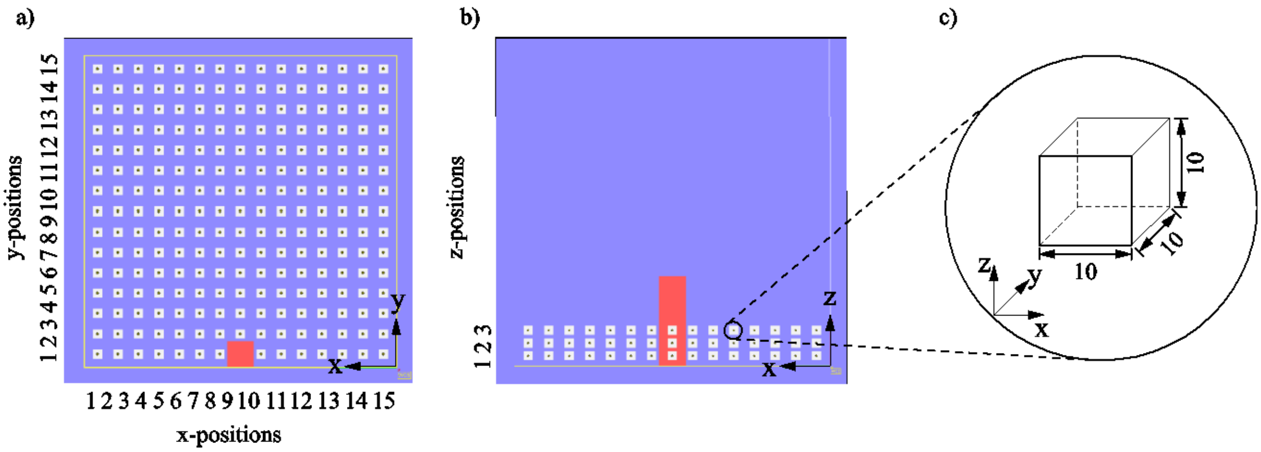

Figure 9: Build job layout for the investigation of position influence on the geometrical accuracy with cubes (c) – x-y plane with 15 positions for each axis (a) and three z-positions (b)

The results for the different positions are shown in Figure 10. The diagrams present the actual dimension for the 15 considered positions in x- and y-alignment. It emerges that the dimensional deviations increase in the boundary areas along the x-axis. Exceptions are found for positions 1 and 15, which demonstrate an abrupt decrease of the actual dimension in comparison to their adjacent positions. However, it must be noted that the positions 1 and 15 are close to the edges and sides. Only the actual dimensions along the z-axis are influenced by the different z-positions. On the contrary, the z-position in the considered range shows no significant influence on the actual dimension in x- and y-alignment. Considering the z-positions, it must be noted that the z-positions are not sufficient because the test specimens were manufacturing in the border area of the z-axis. In other z-positions, a different behavior is conceivable. The results along the x-positions emphasize that constant deviations appear between the positions 5 and 11. The results along the y-positions demonstrate slightly increasing deviations in x- and y-alignment with increasing position along the y-axis. The actual dimensions in z-alignment are influenced by the position along the z-axis as outlined for the x-positions as well. Here, it becomes obvious that the actual dimensions increase when the z-position rises in the considered boundaries.

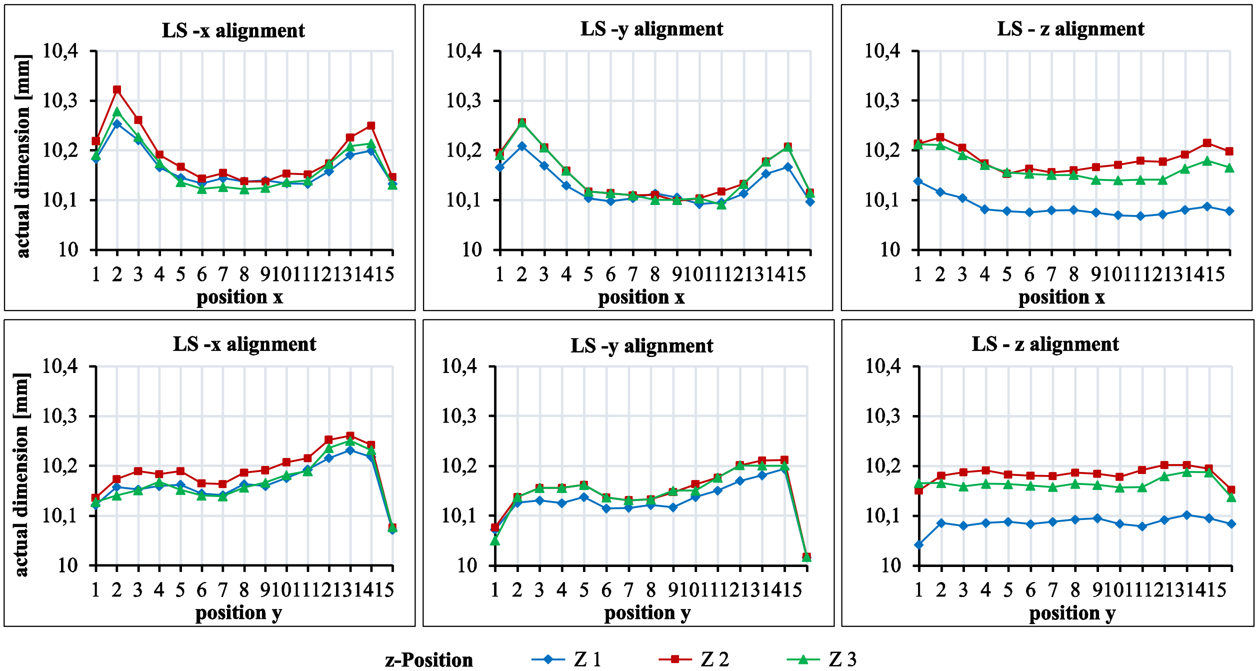

Figure 10: Actual x-, y- and z-dimensions of manufactured cubes in relation to their position in the x-y plane and along the z-axis

In general, the results demonstrate a homogenous area regarding the actual dimension between the position five and eleven in x-direction and between position three and ten in y-direction, which is possibly in correlation to the temperature profile in x-y plane [41]. The defined area should be used for the identification of other selected process influences on the geometrical accuracy. This procedure allows the examination of other process factors and manufacturing influences without a great impact of the selected position.

Comparison to established Manufacturing Processes

The results of the investigations of geometrical factors (Figure 7) were used to classify the additive manufacturing processes into the IT-classes, which are defined in DIN EN ISO 286-1 (Table 4). ISO-tolerances define the tolerance size and the position of the tolerance zone relative to the zero line. The size of the tolerances is represented by IT-numbers (1…18) and the position of the tolerance zone by different letters (A…ZC). Higher IT-classes represent coarser tolerances. This system allows a comparison between additive and established manufacturing processes subject to their achievable tolerances. Through the classification, it becomes clear that additive manufacturing can be stated under the examined boundary conditions with IT-classes 11 to 16. The considered additive manufacturing processes are relative to their tolerances with respect to their tolerances with casting, drop forging, drilling, and cutting. It should be noted that the derived tolerances are mainly influenced by the spatial alignment of the test specimen. Thus, to the spatial alignment was paid attention within Table 4. Laser-melted specimens in z-alignment show particularly high deviations due to the support residues and the melting bath, which penetrates deeper into the powder bed than one layer thickness [36]. This is illustrated by IT-classes 15 and 16 for the z-alignment at Laser Melting (Table 4). However, support material is needed and causes a high surface roughness. In order to meet requirements for functional areas, a subsequent machining of these areas should be provided for laser-melted components.

Table 4: Overview of IT-classes for various manufacturing processes according to FRITZ [42]

Process	IT-Classes (DIN EN ISO 286-1)											
	5	6	7	8	9	10	11	12	13	14	15	16
Casting							■	■	■	■	■	■
Sintering					■	■	■	■				
Drop forging								■	■	■	■	■
Precision forging						■	■	■				
Cold extrusion			■	■	■	■	■	■				
Milling				■	■	■	■					
Cutting								■	■	■		
Turning			■	■	■	■						
Drilling								■	■	■		
Face milling			■	■	■	■	■	■				
Planing				■	■	■	■	■				
Stripping			■	■	■	■						
Circular grinding	■	■	■	■	■							
Additive manufact.							■	■	■	■	■	■
FDM							xyz	xyz	xyz	z		
LS									xyz	xyz	xyz	
LM							xy	xy	xy	xy	z	z

Conclusion and Outlook

Additive manufacturing processes provide technical and economical advantages compared to established processes. However, existing restrictions due to the process principles must be researched in detail to ensure a reliable application. In particular, this applies to the limitation of geometrical deviation of additively manufactured components. Thus, realistic dimensional tolerances are methodically developed for additive manufacturing.

Therefore, relevant influential factors were defined by a literature research. The results were discussed and expanded by technology experts from science and industry. For the experimental investigations, variation boundaries and steps were selected. The experimental investigations document that the existing dimensional deviations depend on a variety of factors. The geometrical factors spatial alignment and nominal dimension show a strong influence on the occurring deviations. Additionally, the position of the component is relevant with regard to the geometrical accuracy at Laser Sintering. However, a significant correlation between position and dimensional deviation is not recognizable. The derived tolerances classify additive manufacturing in comparison with established processes in IT-classes 11 to 16 according to DIN EN ISO 286-1. The division demonstrates that additive manufacturing are comparable to the processes casting, drop forging, drilling, and cutting with respect to the achievable tolerances. So far, only a few variations of geometrical factors were investigated. For the derivation of realistic tolerances, further experimental investigations with a successive change of the geometrical factors are essential.

Further investigations have to consider different dimension groups (e.g. internal dimensions), geometries (e.g. curved elements [36]) or a higher structure complexity (Figure 2).

Within the second aim, investigations of process factors and manufacturing influences with regard to the geometrical accuracy are executed. In this context, approaches and measures to minimize dimensional deviations should be continuously developed. For this purpose, relevant process factors were identified. Experimental investigations of process factors demonstrates that dimensional deviations could be reduced by an optimal selection of different factors. This is also emphasized by literature sources, which grant shrinkage factors an enormous influence on the geometrical accuracy. For this reason, further experimental studies on the influence of process factors are required. The derived approaches should reduce dimensional deviations, which allow a reduction of the IT-classes for additive manufacturing.

References

[1] German Association of Engineers VDI (deutsch: Verein deutscher Ingenieure) : VDI 3405 – Additive Manufacturing Processes – Fundamentals, Terms, Process descriptions, 2014.

[2] Gebhardt, A.: Generative Fertigungsverfahren – Additive Manufacturing und 3D Drucken für Prototyping – Tooling - Produktion, Carl Hanser Publisher, Munich, 2014.

[3] Bagsik, A.; Schöppner, V.; Klemp, E.: FDM Part Quality Manufactured with Ultem*9085. 14th International Scientific Conference “Polymeric Materials”. September 15th – 17th, Halle (Saale), 2010.

[4] Wendel, B.: Prozessbetrachtung des Fused Deposition Modeling. Dissertation, FAU University of Erlangen, 2010.

[5] Schindel, R.: Additive Manufacturing definiert das Produktdesign neu. 8. SWISS RaPiD Forum, IRPD St.Gallen, 2012.

[6] Bourell, D.L.; Leu, M.C.; Rosen, D.W.: Roadmap for Additive Manufacturing – Identifying the Future of Freeform Processing. International Solid Freeform Fabrication Symposium, Austin, 2009.

[7] Wohlers, T.: Wohlers Report 2014 – 3D Printing and Additive Manufacturing State of the Industry. Annual Worldwide Progress Report, 2014.

[8] Gregorian, A.; Elliott, B.; Navarro, R.; Ochoa, F.; Singh, H.; Monge, E.; Foyos, J.; Noorani, R.; Fritz, B.; Jayanthi, S.: Accuracy Improvement in Rapid Prototyping machine (FDM-1650). International Solid Freeform Fabrication Symposium, Austin, 2001.

[9] Sood, A.K.: Study on Parametric Optimization of Fused Deposition Modeling (FDM) Process. Dissertation, National Institute of Technology Rourkela, 2011.

[10] Byun, H.S.; Lee K.H.: Design of a New Test Part for Benchmarking the Accuracy and Surface Finsih of Rapid Prototyping Processes. Lecture Notes in Computer Science, Volume 2669, S. 731-740. doi: 10.1007/3-540-44842-X_74, 2003.

[11] Boschetto, A.; Bottini, L.: Accuracy prediction in fused deposition modeling. International Journal of Advanced Manufacturing Technology, Volume 73, S. 913-928. doi: 10.1007/s00170-014-5886-4, 2014.

[12] Brøtan, V.: A new method for determining and improving the accuracy of a powder bed additive manufacturing machine. International Journal of Advanced Manufacturing Technology, Volume 74, S. 1187-1195. doi: 10.1007/s00170-014-6012-3, 2014.

[13] Brajlih, T.; Valentan, B.; Balic, J.; Drstcensek, I.: Speed and accuracy evaluation of additive manufacturing machines. Rapid Prototyping Journal, Volume 17, S. 64 – 75. doi: 10.1108/13552541111098644, 2011.

[14] Cooke, A.L.; Soons J.A.: Variability in the Geometric Accuracy of Additively Manufactured Test Parts. 21st International Solid Freeform Fabrication Symposium, Austin, 2012.

[15] Tang, Y.; Loh H.T.; Fuh, J.Y.H.; Wong, Y.S.; Lu, L.; Ning, Y.; Wang, X.: Accuracy Analysis and Improvement for Direct Laser Sintering. Innovation in Manufacturing Systems and Technology. http://dspace.mit.edu/handle/1721.1/3898#files-area, 2004. Accessed 22 June 2015

[16] Gregorian, A.; Elliott, B.; Navarro, R.; Ochoa, F.; Singh, H.; Monge, E.; Foyos, J.; Noorani, R.; Fritz, B.; Jayanthi, S: Accuracy Improvement in Rapid Prototyping Machine (FDM-1650). 21st International Solid Freeform Fabrication Symposium, Austin, 2001.

[17] Dimitrov, D.; Van Wijck, W.; Schreve, K.; De Beer, N.: Investigating the achievable accuracy of three dimensional printing. Rapid Prototyping Journal, Volume 12, S. 42-52. doi: 10.1108/13552540610637264, 2006.

[18] Fahad, M.; Hopkinson, N.: A new benchmarking part for evaluating the accuracy and repeatability of Additive Manufacturing (AM) processes. 2nd International Conference on Mechanical Production and Automobile Engineering, http://psrcentre.org/-images/extraimages/6.%20412635.pdf, 2012. Accessed 22 June 2015

[19] Islam, M.N.; Boswell, B.; Pramanik, A.: An Investigation of Dimensional Accuracy of Parts Produced by Three-Dimensional Printing. Proceedings of the World Congress on Engineering, 2013.

[20] Kim, G.D.; Oh, Y.T.: A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost. Journal of Engineering Manufacture, doi: 10.1243/09544054JEM724, 2008.

[21] Kechagian, J.; Stavropoulos, P.; Koutsomichalis, A.; Ntintakis, I.; Vaxevanidis, N.: Dimensional Accuracy Optimization of Prototypes produced by PolyJet Direct 3D Printing Technology. Advances in Engineering Mechanics and Materials, http://www.researchgate.net/profile/John_Kechagias/publication/269809880_Dimensional_Accuracy_Optimization_of_Prototypes_produced_by_PolyJet_Direct_3D_Printing_Technology/links/54b7705b0cf2e68eb2801356.pdf, 2014. Accessed 22 June 2015

[22] Meindl, M.: Beitrag zur Entwicklung generativer Fertigungsverfahren für das Rapid Manufacturing. Dissertation, University of Munich, Herbert Utz Publisher, 2005.

[23] Noriega, A.; Blanco, D.; Alvarez, B.J.; Garcia, A.: Dimensional accuracy improvement of FDM square cross-section parts using artificial neural networks and an optimization algorithm. International Journal of Advanced Manufacturing Technology, Volume 69, S. 2301-2313. doi: 10.1007/s00170-013-5196-2, 2013.

[24] Paul, R.; Anand, S.: Optimal part orientation in Rapid Manufacturing process for achieving geometric tolerances. Journal of Manufacturing Systems, Volume 30, S. 214– 222. doi: 10.1016/j.jmsy.2011.07.010, 2011.

[25] Raghunath, N.; Pandey, P.M.: Improving accuracy through shrinkage modelling by using Taguchi method in selective laser sintering. International Journal of Machine Tools & Manufacture, Volume 47, S. 985–995. doi: 10.1016/j.ijmachtools.2006.07.001, 2007.

[26] Seepersad, C.C.; Govett. T.; Kim, K.; Lundin, M.; Pinero, D.: A Designer´s Guide for Dimensioning and Tolerancing SLS Parts. International Solid Freeform Fabrication Symposium, Austin, 2012.

[27] Sood, A.K.; Ohdar, R.K.; Mahapatra, S.S.: Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method. Materials and Design, Volume 30, S. 4243–4252. doi: 10.1016/j.matdes.2009.04.030, 2009.

[28] Senthilkumaran, K.; Pandey, P.M.; Rao, P.V.M.: Influence of building strategies on the accuracy of parts in selective laser sintering. Materials and Design, Volume 30, S. 2946-2954. doi: 10.1016/j.matdes.2009.01.009, 2009.

[29] Fortus 3D Production Systems – Stratasys: Fortus 360mc/400mc Accuracy Study, 2009.

[30] Taufik, M.; Jain, P.K.: Role of build orientation in layered manufacturing: a review. Int. J. Manufacturing Technology and Management, Volume 27. doi: 10.1504/IJMTM.2013.058637, 2013.

[31] Wegener, K.: Additive Technologien in der Fertigung; Zuverlässigkeit und Standards. 8. SWISS RaPiD Forum, IRPD, St.Gallen, 2012.

[32] Wegner, A.; Witt, G.: Ursachen für eine mangelnde Reproduzierbarkeit beim Laser-Sintern von Kunststoffbauteilen. Rapid.Tech, https://www.rtejournal.de/ausgabe10/-3818/artikelPDF, 2013. Accessed 22 June 2015

[33] Zhou, J.G.; Herscovici, D.; Chen, C.C.: Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts. International Journal of Machine Tools & Manufacture, Volume 40, S. 363–379. doi: 10.1016/S0890-6955(99)00068-1, 2000.

[34] Jorden, W., Schütte, W.: Form- und Lagetoleranzen – Handbuch für Studium und Praxis, Carl Hanser Publisher, Munich, 2012.

[35] German Institute for Standardization DIN (deutsch: Deutsches Institut für Normung): DIN EN ISO 286-1 – Geometrical product specification (GPS) – ISO code system for tolerances on linear sizes – Part 1: Basis of toleracnes, deviations and fits, 2010.

[36] Adam, G.: Systematische Erarbeitung von Konstruktionsregeln für die additiven Fertigungsverfahren Lasersintern, Laserschmelzen und Fused Deposition Moldeling, Dissertation, University of Paderborn, Shaker Publisher, Aachen, 2015.

[37] Josupeit, S.; Schmid, H.-J.: Three-Dimensional In-Process Temperature Measurement of Laser Sintering Part Cakes. International Solid Freeform Fabrication Symposium, Austin, 2014.

[38] Paul, R.; Anand, S.: Optimal part orientation in Rapid Manufacturing process for achieving geometric tolerances. Journal of Manufacturing Systems, Volume 30, S. 214– 222, 2011.

[39] Taufik, M.; Jain, P. K.: Role of build orientation in layered manufacturing: a review. Int. J. Manufacturing Technology and Management, Volume 27, 2013.

[40] Wegener, A.; Witt, G.: Konstruktionsregeln für das Laser-Sintern, Jorunal of Plastics Technology, 2012.

[41] Wegener, A.; Witt, G.: Ursachen für eine mangelnde Reproduzierbarkeit beim Laser-Sintern von Kunststoffbauteilen, RTejournal, 2013.

[42] Fritz, A. H.; Schulze, G.: Fertigungstechnik, Springer Publisher, Berlin, 2010.