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Dimensional tolerances for additive manufacturing: Experimental investigation for Fused Deposition Modeling

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Abstract

Additive manufacturing creates parts in layers without using formative tools. Compared to established manufacturing processes, additive manufacturing offers many advantages. However, only a few research institutions and technology-leading companies use additive manufacturing for end-use part production because relevant challenges have not been sufficiently researched yet. Missing restrictions become apparent in the available geometrical accuracy. The objective of this investigation was the experimental determination of dimensional tolerances using standard parameters. To this end, a methodical procedure was set up. Based on experimentally determined deviations, dimensional tolerances were derived.

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Keywords: Additive manufacturing; Fused Deposition Modeling, geometrical accuracy; methodical procedure, geometrical deviations; dimensional tolerances

1. Introduction

Additive manufacturing emerged for the first time in the 1980s and has mostly been used for Rapid Prototyping since then [1-3]. Further developments turned the processes into a technology capable of production [3]. In recent years, the additive manufacturing of end-use parts increased significantly [5]; this is known as Rapid Manufacturing [2, 4]. Today’s applications focus on products in various fields such as mechanical engineering, medicine, fashion, and art [7, 8], indicating that their industrial relevance has increased significantly [6].

In comparison to established manufacturing processes which start with a solid mass and use subtractive techniques (e.g. milling), additive manufacturing processes create metal or plastic parts by a successive manufacturing of layers. The shaping of a layer occurs in the building plane (x-y plane); the third dimension is generated by the repetitive manufacturing of layers in the z direction (Fig. 1) [4].

Within the investigation, the processes Fused Deposition Modeling (FDM), Laser Sintering (LS), and Laser Melting (LM) were considered. The present publication focuses on FDM (Fig. 1). FDM is an extrusion processes [9] using a thermoplastic polymer filament on coils. The filament is melted, extruded, and positioned on the substrate (x-y plane) by a heated nozzle. Due to the thermal fusion, the deposited filaments form solid bonds with the substrate or other filaments [8].

Fig. 1. Schematic representation of the FDM process
After the deposition of multiple filaments and completing the actual layer, the build platform is lowered by one layer thickness at a time in the z direction to create space for the next layer. This procedure is repeated until the part is completed. In order to ensure the fixation of the parts and the manufacturing of overhangs, support material, which can be removed mechanically or chemically after the process, is used [7, 10].

1.1. Motivation and aim

The layer-by-layer manufacturing affords new technical and economic advantages. Technically, the great design freedom is one of the potentials most worth mentioning [1]. Economically, manufacturing costs can be decoupled from the complexity of the part [11], which increases the industrial demand of additive manufacturing as well [6].

Despite these benefits, the usage of additive manufacturing for end-use part production is still limited [12]. Different process-specific challenges such as rough surfaces or the stair-stepping effect caused by the layer-by-layer manufacturing harm the industrial establishment [7]. Furthermore, the end-use part production requires an accurate knowledge and understanding of all restrictions and possibilities [13]. Therefore, manufacturing design restrictions have been the subject of numerous studies [14-17]. Geometrical accuracy is another very important aspect requiring further determinations and improvements [1, 3]. Thus, the long-term aim of this study is the investigation of the geometrical accuracy (dimension, form, and location) for additive manufacturing. To get a first appreciation of the occurring deviations, the experimental investigations started with dimensional deviations. The focus of this paper is on dimensional accuracies of FDM parts.

1.2. Proceeding

The investigations regarding the dimensional accuracies were performed within the project “Dimensional Tolerances for Additive Manufacturing” (DT-AM), which handles the processes FDM, LS, and LM in collaboration with the “Direct Manufacturing Research Center” (DMRC, Paderborn University) and the Chair of Design and Drive Technology (KAt, Paderborn University).

In order to investigate dimensional accuracies for additive manufacturing and to deduce dimensional tolerance values, the state of the art was reviewed and the lack of geometrical tolerances described. Based on the gained knowledge, a new method was developed that can be used to systematically analyze geometrical accuracies. This method defines relevant geometries and influencing factors for the experimental tolerance development. Finally, the derived tolerance values were compared to values reached by conventional manufacturing technologies.

2. State of the art: Tolerances for FDM

Parts manufactured with FDM exhibit a shortcoming in achievable accuracy [18]. The geometrical accuracy in FDM has been evaluated in different studies. IULIANO et al. designed and manufactured benchmark parts that showed geometrical deviations up to ±0.7 mm [19]. MAHESH et al. analyzed freeform surfaces and observed deviations up to +2.5 mm depending on different nominal dimensions [20]. The scattering of occurring deviations on small-sized parts was discussed within the publication of SINGH [21], who derived tolerances that spread across four IT classes according to DIN EN ISO 286-1 [22]. STRATASYS, a machine manufacturer, advertises with achievable tolerances of ±0.127 mm and ±0.04 mm per mm. The results are based on an accuracy study with 108 test specimen and 2,916 measurements [23]. BOSCHETTO and BOTTINI [18, 24] discussed the strong impact of the orientation of parts on geometrical deviations. The results highlight that vertical walls showed the smallest deviations. Deviations increased with an angle smaller or greater than 90° [24]. SOOD et al. discussed the effect of several factors on the geometrical accuracy using Design of Experiment (DoE) methods and found significant factors and optimal parameter settings to minimize geometrical deviations [25, 26]. MOHAMED et al. pointed out a summary of current investigations aimed at improving the geometrical accuracy [27].

For additive manufacturing, the required realistic geometrical tolerance values are currently not known. The abovementioned literature demonstrates a large variation in observed geometrical deviations for FDM. These differences can probably be explained by the used manufacturing boundary conditions. This emphasizes that reliable and comprehensive information about geometrical tolerances is hardly known - neither in literature nor in standards. Thus, within this investigation a method to examine dimensional deviations and to derive realistic tolerance values for additive manufacturing was developed. The method shall be universally applicable for additive manufacturing processes.

3. Methodical background and experimental setup for the development of dimensional tolerances

A methodical approach is essential for a systematic determination of dimensional tolerances. First, the boundary conditions for manufacturing were defined (chap. 3.1). Based on literature research and a workshop with industry partners of the DMRC, factors influencing the geometrical accuracy were identified (chap. 3.2). Next, a measurement method was developed to analyze the geometrical accuracy (chap. 3.3).

3.1. Boundary conditions

The manufacturing was executed on a Stratasys machine Fortus 400mc using ABS-M30 material. According to the tip size T12 and a layer thickness of 0.178 mm, standard process parameters of the Insight 9.1 software were used and kept constant. The shrinkage factors were fixed at 0.55% along the x- and y-axes and at 0.59% along the z-axis. The solid support material was removed mechanically using a side cutter.

3.2. Influencing factors

The literature already demonstrated that a number of factors influence the geometrical accuracy of additively manufactured
parts (chap. 2). These factors were identified through a literature research and experiences of DMRC partners. The results were collected in Ishikawa diagrams for FDM, LS, and LM. Figure 2 exemplarily lists influencing factors for FDM which belong to the heading “human”.

The detail of the Ishikawa diagram emphasizes that the geometrical accuracy of additively manufactured parts is affected by numerous factors. Due to the pre-process, human decisions and activities indirectly influence the accuracy of parts (Fig. 2). The process started with the part generation in a CAD system. In this step, element type, dimension and the complexity were defined. The conversion into an STL file allows the preparation of data for additive manufacturing processes including the definition of the position and orientation of the parts as well as the distance between parts in the building chamber (Fig. 2).

For the first experimental investigations, the identified influencing factors were reduced to those key factors that are likely to have the greatest influence on the geometrical accuracy. Within the systematical determination of dimensional tolerances, the specifications of the key factors were varied. The specifications of the other identified factors were kept constant during the experimental investigations. In this paper, geometrical key factors for the method development are presented.

Geometrical key factors describe the shape of parts and their spatial arrangement in the building chamber. In the following section, the specifications of the geometrical factors element type, dimension group, nominal dimension, position, orientation and direction are considered in detail. The element type of parts is a fundamental geometrical factor, especially since additive manufacturing provides that freedom of design. ADAM developed a proven subdivision of geometrical elements. He divided basic elements into the types non-curved (i.e. cuboids), simple-curved (i.e. cylinders), and double-curved elements (i.e. spheres) (Fig. 3) [14, 28, 29]. This subdivision is applied for the examination of dimensional deviations.

The dimension group included four different types of dimensions: external, internal, distance dimensions and dimensions of various steps [30]. The nominal dimensions were derived from DIN EN ISO 286-1 [22]. The selected nominal dimensions (3, 6, 10, 18, 30, 50, 80, 120, 180, 250, 315, 400 mm) allow a comparison between additive manufacturing and established manufacturing processes with respect to the achievable tolerances as already mentioned by LIENEKE et al. [31, 32]. Due to the limitations of the building chamber of FDM, only nominal dimensions up to 400 mm are manufacturable on the abovementioned machine.

In addition, the spatial arrangement of parts has an influence on the occurring deviations. One important influencing factor results from the position of the parts in the build chamber [14]. Thus, nine different positions (1-9) in the x-y plane were considered [31, 32]. For nominal dimensions exceeding the defined positions, adjacent positions were summarized. Large nominal dimensions in the x-alignment were analyzed along positions 7, 8, and 9 (Position 789); 6, 1, and 2 (Position 612); or 5, 4, and 3 (Position 543). Similarly, in the y-alignment, the positions 567, 418, and 329 were investigated. In the z-alignment, the positions 7, 1, and 3 were considered. Additionally, for laser sintering three levels (A, B, C) along the z-axis were tested (Fig. 4).

The literature documents the influence of the orientation of parts within the building chamber. According to ADAM [14], the spatial alignment of parts is clearly defined by the orientation and direction [14]. For the examination of dimensional deviations, combinations between orientation and direction were tested. Therefore, three spatial alignments along the x-, y-, and z-axis were investigated.
3.3. Test specimen and measurement

To determine tolerances for additive manufacturing, the occurring deviations need to be examined taking the influencing factors into account. First, cuboids were selected to allow the consideration of the defined influences and their specifications. The cross sectional area of the test specimen was 10 mm by 10 mm. Then, the cuboids were aligned with their nominal length along the x-, y- and z-axes.

According to DIN EN ISO 14405-1 [33], a dimension is defined as the distance between two points, and a dimensional tolerance is typically checked by a two-point measurement, if no other requirements are indicated in the technical drawing (default) [30, 33]. For the measurement of external dimensions, standard measurement equipment was used. Within the experimental tests, the measurement was carried out by micrometer screws with accuracy according to DIN 863. The micrometer screws were equipped with ratchets which guarantee a defined measuring force between 5 N and 10 N.

As shown in Figure 5a, three local two-point measurements were recorded along the diagonal of the cross sectional area on each test specimen. By means of these measurements, a global dimension for each test specimen was calculated, representing the maximum, minimum and averaged deviation in order to derive dimensional tolerance values (Fig. 5b).

4. Experimental investigations of dimensional deviations

To derive tolerances for FDM, occurring deviations and the influences of the selected geometrical key factors on the deviations need to be investigated. For this purpose, test specimen were manufactured up to a nominal length of 400 mm. Up to a nominal length of 80 mm, the test specimen were manufactured six times for each position and alignment to be statistically reliable; longer nominal lengths were considered three times. In the following, the impact of nominal dimension and alignment is represented in order to demonstrate the procedure within the experimental investigation.

Figure 6 shows the average values of the occurring deviations (y-axis) and their linear trend line for each alignment (x, y, and z) versus the nominal dimensions (x-axis). The results were averaged over all considered positions. The diagram emphasizes that the alignment and nominal dimension show a major impact on the dimensional deviations. For the x alignment, an increase of the average deviations appears dependent on the nominal dimension, while for the y alignment the deviations decrease. The average deviations range between +0.03 mm and +0.50 mm in the x alignment and between +0.06 mm to -0.30 mm in the y alignment. In the z alignment, alternating dimensional deviations are indicated between +0.12 mm and +0.47 mm. The greater distance between average values and the trend line compared to the x and y alignment is caused by the approximation of nominal dimensions through layers along the z-axis. Nominal dimensions, which are an integer multiple of layers, show a better dimensional accuracy in the building direction. Further investigations showed that the different deviations in x, y, and z alignment were mainly caused by material shrinkage. Thus, the shrinkage factors in x, y, and z alignment, which should compensate the material shrinkage within the pre-process, show a huge optimization potential. The presented result indicates that the processes create new geometrical factors, which have to be considered in detail for the definition of realistic tolerance values.

5. Classification into ISO tolerance system and comparison to established manufacturing processes

In this chapter, dimensional tolerance values for FDM are derived based on the experimental investigations. The results point out that the measuring data is often not normally distributed. Consequently, an inclusion of the standard deviation is not expedient. Therefore, the occurring minimum and maximum of all locally measured deviations were used to set up dimensional tolerances.
Figure 7 shows the minimum and maximum values of the measured local dimensions for FDM in the x, y, and z alignment. The diagram represents the tolerance range depending on nominal dimension and spatial alignment. These values were used to classify FDM into IT classes according to DIN EN ISO 286-1 [22] (Tab. 1). The classification shows that the FDM process at the given boundary conditions reached IT classes between IT09 and IT14.

To get an appreciation of the geometrical accuracy of FDM, the derived IT classes were compared to other manufacturing processes. Thus, the overview of different manufacturing processes regarding their possible IT classes according to [34] was extended with regard to FDM (Tab. 2). The comparison shows that the FDM process is comparable in terms of sintering, milling, cutting, and drilling with respect to the achievable tolerance values.

Table 1. IT classes and positions of the tolerance zone according to the fit system of DIN EN ISO 286-1 [22]

| Dimension [mm] | IT class | Position of tolerance zone |
|----------------|----------|----------------------------|
| 3              | IT14     | j k r                      |
| 6              | IT13     | j j k                      |
| 10             | IT13     | j j k                      |
| 18             | IT13     | j j k                      |
| 30             | IT12     | j j y                      |
| 50             | IT12     | j j z                      |
| 80             | IT12     | j j r                      |
| 120            | IT11     | u f t                      |
| 180            | IT11     | u f u                      |
| 250            | IT11     | v d v                      |
| 315            | IT09     | v e t                      |
| 400            | -        | - r                       |

Table 2. Overview of IT classes for various manufacturing processes [34]

| Process         | IT classes |
|-----------------|------------|
| Casting         | 7 8 9      |
| Sintering       | 10 11 12 13 14 15 16 17 |
| Drop forging    |            |
| Milling         |            |
| Cutting         |            |
| Turning         |            |
| Drilling        |            |
| Planning        |            |
| Stripping       |            |
| FDM             | x y z      |

6. Conclusion and prospects

Additive manufacturing offers several benefits compared to established manufacturing processes. However, the industrial distribution for end-use part production purposes is still limited. Reasons become apparent in process-specific challenges. This applies particularly to the limitation of geometrical deviations. The research project DT-AM at the DMRC of Paderborn University deals with this research subject. Realistic tolerance values were methodically identified under common conditions for additive manufacturing.

The method development started with the definition of materials, machines, and process parameters for FDM, LS, and LM. Furthermore, factors influencing the geometrical accuracy of additively manufactured parts were identified. For the experimental tests, the key influencing factors were selected.
The first underlying results are based on solid cuboids with constant cross sectional areas. Occurring deviations were detected metrologically and the findings were discussed considering the geometrical key factors. The nominal dimension and alignment showed a strong impact on the dimensional deviations.

The classification of the derived dimensional tolerance values into the IT system according to DIN EN ISO 286-1 illustrates that the FDM process reaches IT classes between IT09 and IT14; it is comparable in terms of sintering, milling, cutting, and drilling with respect to the achievable dimensional tolerances. The results point out that the position of the tolerance zone needs to be considered as well. This requirement was examined by means of the international fit system according to DIN EN ISO 286-1. The combinations of IT classes and positions of the tolerance zone permit a useful classification of the expected deviations. Boundary conditions during manufacturing also have to be taken into account. The variation of process parameters and manufacturing influences probably leads to different dimensional deviations. This highlights that a unique methodical approach is essential to determine geometrical deviations for additive manufacturing.

Next, the specifications of the defined geometrical key factors need to be varied to expand the methodical procedure and to determine deviations for several geometrical shapes. The step-by-step variation of geometrical factors and the related experimental tests allow the systematical derivation of dimensional tolerances. The long-term objective of the collaboration between DMRC and KAT is the extension of the methodical approach to form and location tolerances for additive manufacturing.

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