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Pre-compensation of Warpage for Additive Manufacturing

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Abstract: Additive manufacturing technologies enable the production of parts by successively adding layers. In powder-based technologies, each powder layer is selectively solidified following the respective cross-section of the parts either by the application of high-energy radiation or by the selective deposition of binder. By repeating the steps of layer deposition and selective solidification, parts are fabricated. The layer-wise build-up and the ambient conditions lead to warpage of the parts due to the temporarily and locally uneven distribution of shrinkage throughout the part. This leads to deviations in shape and dimension. The development of these technologies fosters a change from prototyping to manufacturing applications. As a consequence, higher standards regarding the shape and dimensional accuracy are required. Therefore, new strategies to minimize the resulting deformations are necessary to reduce rejects and widen the range of applications of the described technologies. In this paper, an empirical, a knowledge-based and a simulative approach for warpage compensation are introduced. They are all based on the pre-deformation of the digital 3D part geometry inverse to the expected deformation during manufacturing. The aim of the research is the development of a comprehensive method that enables users to improve their part-quality by supporting the pre-deformation process. Contrary to existing work, this method should not be process-specific but cover a wide range of additive manufacturing techniques. Typical forms of deformation of the processes laser sintering, laser beam melting and 3D printing (powder-binder) are presented and compensation strategies are discussed. Finally, an outlook on the ongoing research is given.

Key words: Additive manufacturing, shrinkage, warpage, compensation, pre-deformation, simulation.

1. Introduction

AM (additive manufacturing) technologies is a collective term for a multitude of different processes using different principles to fabricate parts from diverse materials in successive layers or units [1]. The most common fields of application in industrial enterprises are the production of metal and plastic components [2]. Besides the material properties of the manufactured components, the dimensional and shape accuracy are important criteria for an economic use of AM technologies [3].

A frequent reason for deviations in shape and dimension is an inhomogeneous shrinkage of the material during the build-up of the component. Although the solidification of the layers is based on different chemical or physical principles [4], analogies regarding mechanisms for warpage behavior can often be found, e.g., the “curling” effect [3, 5-7]. In this manuscript, process related distortions occurring in three manufacturing technologies are discussed: LBM (laser beam melting), LS (laser sintering) and 3D printing (powder-binder, 3DP). Additionally, three approaches for pre-compensation of the resulting warpage by an adjustment of the digital 3D input geometry data of the component are given. In the following, LBM refers to the standard manufacturing process of Inconel718 on an EOS M270 system. LS experiments were conducted on an EOS Formiga P100 with polyamide (PA2200) powder and 3DP was investigated with polymethylmethacrylate (PolyPor A) powder in combination with a voxeljet laboratory machine VTS128.

The three processes investigated within this work are

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all powder bed based but use different principles. During LBM and LS, the powder layer is melted by a selective exposure to laser light via small single weld tracks, so called hatches. Whereas in LBM, the applied fusion energy is quickly transferred to the machine interface by support structures; in LS, the powder bed is heated just below the melting temperature and the laser powder interaction causes only little temperature differences. After the LS fabrication process, the build chamber is homogenously cooled. Consequently, there is a higher local energy input via laser in LBM and there are differences in the thermal balance between LS and LBM. In 3DP a second material, the binder, is selectively applied by an ink-jet print head. The binder creates a local cohesion between powder particles. In contrast to the two thermally activated processes, the binder partly solves the particles [8]. Subsequently, a part of the binder starts a polymerization reaction with radicals embedded in the powder, the other part evaporates [8].

2. Shrinkage and Warpage

In this paper, deformations caused by inhomogeneous shrinkage during the fabrication are discussed. Shrinkage is defined as a change of length, area or volume of a component without external forces [3]. In the presented examples, shrinkage always leads to a decrease of the specific volume.

2.1 Reasons for Shrinkage

The reasons for shrinkage in additive manufacturing are manifold. The most important ones for the technologies in question are presented in the following. For thermal processes such as LS and LBM the thermal shrinkage during the cooling of the part and the shrinkage based on higher packing density during crystallization is one of the driving forces [3].

Additionally, for all powder-based technologies, the packing density of the powder bed prior to solidification is another possible source of shrinkage. Assuming a similar density of the powder particles and the finished part, the packed bed’s porosity (depending on the grain size distribution) reaches about 35% in plastics [7] and up to about 50% in metal [9]. Depending on the timescale of the underlying solidification process, this does not necessarily lead to deviations from the nominal dimensions as subsequent layers may compensate for the missing volume, as apparent e.g., in LBM.

Moreover, for e.g., 3DP, there are other, process specific reasons for shrinkage. With the physical and chemical reactions caused by the deposition of binder, particles are contracted by capillary forces. Moreover, the binder partly dissolves the particles, whereby a closer packing is possible. A part of the binder evaporates, leading to a reduction of mass and volume [8]. Last, the polymerization reaction leads to an increase of the density resulting in a declining specific volume [7].

However, the global thermal shrinkage effect due to a significant difference between build-up and intended operation temperature is not within the scope of this investigation.

2.2 Examples for Warpage Caused by Inhomogeneous Shrinkage

One important reason for the deformation of parts produced with AM technologies is an inhomogeneous shrinkage. This means that the shrinkage rate of the component depends on location and time [7, 10]. This results in different changes in length within the component, leading to residual stresses and warpage. The size of the resulting warpage is always dependent on mechanical boundary conditions.

The layered structure of the components leads to time-dependent solidification and shrinkage rates of the individual layers [9]. The resulting different elongations are leading to an upward bending comparable to a bimetal, what is referred to as curling effect [5], see Fig. 1. Moreover, there is a force transmission between the layers. On one hand, the shrinkage of later printed layers results in an additional compaction of the layers below. On the other hand, this effect inhibits the contraction of later produced layers. The result is a trapezoidal deformation of vertical orientated side faces of the component towards the middle of the part [11].

Additionally, there are process-specific effects introducing warpage in thermal processing. With the high local energy input inherent to LBM, the so-called temperature gradient mechanism is an additional driver for stresses within the part. With local stress exceeding the yield stress and subsequent shrinkage, a bending towards the energy source develops [12]. This describes the effect in the length scale of single melt tracks. The resulting net effect depends on the layout of the melt tracks, i.e., the scanning pattern. As a result, tensile stresses and corresponding warpage always occurs in the boundary areas [12]. Fig. 2 exhibits simulation results of the build-up of a cantilever (T-structure) by means of LBM. In this example, warpage as a result of residual stress relieve leads to deviations in dimensional accuracy up to 0.651 mm [13].

Another effect, but in the context of 3DP, is the faster solidification of boundary areas due to a higher evaporation rate at the part surface. Internal component regions continue to shrink, resulting in a subsidence of the surface comparable to a pincushion, particularly in solid areas [11], cf. Fig. 1.

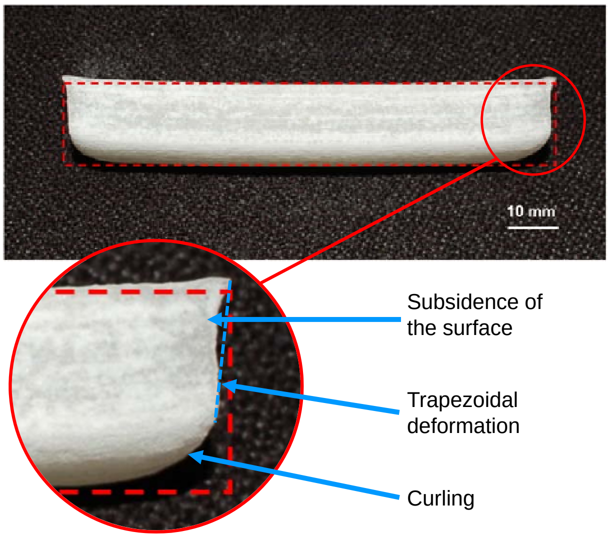

Fig. 1 Deformation of a cuboid produced with 3DP.

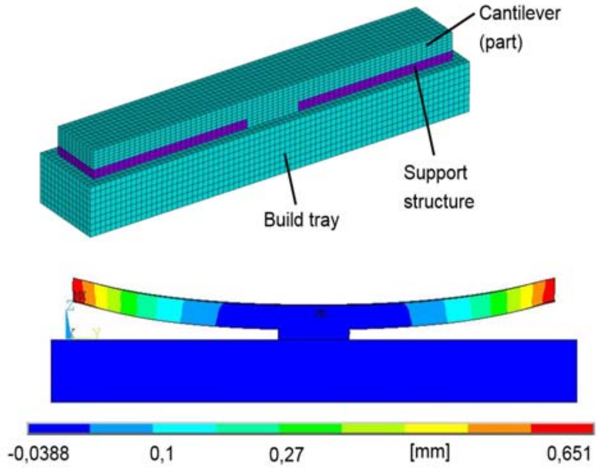

Fig. 2 Simulation result of warpage of a Cantilever (T-structure) after build-up by LBM and the removal of support structures [13].

Furthermore, loose powder is not subject to the shrinkage effect. Consequently the contraction of the part is prevented by enclosed powder, e.g., in holes or undercuts. The consequence is a deformation of the part caused by the blocked shrinkage effect [11].

3. Methods of Compensation

In this manuscript, the term “compensation” is defined as a procedure to increase the size and shape accuracy of parts manufactured by AM processes. The methods described here use techniques to adapt the digital 3D volume data of a component before the production in order to reduce deviations. For this purpose, an adaption of process parameters is not considered. This is because there are complex interdependencies in terms of resulting mechanical properties that need to be taken into account but cannot be addressed within this work. However, the example of LBM shows that adapting process parameters with the objective to homogenize temperature distributions during the build-up leads to an improved dimensional accuracy [13]. Summarizing, it is recommended to pursue a two-step procedure: first adapting fabrication parameters to homogenize process conditions, e.g., by avoiding heat or binder accumulations in thin-walled part areas, and second using methods of compensation as described in the following.

3.1 Pre-compensation Using Free-Form-Deformation

FFD (free-form-deformation) is a geometric method to distort the digital part geometry by deforming a cuboid area surrounding the component [14]. By deforming the cuboid, distortion is transmitted to the digital geometry [11], see Fig. 3. Provided that the later warpage of the geometry is known, the component geometry can be pre-deformed with this method in order to eliminate or at least reduce the subsequent deviation. Two approaches for acquiring the required knowledge about the deformations are introduced.

The most basic approach for warpage compensation is the examination and gauging of an already produced component according to the original CAD geometry data. The discrepancy is calculated and used as input data for the compensation. The pre-deformation is performed contrary to the measured deviation using the FFD technique. In the next step, the component is produced again using the pre-deformed geometry data. The product is compared with the original CAD data. If the part still is beyond the specifications the pre-compensation and validation process is repeated iteratively until the requirements are met.

As advancement, the second approach uses an experience based pre-compensation. For typical shapes of deformations mathematical descriptions in order to characterize the deviations are created. These functions are implemented as a macro in software-supported FFD. In empirical studies, suitable parameters for compensation depending on conditions such as geometry, orientation and material system are determined. Thus, simple geometries like tensile bars and frames were produced and geometrical parameters such as the orientation in the build chamber or the size were varied. Initially, an iterative pre-compensation according to the first approach was used. The parameters and the observed influence of geometry adaption were documented. This knowledge was then applied to subsequently produced, more complex geometries. Moreover, for some deformation effects, geometries, process and material properties, the pre-deformation cannot be straightforwardly applied and a scaling factor for the compensation is necessary [11]. Provided that the parameters were identified in previous studies, components are intelligently pre-deformed for the first iteration saving additional production loops and thus costs and time, compared to the first approach. The ongoing application of this compensation method will contribute to a knowledge database for pre-compensation.

3.2 Geometry Adaption by Simulation

To further eliminate costs of manufacturing test samples, a simulation-based process chain can be employed. The necessary simplifications and abstractions to simulate the transient build-up process need to be adjusted according to the intended use of the model, as result quality always competes with computing time.

The simulation results within this paper were generated with a sequentially coupled finite element simulation model that relies on a simultaneous, uniform heat input into layer compounds, i.e., the combination of multiple real layers, in order to simulate the build-up process of complete parts [15]. The corresponding material data were obtained in specially designed experiments and contain e.g., a kinematic hardening model for the nickel-base superalloy 718 [13]. Validation trials were carried out both in terms of deformations and residual stresses and show reasonable agreement [16-19].

Utilizing simulation models allows both improving experience based pre-compensation methods (cf.

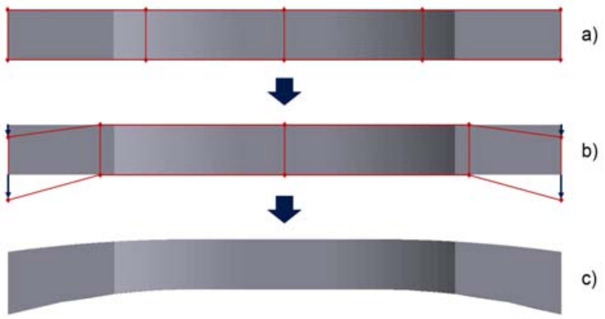

Fig. 3 Example for the application of the FFD: (a) non-deformed cuboid and part, (b) deformed cuboid and (c) deformed part.

Section 3.1) and pre-deformation to compensate for the mentioned warpage. A straightforward approach for simulation based pre-compensation is the uniform inversion of the nodal displacement values, also described in Ref. [18]. With most of numerical methods relying on a discretization of the domain, the described technique is independent of computational deformation methods like FFD as the corresponding mesh can be used. To account for the likely non-linearity of the process, this pre-deformation can be applied in an iterative approach, re-simulating the process with the adjusted geometry until the results from subsequent iterations stay within a given tolerance [15].

This approach will, however, fail to work for highly non-linear, instable structures, such as filigree, slightly bent walls, where a pre-deformation will result in an inverse bending and not reduce the deviation from the nominal dimension. For these cases, a non-uniform pre-deformation factor, respecting local convergence behavior, is expected to yield suitable results in the future.

4. Use Cases

Suitable approaches for warpage compensation can be chosen according to the considered use case. In this sense, simple trial-and-error might be applicable for low-cost materials and machines. The benefit of an experience or simulation based approach increases with the cost of the basic material and the machine-hour rate of the used system. Thus, for high-end applications the effort for complex pre-deformation techniques is more likely to be economically sound.

The first case study demonstrates an example for the development of an experience based approach. First, critical areas of the components need to be identified and the value of the deviation must be predicted. Second, the effect of the pre-deformation must be known. For compensation, it is not always sufficient to apply the negated value of the measured warpage. This is due to the change in geometry that is caused by pre deformation, which has a repercussion to the warpage, as shown later.

Simple geometries like tensile bars and frames were manufactured for investigation using 3DP while varying the process parameters orientation and size of the component as well as the material system in three factor steps with six specimens per step, cf. Ref. [11]. The produced specimens were measured with a laser scanner type scan CONTROL from Micro-Epsilon. In the next step, value and shape as a result of identified warpage were determined and described. After this, components were pre-deformed and produced, measured and analyzed again. The gained knowledge was also used to pre-deform similar objects by varying geometric features.

In this paper, the procedure is exemplified by a frame with the dimensions of $60 \times 24 \times 10$ mm^3. It consists of two massive blocks at the short sides with a thickness of 10 mm, connected by two thin struts with a wall thickness of 2 mm in longitudinal direction, cf. Fig. 5. For this object, the significant effects described in Section 2.2 appeared as follows:

- the curling effect at the down-skin;
- a subsidence of the surface at side areas of the massive blocks;
- a bulge at the thin strut.

Subsequently, the underlying procedures are explained by the example of the deformation of the thin struts. The deformation is caused by a large shrinkage of the massive block. The enclosed loose powder constitutes a resistance against the contraction of the part leading to the deformation of the strut (cf. Section 2.2). The analysis of the component showed a shift of the strut by about 0.3 to 0.4 mm with a transitional region toward the massive block. A pre-deformation of 0.4 mm led to an overcompensation of -0.3 mm. This is caused by the reinforcement of the previously straight geometry achieved by adapting the 3D component data. Thus, a scaling factor smaller than one is necessary in this case. The best results were achieved with a pre-compensation of 0.2 mm, see Fig. 4. Comparable results were achieved by increasing the length or the width of the frame without changing the thickness of the strut and the block. A global scaling of the frame by a factor of 2 leads to a doubling of the deviation and the best compensation was achieved with a pre-deformation of 0.4 mm. Consequently, the warpage depends on the dimensions of the massive block as its shrinkage increases with its cross-section. This and similar rules must be identified and documented in order to compensate objects based on experience. A database for pre-deformation can be generated by a further variation of geometry and parameters.

Similar to the effects observed in the 3D-printed part, a simulation of the LBM manufacturing process of the exemplary frame part also exhibits an outward bending of the thin structures (cf. Fig. 5b) and a curling of the whole structure (cf. Fig. 5e). In contrast however, due to the rigid connection of the part to the building plate, the effects only manifest in deformations in unconstrained regions.

The iterative improvement in dimensional deviations is shown in Table 1. While the maximum deviation is quickly reduced, the mean deviations require five iterations to converge, i.e., exhibit less than ten percent change from one iteration to the other for the given algorithm with a uniform pre-deformation factor [17]. The result of this iterative process is shown in Fig. 5. With the initial geometry (a) representing also the target geometry, a simulation is performed, yielding a deformed geometry (b). Upon the fifth iteration a pre-deformed part (c) is determined that yields a simulated manufacturing result (d) close to the target shape. The level of agreement between simulation and experiment as the most important criterion for assessing the helpfulness of this approach remains, but the topic of validation exceeds the scope of this document.

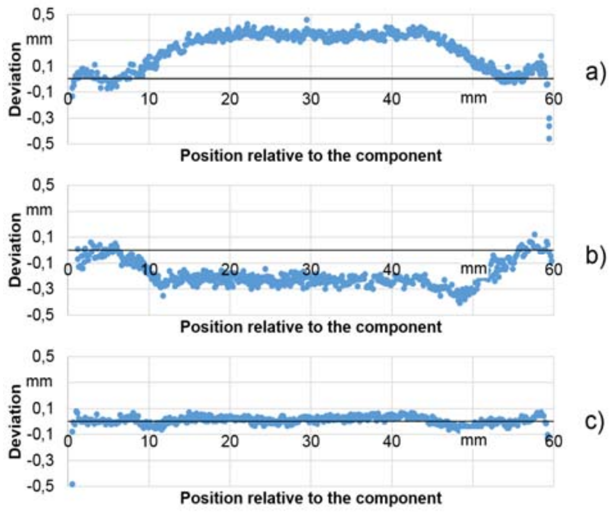

Fig. 4 Measurement data of the thin strut of the frame with (a) no compensation, (b) a pre-deformation of 0.4 mm and (c) a pre-deformation of 0.2 mm.

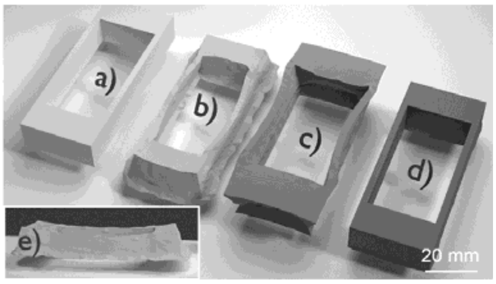

Fig. 5 Pre-deformation procedure by inversion of the simulation results: (a) initial geometry, (b) result of the 1st iteration, (c) pre-deformed part (5th iteration), (d) result of the 5th iteration and (e) side view of the result of the 1st iteration with the apparent curling effect. The warpage is magnified 50 times.

Table 1 Overview of the development of dimensional deviations for the given geometry in an LBM simulation over the course of five iterations.

Iteration	Absolute deviations in μm			Improvement in %	
	Maximum	Mean	Standard deviation	Improvement of the maximum	Improvement of the mean
1	103.8	44.7	26.3	-	-
2	25.1	5.1	2.7	76	89
3	25.3	1.8	3.4	1	65
4	25.4	1.5	3.5	0	16
5	25.4	1.5	3.5	0	2

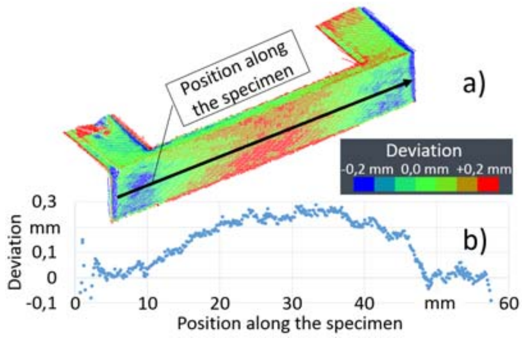

Fig. 6 False color plot of the measurement data of the laser-scan of an uncompensated specimen (a) and evaluation of the deformation along the specimen (b).

For LS comparable results could be observed. As shown in Fig. 6, the frame-specimens exhibited shrinkage in the compact areas (blue). The thinner walls of the struts were bent outside by the inlying powder thus showing a bulge (red) of 0.2 mm to 0.3 mm. Curling of the specimens as shown in Fig. 1 and 2 could also be determined.

5. Conclusions and Outlook

In AM, there are different processes depending on the material and type of solidification. However, analogies regarding the warpage behavior can be found between different processes. This enables the development of a comprehensive method for the compensation of dimensional deviations.

The presented methods require a successively increasing understanding of the processes and can also be combined. Accordingly, the effort of their application rises.

The first approach shows a trial-and-error procedure. Components are produced, measured and the virtual data are subsequently pre-deformed. This assumes that the process conditions such as the position and the used capacity of the process chamber are kept constant while repeating the manufacturing process. In most cases several iterations are necessary because the pre-deformation affects the component geometry. Thus, the compensation is not directly mapped to the later model. The knowledge about these relations and the expected deviations at a certain type of geometry enable a pre-deformation based on experience as a second approach. Hence, iteration loops are reduced or completely eliminated. An appropriate knowledge about the active principles and their influencing factors also enables simulation of the process. Using simulation in the third approach helps to reduce costly investigations to determine the parameter sets for pre-deformation. If the simulation is sufficiently accurate, appropriate parameters for pre-deformation can be adjusted iteratively with the model in the final approach. The costs for producing parts several times using the first approach is shifted to the effort needed for setup and implementation of the database or simulation. The decision for one of the approaches depends on the use case scenario and the existing process knowledge.

It is shown that, in principle, the three approaches for warpage compensation can be applied to the different AM technologies presented in this paper. In the future it has to be investigated if specific forms of warpage occur for the process of interest. For the knowledge and especially for the simulation based approach, a sound understanding of the process and material behavior is essential for making valid predictions regarding the expected warpage. Even for further AM processes that were not included in this work the observation of analogies can help to efficiently develop suitable parameter settings and increase process understanding.

In future research, further studies about the direct transferability between different AM processes and the transfer of parameter sets for pre-deformation have to be investigated. Furthermore, the analogies between the processes have to be used to develop and improve simulation models for additional AM production techniques. Thus, the overall acceptance of AM technologies can be increased and the field of potential applications can be extended to challenging industries such as the aerospace and the medical sector.

Acknowledgments

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