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VALIDATION AND COMPARISON OF FEM-SIMULATION RESULTS OF THE FUSED DEPOSITION MODELING PROCESS UNDER CONSIDERATION OF DIFFERENT MESH RESOLUTIONS

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Abstract

The Fused Deposition Modeling (FDM) process is an Additive Manufacturing (AM) technology. In the FDM process, components are generated by feeding a thermoplastic polymer filament into a heated nozzle and depositing the molten material layer-by-layer in a defined way onto the building platform or an already existing component structure. The strand-by-strand deposition leads to a complex cooling situation which contributes to the non-uniform shrinkage of components in the FDM-process. Using an AM plug-in for the FEM-simulation software Abaqus, the thermal and mechanical aspects of a component can be simulated according to the temporal sequence of the manufacturing process. For this, the birth-death-method is used in the simulations. During the investigations, the simulation results regarding geometrical deviations are compared to the actual deviation of the manufactured specimens. Furthermore, the influences of the mesh resolution on the simulation results and the required time for the simulations are considered.

Introduction

In this paper the Finite Element Method (FEM) was used to simulate the Fused Deposition Modeling process to obtain the geometric deviations in the x-y-plane. For this, the commercial simulation software Abaqus 2019 in combination with the AM plug-in provided by Dassault Systèmes was utilized. With the simulation software a cube with an edge length of 15 mm was simulated with different configurations regarding the mesh resolution and increment size. In a first step, the time necessary for the simulations is analyzed under consideration of the selected configuration. Following, specimens are built and measured using a coordinate measuring machine (CMM). The results of the geometric deviations of the physical specimens were then compared to the results derived from the simulation results.

State of the Art

The Fused Deposition Modeling currently is the most used Additive Manufacturing technology [1]. In 1989 the FDM technology was developed and patented by Stratasys [2]. As the FDM process is an Additive Manufacturing technology, it is based on the characteristic layer wise generation of components. For this, the FDM process processes a thermoplastic polymer filament which is stored on a spool. The filament is fed into a heated nozzle, where it is molten. By a precise positioning and traversing of the nozzle in the x-y-plane, a molten thermoplastic polymer strand is deposited onto a building platform or an already existing component structure. After the completion of a layer, the distance between the building platform and the nozzle tip in the z-direction is increased by one layer height.

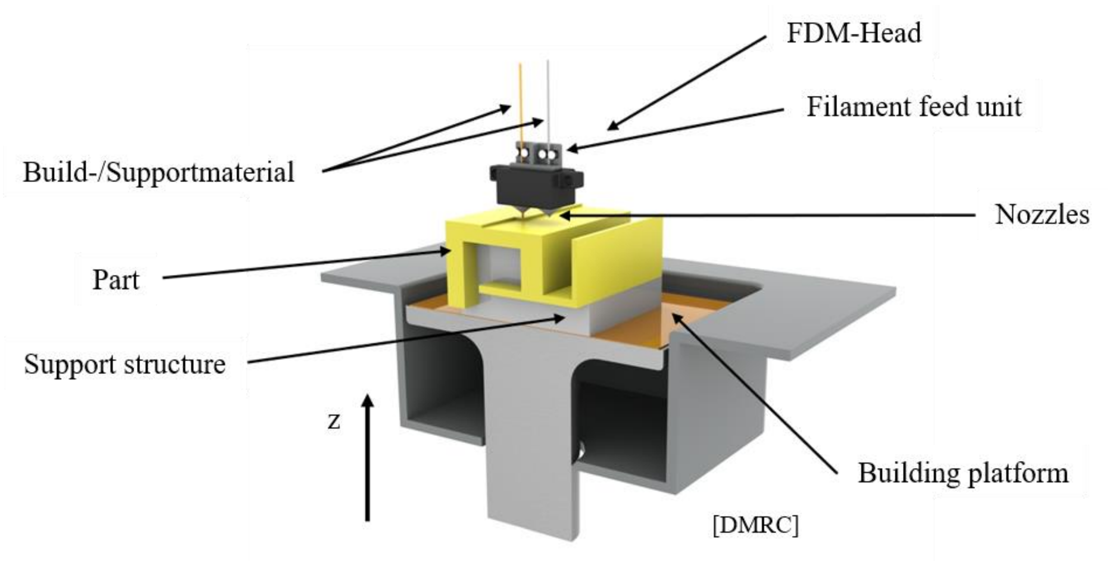

Figure 1: *Schematic of the FDM process.*

Following, the deposition process continues. This is repeated until the component is completed [3]. The machine principle is shown in Figure 1. When cooling down after processing, thermoplastic polymers show a characteristic shrinkage behavior. As the FDM process is a tool less technology the shrinkage cannot be prohibited by formative elements [4].

Regarding the process simulation of the FDM process, several approaches have been made in the past. In some publications the focus is on the melting process taking place in the nozzle and consider the melting of the polymer, the pressure gradient and the flow of the melt in the nozzle [5, 6, 7]. Again, other publications cover the deposition process with the cooling behavior and the reheating process caused by the layer-layer interaction. Also, some publications consider the change in volume during the cooling of the deposited strands [8, 9, 10, 11, 12, 13].

The FEM simulation of the FDM process has also been investigated in the past. To consider the successive generation of the component the Birth-Death-Method is used. Here, the elements of the mesh are activated according to the movement of the nozzle described by the g-code during the deposition [14]. There are approaches to reduce the computation time needed for the simulations by re-combining mesh elements after a certain time [15]. Further studies have already used the simulation of the FDM process to investigate the influence of selected process parameters on the residual stresses and deteriorations of the specimen geometry [16]. In the literature available at the moment the focus is mainly on the specimen warpage in z-direction and the detachment from the building platform to identify possible complications resulting in a failed build job prior to manufacturing [14].

Research Approach

For the validation and comparison of FEM simulations of the FDM process, several simulations are conducted while varying the mesh resolution and increment size. The material ABS-M30 distributed by Stratasys is used for the experimental investigations as well as for the material properties needed for the simulations. For manufacturing of the physical specimens, a Prusa MK3s with an upgraded BondTech extruder is used. During processing, the printer is situated in a thermally isolated chamber which results in a passively heated build chamber, as higher temperature levels lead to better mechanical properties [17]. The STL files are sliced using the PrusaSlicer 2.4.0. A python script is used to extract the necessary G-code commands from the original G-code file for the input used by the simulation software to describe the movement of the nozzle.

The investigations aim at simulating the manufacturing process of the specimens using the AM plug-in for the Abaqus 2019 software and deriving measurements of the resulting mesh files. To validate and compare the simulation results, specimens are manufactured using the G-code the simulation is based on. The specimens are then measured using a CCM at the identical points where the measurements are taken from the deformed mesh files. A comparison between the single simulation configurations is drawn. Additionally, the computation time is analyzed depending on the mesh resolution and the increment size.

Experimental Investigations

A standard simulation is set up for the experimental investigations. This consist of a first thermal step and a second mechanical step which uses the output database from the thermal step as input for the temperature field. The specimen for the simulation is a cube with an edge length of 15 mm. The boundary conditions for the thermal step (step 1) are defined as the building platform temperature at 100 °C for the bottom surface of the specimen. The measured build chamber temperature of 38 °C (passively heated / see Research Approach) is applied to the remaining five surfaces of the cube. The activation temperature for the single elements is set to the nominal nozzle temperature of 255 °C. For the mechanical step (step 2) the bottom surface of the specimen which is connected to the building platform is defined as clamped. The material is defined using the values shown in Table 1.

Table 1: Material properties defined for the simulation of the FDM process.

Material Property	Value	Unit
Density	1040	kg / m^3
Young‘s Modulus	2150E06	Pa
Poisson‘s Ratio	0.4	-
Yield Stress	47E06	Pa
Specific Heat Capacity	1040	J / (kg * K)
Coefficient of thermal expansion	5E-06	1 / K
Heat conductivity	0.17	W / (m * K)

To determine the influence of the mesh resolution and increment size, different configurations based on the standard simulation are considered. The standard configuration has a mesh resolution of 0.45 mm in the x-y-direction (strand width) and 0.2 mm in the z-direction (layer height). Adjustment of the mesh resolution is done using multiples of the strand width and layer height. The increment size is varied between 1, 20, 50 and 100. In Table 2 the considered configurations are shown.

Table 2: Configurations of the standard simulation.

Name	Simulation configurations		
	Mesh		Increment size
	z - layer height	x-y - strand width	
mech-01	x1	x1	50
mech-02	x1	x0.5	50
mech-03	x1	x0.2	50

mech-04	x2	x1	50
mech-05	x3	x1	50
mech-06	x5	x1	50
mech-07	x1	x1	1
mech-08	x1	x1	20
mech-09 (01)	x1	x1	50
mech-10	x1	x1	100

To validate the simulations, five cubes are built using the G-code which is also used in the simulation. After manufacturing, the specimens are measured using a CMM. On each of the upright surfaces of the cubes 25 individual points are measured. The final measurements are then calculated by determining the distance between the opposing points on each cube resulting in 25 measurements for each cube and measuring direction (x- & y-direction).

The measurement of the simulated specimen geometry using the deformed mesh is conducted by extending rods with a diameter of 0.5 mm in between the upright surfaces using SolidWorks CAD software. In a following step, the surface area of each rod is measured and the rod length is calculated. Analogue to the physical measurements, 25 rods are positioned and measured for each measuring direction. For the comparison, only the center line at a z-height of 7.5 mm is considered.

Results and Discussion

Figure 2 and Figure 3 show the measurement results of the geometric deviation in the x- and y- direction for the different configurations as well as for the real measurements of the physical specimens. Mech-03 could not be processed due to a lack of RAM.

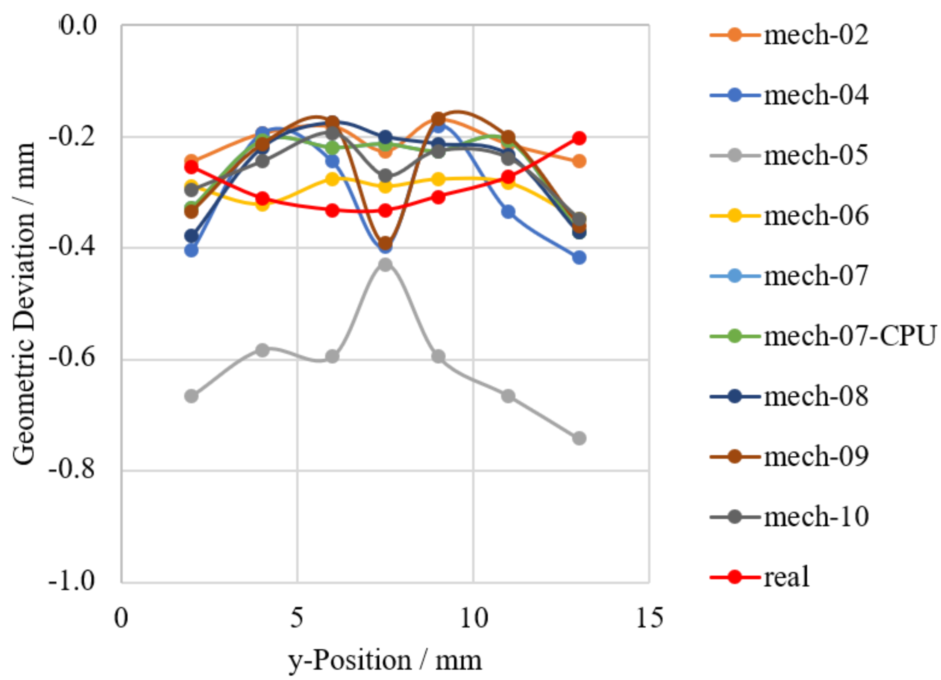

Figure 2: Measurements of the geometric deviation in x-direction.

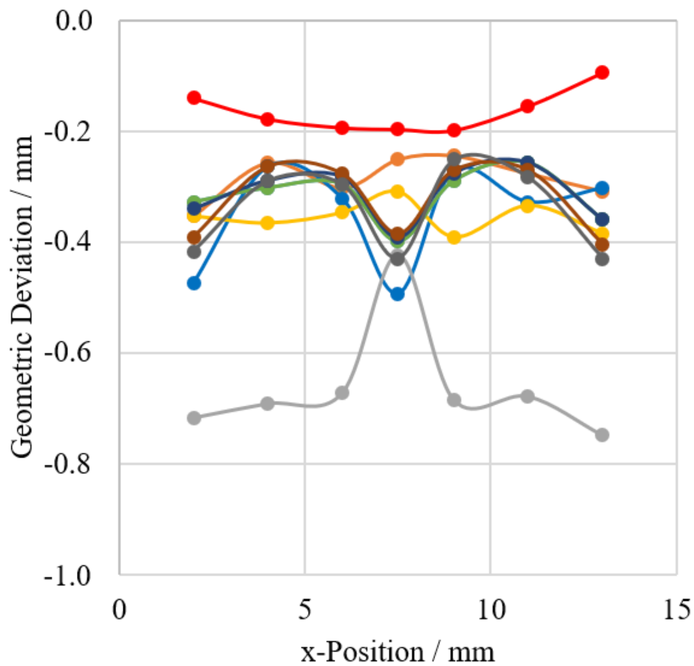

Figure 3: *Measurements of the geometric deviation in y-direction.*

According to the results, the increment size does not have a significant influence on the simulation outcome. The mesh resolution on the other hand has a significant impact on the results obtained from the simulation. As an increase in increment size basically causes more elements to be activated in a single time step, a lower mesh resolution has a similar effect and vice versa. Therefore, the differences regarding the results has to be caused by the cooling behavior and the associated material behavior which is apparently dependent on the mesh resolution.

Especially for the x-direction (see Figure 2), the values, except for mech-05, are in the same range. But different qualitative progressions are shown compared to the real measurements of the physical specimens. In Figure 3 (y-direction) the geometric deviations measured for the simulated specimens are higher than the real measurements. Analogue to the x-direction the qualitative progressions are different to the real measurement results of the physical specimens. A possible reason for the difference in the range of the values might be positioning errors of the printer. Such errors cannot be foreseen in the simulation and therefore cannot be represented in the results.

For the analysis of the computation time, the effect of the mesh resolution (see Figure 4) and the increment size (see Figure 5) is considered. Figure 4 shows a linear increase of the computation time with increasing number of elements. Regarding the increment size, the computation time remains at a close to constant level between an increment size of 20 to 100. At an increment size of 1, a significant increase of the computation time was recorded. As the increment size supposedly does not have a significant effect on the simulation results, higher values can be chosen to reduce the computation time. The mech-07 configuration was also simulated using 40 CPU threads instead of a single thread. Here, the computation time was higher compared to the single thread performance. A parallelization therefore does not result in a lower computation time.

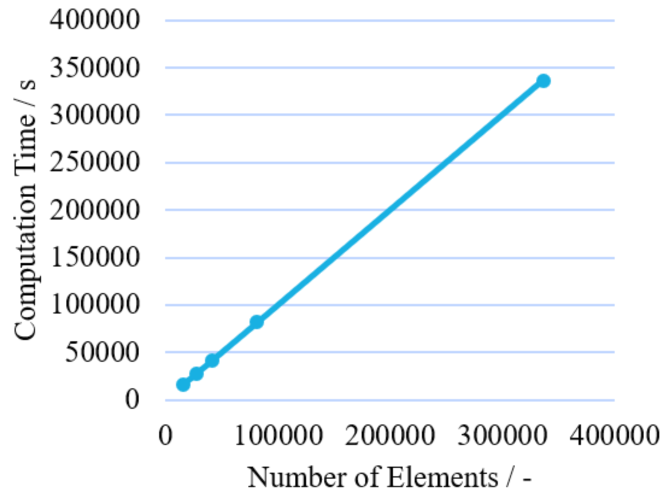

Figure 4: *Influence of the mesh resolution and the resulting number of elements on the computation time.*

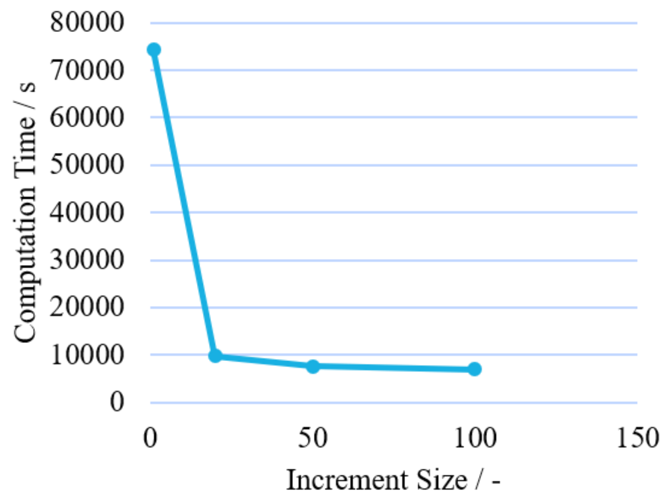

Figure 5 *Influence of the increment size on the computation time.*

Conclusion and Outlook

In this paper a simulation of the FDM-process was conducted using a commercially available simulation software (Abaqus 2019). The mesh resolution and the increment size were varied and the resulting distortions were compared to those of physical specimens. Also, the computation time was analyzed depending on the number of elements and increment size. The results show, that the simulation results are in a similar range compared to the physical specimens but do not show an identical shape. Therefore, this approach of simulating the FDM process does not pose a viable option regarding a precise prediction of geometric deviations. The increment size does not show a significant influence and therefore can be increased to reduce the computation time. Based on these investigations, following simulations shall be conducted using temperature dependent data to increase the simulation accuracy. Possible further influencing factors on the simulation results are to be identified, quantified and considered. It shall also be investigated whether there is an optimum mesh resolution and if so, whether it is geometry dependent. On the side of the validation it shall be assured that no positioning errors during manufacturing influence the measurements of the physical specimens.

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