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NUMERICAL SIMULATION OF FDM TO PREDICT THERMOMECHANICAL PERFORMANCE OF IMPELLER

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Abstract

Fused deposition modeling (FDM) is material extrusion based additive manufacturing (AM) technology used to build various prototypes and functional parts. FDM is widely used AM process that works with thermoplastic material and is inexpensive relative to other AM technologies. Several research works had experimentally investigated the effect of FDM process parameters on the performance of the parts however, due to wider scope of using different materials and design flexibilities, it is imperative to use numerical simulation approach to speed up the research work in order to reduce the delay and research costs. In this study, numerical simulation tool Digimat-AM was used to predict the effect of infill density and layer thickness upon process defects such as deflection and residual stress. Impeller made up of ABS material was used as a specimen for numerical simulation. Simulation results were analysed using ANOVA which indicated that layer thickness had significant impact on deflection and residual stress, while the infill density did not influence the output parameters.

Keywords: fused deposition modeling, impeller, process simulation, deflection, residual stress

1. INTRODUCTION

In the era of Industry 4.0, additive manufacturing (AM) is emerging manufacturing process also referred to as layered manufacturing utilized for manufacturing of three-dimensional (3D) parts [1]. Fused deposition modeling (FDM) is material extrusion based AM process, also known as fused filament fabrication (FFF) method. The AM technologies have found widespread applications across various sectors, including automotive, energy and healthcare [2-8]. The recent advancements in metallurgical science and manufacturing techniques have accelerated the utilization of AM processes, such as powder bed fusion, material jetting, photopolymerisation, material extrusion, sheet lamination, directed energy deposition and binder jetting for the production of functional parts [9]. The widespread applications of FDM process among AM practioners are attributed to its simplicity, affordability, flexibility and the ability to control the process parameters effectively [10-14].

As an initial step in the manufacturing of a part using the FDM process, slicing software is employed to convert the computer aided design (CAD) model into a tessellated file format (STL) which provides the requisite printing instructions [15-17]. Raw material in form of polymer filaments is unwound from the material spool and fed into the heated nozzle assembly for extrusion. The filaments are melted and transformed into a viscous extrudate, which is deposited onto the printer's build plate through the fine-diameter nozzle opening. The movement of the nozzle is synchronized with G-codes, which are predefined motion control instructions generated by slicing software. Each deposited layer is followed by subsequent layers added over the previous one, leading to the layer-by-layer fabrication of the entire part [18-20].

Among the challenges associated with the FDM process, residual stress and warpage significantly affect the mechanical behavior of FDM manufactured parts. Additionally, selecting an appropriate material for particular applications presents another significant challenge [21-24]. Despite its high quality and superior functionality, the effectiveness of FDM process is influenced by several parameters, including nozzle temperature, raster angle, print speed, layer thickness, shell thickness, infill density, build orientation, and infill pattern. These control parameters have the potential to alter the microstructure of the parts, ultimately affecting their structural performance [25]. In addition, there are new polymers and composite materials which have high potential for extensive utilization in FDM process [26]. Predicting the influence of all variables on mechanical behavior of FDM manufactured components is challenging by relying solely on the experimental approach, as it can be cumbersome and costly. Additionally, it is nearly impossible to utilize experimental methods for investigating the effects of materials with varying blends and compositions [27]. In this context, for assessing the influence of process variables on the microstructure, a simulation approach was employed. The results obtained were subsequently extrapolated to analyse their impact at macroscopic level [28]. Hussein Azyod et al. [29] employed a simulation approach and selected three process parameters including infill pattern, print orientation and raster angle to investigate its effect on residual stress of ABS components produced using the FDM technique. The simulation results revealed that the print orientation has significant impact on residual stresses. Rashid et al. [30] simulated a thermo-mechanical behavior of composite samples. Process parameters selected were infill density and infill pattern and its impact was investigated on output parameters such as residual stresses, warpage, and mechanical response. The simulation results were validated with experimental results.

Sharafi et al. [31] employed a multiscale modeling approach to predict the mechanical behavior of parts manufactured using the FDM process. The methodology involved use of Digimat software for micro level study and ANSYS for macro level simulations. This approach was utilised to evaluate the performance of tensile testing samples fabricated from Polyaryletherketone (PAEK) and Acrylonitrile Butadiene Styrene (ABS). The study indicated the capability of integrating multiscale simulation techniques to understand mechanical properties of FDM manufactured parts. Mohamed Daly et al. [32] simulate the FDM process using a numerical model that combined Abaqus and Digimat software. The analysis focused on investigating the impact of printing speed on residual stress, warpage, deflection and mechanical response of the FDM built parts. The study was conducted varying the printing speed at four different level of printing speed, providing insights into impact of process parameters and part performance. Ashu Garg and Anirban Bhattacharya [33] conducted finite element analysis (FEA) to investigate the failure mechanism of FDM manufactured parts. Their study integrated FEA with fractographic analysis to complement the experimental results. Three levels of layer thickness and raster angle were considered for generating the finite element model. The researchers concluded that a greater number of layers aligned in the loading direction leads to higher stress generation, specifically when the layer thickness is small. Conversely, parts with higher layer thickness results exhibited superior tensile strength.

Martinez et al [34] attempted the comparative simulation study to predict the response of composite parts subjected to varying loading conditions. Saleh Khanjar et al. [35] performed thermomechanical simulation to compare the part properties such as warpage and printing time of two different parts. Taguchi method of design of experiment (DOE) was employed to plan the experimental and simulated runs. Results were tested statistically be using analysis of variance (ANOVA). Wendt et al [36] used finite element methods to predict the tensile loading response of specimen by simulating the different extrusion paths. It was claimed that tensile test specimen with rectangular path is better alternative for the tensile tests. Xingchen Liu and Vadim Shapiro [37] explored the homogenization of material properties in FDM parts. A new approach was developed to predict the properties based on implicit representation of mesoscale geometry. Berkay Ergene and Cagin Bolat [38] simulated the FDM process for investigating the impact of fibre ratio, infill pattern and infill density on residual stress and warpage of glass fibre reinforced ABS specimens.

This study employs Digimat simulation software to develop a numerical model for predicting deflection and residual stress in FDM manufactured parts. The material consumption, printing time and warpage were also recorded for each sample. A simulation study was conducted by selecting three levels for each process parameters - infill density and layer thickness. The results obtained from the numerical study were analyzed using analysis of variance to reveal the important factors and quantify its contributions on impacting the output variables.

2. SIMULATION STUDY FOR IMPELLER

2.1 Design of the experiment, impeller model, and material: This work serves as the initial phase of a broader research study aimed at exploring the possibility of using the FDM technique for fabricating the turbomachinery components. A numerical approach was selected over the experimental approach due to its advantages like reduced time consumption and minimized material wastages. For this investigation, an impeller illustrated in figure 1 was preselected as specimen. The investigation primarily focused on investigating the capability of the FDM techniques to manufacture complex and functional components, with less emphasis on the design of the parts.

Acrylonitrile Butadiene Styrene (ABS), a thermoplastic material was chosen as the material for the current study owing to its superior mechanical properties. Process parameters selected for this investigation includes infill density and layer thickness as detailed in Table 1. A full factorial design was employed for conducting the simulation experiments, incorporating three levels of both process parameters to comprehensively analyse their impact on the output parameters.

Figure 1. Specimen for numerical simulation

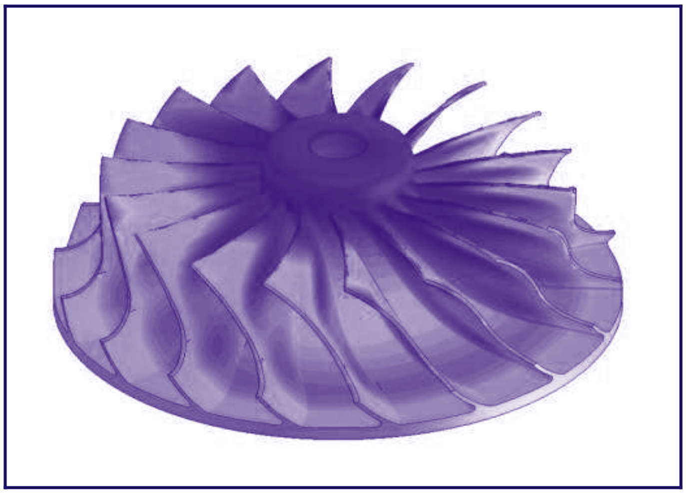


Table 1. Process variables used in simulation

Variables, (Unit)	Levels		
	1	2	3
Layer thickness SH (mm)	0.127	0.254	0.33
Infill density D (%)	20	60	100

2.2 Methodology for numerical simulation: Slicer software is employed to convert the digital 3D model into G-codes. It acts as connecting link between CAD model and 3D printed model. The G-codes are generated to determine the number of layers required and toolpath that nozzle needs to follow for building the part. In this current work, nine G-code files were developed, one for each impeller specimen. Furthermore, for simulating the FDM process Digimat-AM (Additive Manufacturing) software was employed.

Table 2. Results obtained

Specimen	SH	D	MC (gm)	PT (Minute)
1	0.127	20	13	136
2	0.127	60	17	158
3	0.127	100	21	224
4	0.254	20	14	72
5	0.254	60	17	83
6	0.254	100	21	115
7	0.33	20	13	56
8	0.33	60	17	65
9	0.33	100	21	90

In the definition stage, a generic FFF printer of chamber dimension 400 x 400 x 400 mm, with fixed platform configuration and warpage analysis with default inherent strain setting was selected. Specimen geometry is uploaded with stl file format. In manufacturing stage, sequence set for the manufacturing was in order of printing, cooling, holding and support removal.

Table 3. Simulation parameters

Specimen	
Printer Type	Generic FFF printer
Size of chamber (mm)	400 x 400 x 400
Printing platforms	Fixed platform
Type of Analysis	Warpage-inherent strain
Component	
Material name	ABS
Material type	Unfilled
Material structure	Amorphous
Manufacturing	
Max refined element (mm)	30.12
Chamber temperature type	Constant
Chamber temperature (ºC)	100
Extrusion temperature (ºC)	250
Bead width (mm)	0.5
Printing speed (mm/s)	60
Convection coefficient ($mW/mm^2.ºC$)	0.015
Room temperature (ºC)	23ºC
Solver	
Discretization	Layer-by-layer
Voxel size (mm)	0.635
Job submission	
Temperature	End of all layer
Displacement	End of all layer
Residual stresses	Minimum

Toolpath information was inserted in form of g-code file. In simulation stage, option of two discretization approaches layer-by-layer discretization and filament discretization are available. Layer-by-layer discretization approach was selected as it focuses on one layer at a time and simplifies the simulation process. In results stage, final result is obtained for warpage, residual stress and deflections. Detailed settings used in FDM process simulation is reported in Table 3.

3. RESULTS AND DISCUSSION:

Table 4. Details of simulation results

Specimen	σ (Mpa)		d (mm)		w
	Max	Min	Max	Min	
1	86.49	3.68	0.6794	0.0030	0.4529
2	87.54	2.583	0.7886	0.0013	0.5257
3	87.54	2.583	0.7886	0.0013	0.5257
4	45.45	3.324	0.5341	0.0116	0.3561
5	46.85	3.051	0.528	0.0116	0.3520
6	46.85	3.051	0.528	0.0116	0.3520
7	36.57	3.895	0.5215	0.0167	0.3477
8	36.97	3.729	0.518	0.0170	0.3454
9	36.97	3.729	0.518	0.0170	0.3454

The interplay of heating and cooling during the FDM process leads to inherent geometric variations including deflections, and the development of residual stresses between deposited layers. These variations are critical as they directly affect the structural integrity and dimensional accuracy of the part. The numerical simulation results as detailed in Table 4, reports detailed analysis of deflection (d), warpage (w) and residual stresses (σ) observed for varying infill density and layer thickness.

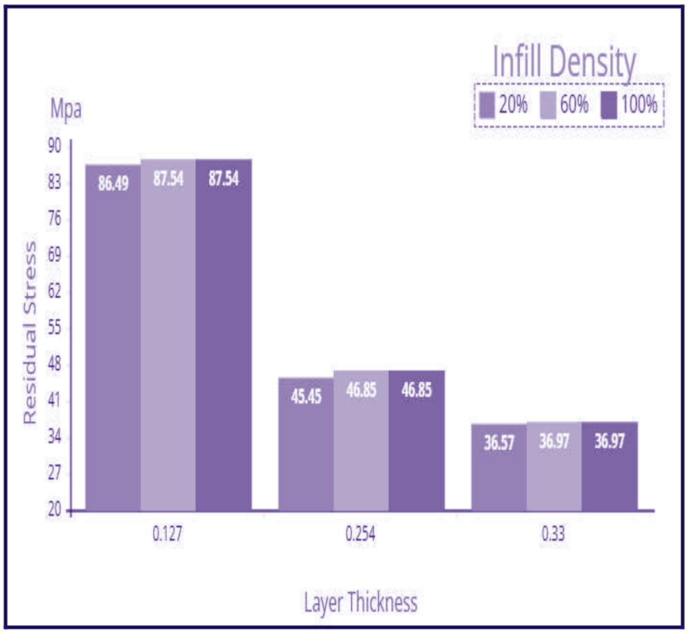
3.1 Residual stress: In this study, Digimat software provided stress distribution results in - X, Y and Z directions and across transverse planes. The Von Mises stress criterion was adopted to represent residual stresses as it offers comprehensive measure of stress distribution. Table 4 summarizes the maximum and minimum residual stress obtained from the simulations. Additionally, ANOVA was conducted to analyze the effect of process variables on maximum residual stresses, with detailed results depicted in Table 5.

Table 5. Analysis of variance for residual stress

Source	DF	SS	MS	P
SH	2	4291.7	2145.8	0.000
D	2	1.81	0.90	0.026
Error	4	0.34	0.09	
Total	8	4293.9		
Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.292973	99.99	99.98	99.96	

The layer thickness was observed to significantly impacting the maximum residual stresses in the FDM process. The maximum residual stress reached 87.54 Mpa when layer thickness is 0.127 mm, whereas significantly lower residual stress of 36.57 Mpa was recorded when layer thickness is 0.33 mm. The relationship between layer thickness and residual stress is attributed to the number of layers deposited in the fabrication of the part. A lower layer thickness involves a greater number of extrudate layers to manufacture the part, leading to increased number of heating and cooling cycles. These increased thermal cycles amplify the residual stresses generated in the part. Conversely, higher layer thickness reduces the number of layers required to build the part and also reduces the associated thermal cycles, resulting in lower residual stress values.

Figure 2. Residual stresses



3.2 Deflection: In this study, overall deflections were chosen for the analysis. The simulation software provided deflection results in directions - X, Y, Z and overall deflections. Table 4 summarizes the maximum and minimum deflection obtained from the simulations. Additionally, ANOVA was conducted to analyze the effect of process variables on maximum deflection, with detailed results depicted in Table 6.

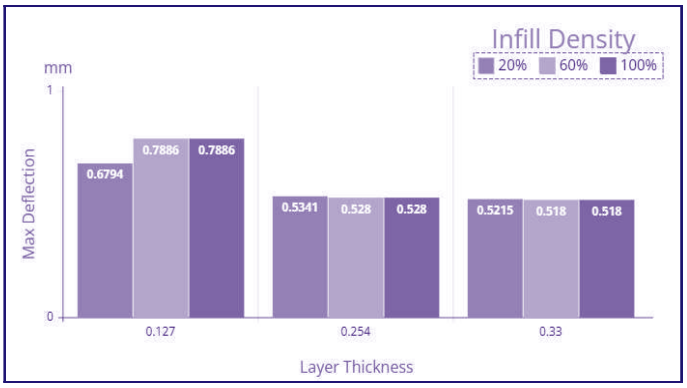
The layer thickness was observed to significantly impacting the deflections in the FDM manufactured parts. The maximum deflection of 0.7886 mm occurred when layer thickness is 0.127 mm, whereas a significantly lower deflection of 0.518 mm was recorded when layer thickness is 0.33 mm.

The relationship between deflection and layer thickness is also attributed to the layers deposited during the fabrication of the part. A lower layer thickness increases the number of deposited layers, leading to frequent heating and cooling cycles, causing greater deflections. Alternatively, a larger layer thickness involves lesser number of layers to build the part, minimizing the number of thermal cycles, and thereby associated deflections in the part.

Table 6. Analysis of variation for deflection

Source	DF	SS	MS	P
SH	2	0.103781	0.05189	0.003
D	2	0.002204	0.00110	0. 524
Error	4	0.005778	0.00144	
Total	8	0.111763		
Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.038007	94.83	89.66	73.83	

Figure 3. Maximum deflections



CONCLUSION

Numerical simulation of FDM process was conducted utilizing Digimat-AM simulation software to investigate the effects of process variables on deflection and residual stress as process induced defects. A simulation study involved three levels of infill density and layer thickness. Additionally, parameters such as material consumption, warpage and printing time were recorded. Statistical analysis using ANOVA indicated that layer thickness had significant impact on deflection and residual stress than infill density. The increase in deflection and residual stress associated with lower layer thickness was attributed to higher number of layers required to build the part. A key limitation of this study is its reliance solely on numerical simulations, without incorporating physical testing. However, the numerical approach employed presents significant potential as a predictive technique to investigate the performance FDM manufactured parts using various materials. Future research directions include the exploration of different FDM-compatible materials to manufacture complex and functional parts, such as turbomachinery components, to validate and extend these findings.

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