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NUMERICAL STUDY TO INVESTIGATE THE CORRELATION BETWEEN PRINTING PARAMETERS AND THE WARPING OF 3D MODELS USING FFF

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ABSTRACT
Prototypes are built using rapid prototyping (RP) technology by the sequential deposition of material layers. Thermal stresses will arise when temperature gradients are present during the deposition process. The prototype deformation in Fused Filament Fabrication (FFF) procedures was investigated in this work. A numerical simulation of the prototype warp deformation was created, and each of the affecting parameters, including printing speed, layer thickness, and printing temperature, was quantified. Based on the analysis results, the correlation between the printing parameters and the warping deformation was identified.

1. INTRODUCTION

Engineers can use the capabilities of Additive Manufacturing (AM) to create a one-of-a-kind design. On the one side, the machining shape and movement circumstances do not impose any limitations. On the other side, each AM technology has its own set of constraints that must be considered [1], [2]. 3D printing components are currently widely employed in a range of industries, including food [3], aerospace [4], and automobile manufacturing [5]. The different techniques associated with the AM are used in the standard: Additive Manufacturing - General Principles – Terminology, ISO/ASTM 52900:2021. One of the best-known is Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM). FFF is the most commonly utilized technique because it is significantly easier and less costly to employ than other methods, and it may use a wide range of raw materials such as polylactic acid (PLA), acrylonitrile–butadiene–styrene (ABS), polyamide (PA) 6 and 12, and polyetherimide (PEI) [6]. The raw material, in filament state, is forced through the print head's heated extruder while it moves relative to the build plate, and the molten material is deposited on the plate. This deposition process occurs solely in 2D; after completing a layer, the print head begins to produce a new layer on top of the previous one. This process has the significant advantage of being able to make hollowed components, which can result in significant weight reduction and cost - savings. However, it must be kept in mind that the printing process might significantly impact the part's qualities. Numerous studies have investigated the qualities of the fabricated parts. Ficzere P, Borbás L [7] studied the effect of the printing direction on the damping properties of PLA material. Shanmugam et al. [8] analyzed the affecting parameters for FDM technology, with a specific focus on fatigue behavior. J. R. C. Dizon, A. H. Espera, Q. Chen, and R. C. Advincula [9] examined the impact of raster angle, layer thickness, and infill pattern on the tensile strength. R. A. Mensah et al. [10] compared the mechanical strength of different parts with different infill densities. Other studies investigated the environmental and economic of AM [11], [12]. P. Ficzere, L. Borbas, and G. Szebenyi [13] investigated the relationship between stress capacity and printing orientation. M. S. Alsoufi and A. El-Sayed [14] investigated the effect of printing speed and printing temperature on the warping deformation.

2. NUMERICAL SIMULATION

2.1. Material and model description

For numerical simulation, bridge geometry with dimensions, as shown in figure 1, was implemented because the warping can easily influence the pillars. The used material is ABS with an ultimate strength of 30.46 MPa [15], Poisson's ratio of 0.36, and thermal conductivity of 0.18 mW/(mm.°C). Poisson's ratio and thermal conductivity data were obtained from Digimat-MX, one of Digimat's platforms used for the material database.

2.2. Printing parameters

This work studied the correlation between printing parameters and the warpage.

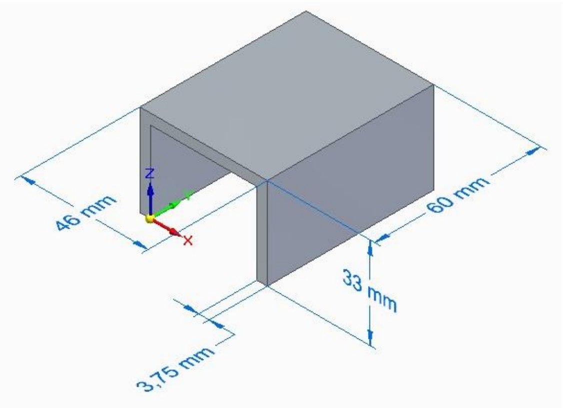

Figure 1. Bridge geometry dimensions

Three printing factors with four levels of each factor, as illustrated in table 1. The default printing parameters were 60 mm/s for the printing speed, 0.19 mm for the layer thickness, and 250 °C for the printing temperature. The rest of the printing parameters were 70 °C for plate temperature, 100% for infill density, and Zig Zag infill pattern.

Table 1. factors and levels of simulation

Factor	levels			
	1	2	3	4
Printing speed (mm/s)	20	40	60	100
Layer thickness (mm)	0.19	0.29	0.39	0.49
Printing (Extrusion) temperature (°C)	230	240	250	260

2.3. finite element analysis (FEA) of FFF

The Computer-Aided Engineering (CAE) presented in this investigation was executed in Digimat-AM. It is a platform that offers an FEA analysis of AM processes. Digimat-AM is software used to collect data of samples built by one of the manufacturing processes and their mechanical characteristics. Digimat-AM simulates AM of composites and polymers, and predicts warpage and residual stresses of a printed part. That program provides a workflow that includes the stages depicted in figure 2. In the definition stage, the FFF process is selected along with the build plate dimension of a generic printer. The selected printer is a moving build plate with 200 x 200 x 180 mm dimensions. Digimat-AM uses a thermos-mechanical or inherent strain approach, selecting the former one for analysis. Then, the geometry is defined using a stereolithography (STL) file. The final step is to select the material, which is ABS, unfilled, and amorphous. In the manufacturing stage, the toolpath is provided in a G-Code file which is exported from a slicing program such as Slic3r, Cura, or PrusaSlicer. The printing speed and the extrusion temperature are set based on the levels in table 1. The rest of the manufacturing parameters were 30 °C for chamber temperature, 23 °C for room temperature, 23 °C for final temperature, and the convection coefficient is equal to 0.015 mW/mm^2 °C. The printing steps are ordered as printing, then cooling, and lastly, support removal. In the simulation stage, the mesh is created by defining the voxel size. Finally, the results given by the simulation consist of residual stress and warpage.

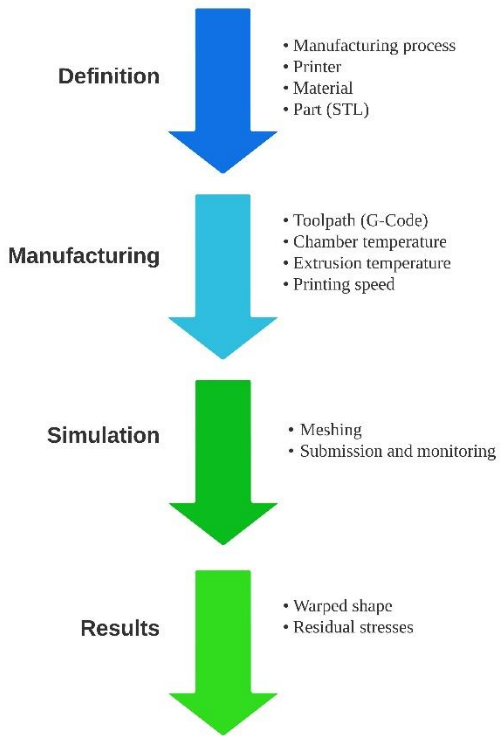

Figure 2. Digimat-AM workflow

3. RESULTS AND DISCUSSION

A total of twelve runs were executed, and the results were obtained. For the printing speed factor, the results showed that by increasing the printing speed, the warping slightly decreases, and figure 3 illustrates the trend. At 20 mm/s speed, the warping was 3.9 mm, whereas, at a speed of 100 mm/s, the warping was 3.2 mm. The reason behind this trend is that by increasing the printing speed, the temperature difference between the new and previous layers will be less. For the layer thickness effect, the results, as demonstrated in figure 4, showed that the layer thickness significantly influences the warping deformation. By increasing the layer thickness, the warping deformation decreases. At 0.19 mm layer thickness, the warping was 3.59 mm, while at 0.49 mm layer thickness, the warping deformation was 1.78 mm. This decrease in the warping happened because by increasing the layer thickness, the number of layers will decrease, and then the thermal loss will decrease.

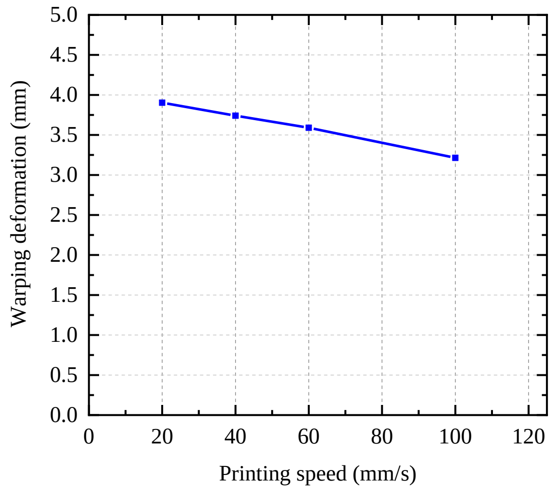

Figure 3.The influence of printing speed on the warping deformation

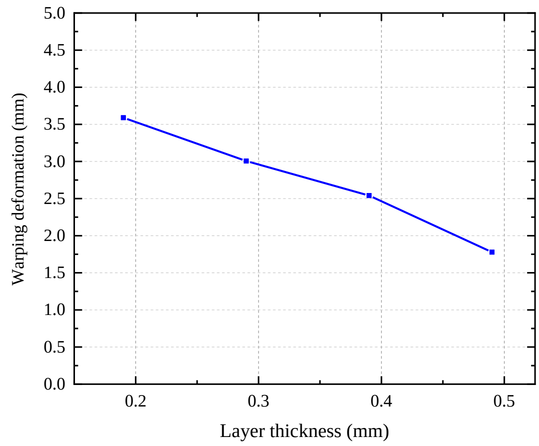

Figure 4. The effect of layer thickness on the warping deformation

The printing temperature had the opposite influence on the warping deformation. As depicted in figure 5, the printing temperature was proportional to the warping deformation. The warping deformation lightly increases by increasing the printing temperature. The warping deformation was 3.3 mm at 230 °C, then increased to 3.73 mm at 260 °C. Figure 6 demonstrates the warping deformation results provided by Digimat-AM with the default printing parameters.

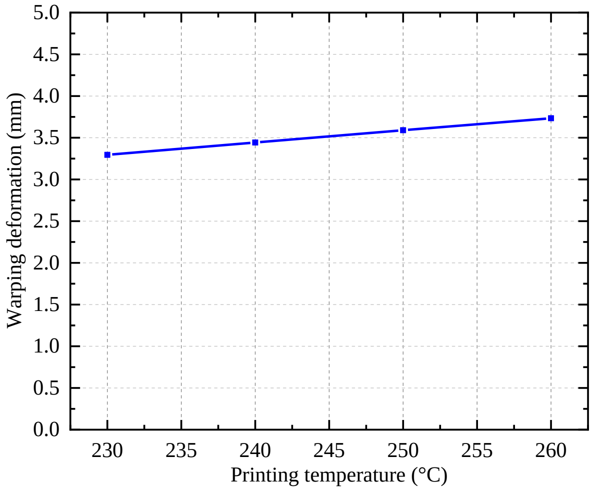

Figure 5. The correlation between the printing temperature and the warping deformation

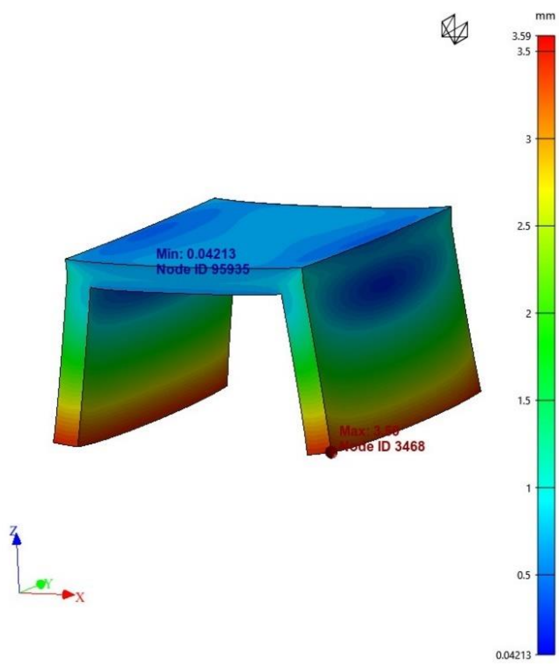

Figure 6. Results provided by Digimat-AM with the default printing parameters

4. CONCLUSION

Warp deformation is a crucial success factor for evaluating the quality of a Fused Filament Fabrication (FFF) prototype. Some factors influence the deformation of the FFF prototype. These considerations include material properties, printing parameter configuration, the geometrical structure of the CAD model, and deposition path design. Three printing parameters with four levels of each parameter, including the printing speed, the layer thickness, and the printing temperature, were numerically analyzed. Based on the results, it can be found that the warping deformation is negatively correlated with both of the printing speed and the layer thickness whereas it is positively correlated with the printing temperature. The numerical solution can provide a scientific tool for minimizing and controlling the deformation.

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