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PREDICTION OF THE INFLUENCE OF PRINTING PARAMETERS ON THE RESIDUAL STRESS USING NUMERICAL SIMULATION

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Abstract: Fused Deposition Modeling is an additive manufacturing technology that is used to create a wide range of parts and applications. Along with its benefits, there are some challenges regarding the printed parts' mechanical properties, which are associated with printing parameters like layer thickness, printing speed, infill density, printing temperature, bed temperature, infill pattern, chamber temperature, and printing orientation. One of the most crucial challenges in additive manufacturing technology is the residual stress, which significantly affects the parts like fatigue life, cracks propagation, distortions, dimensional accuracy, and corrosion resistance. Residual stress is hard to detect in the components and sometimes is costly to investigate. Printing specimens with different parameters costs money and is time-consuming. In this work, numerical simulation using Digimat-AM software was employed to predict and minimize the residual stress in printed Acrylonitrile Butadiene Styrene material using Fused Deposition Modeling technology. The printing was done by choosing six different printing parameters with three values for each parameter. The results showed a significant positive correlation between residual stress and printing temperature and infill percentage and a negative correlation with layer thickness and printing speed. At the same time, we found no effect of the bed temperature on the residual stress. Finally, the minimum residual stress was obtained with a concentric infill pattern.
Keywords: Fused Deposition Modeling, 3D printing, Residual stress, Digimat-AM, ABS.

1. INTRODUCTION

Additive manufacturing (AM), often known as 3D printing, is a rapidly evolving complex manufacturing technique that enables the production of physical geometry and complicated structures with high precision and inexpensive cost. AM fabricates a three-dimensional design model using layer upon layer printing technology, which overcomes the need for conventional techniques such as cutting and casting (Gebhardt, 2011). The promising benefits of AM enable them to be used in the production of complicated structures for various applications. AM technology is being used in a variety of technical applications, including the aerospace (Jyothishand Kumar and Krishnadas Nair, 2017), mechanical (Dilberoglu et al., 2017), food sectors (Lipton et al., 2015), and biomedical (Harun et al., 2018), as well as the academic research field. Based on the state of the raw material, AM is classified into four main categories: filament, powder, liquid, and solid layer (Alsardia et al., 2021). In the filament category, Fused Deposition Modeling (FDM) is the extrusion-based technique employed to manufacture structures and geometries made of polymer (Gibson et al., 2015). FDM machines contain a heater source, a nozzle (extruder), and a platform. The mechanism is different from manufacturer to manufacturer, but the principle is the same: either movable heater and extruder and fixed platform or fixed heater and extruder and movable platform. The filament feedstock is partly melted after being inserted into the heater block using a stepper motor. The filament is extruded as a semi-cylindrical material via the nozzle and placed on the platform. This procedure is illustrated in Fig. 1 (Cuan-Urquizo et al., 2019). The principle of AM technology starts with generating a 3D model in any Computer-Aided Design (CAD) and then exporting it as a stereolithography file (STL). Then, this file is sliced into a 2D cross-section using slicer software and exported as a G-Code file. The G-Code file contains a set of commands that the printer used for printing.

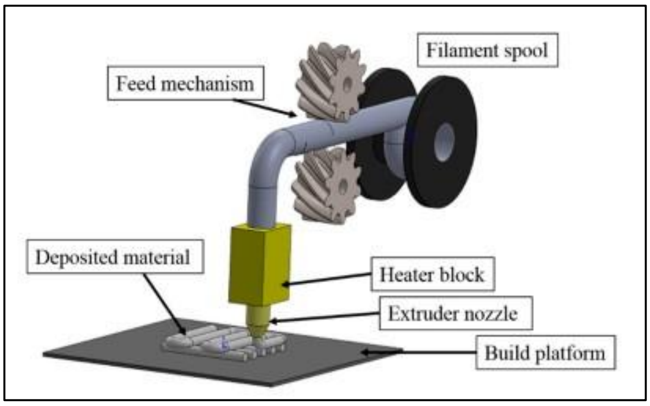

Fig. 1. Schematic of Fused Deposition Modeling technology (Cuan-Urquizo et al., 2019)

The parameters used in the FDM process can be divided into two categories: structural parameters and manufacturing parameters. The former group includes the raster angle, infill density, and part and print orientation. The latter group includes printing speed, platform temperature, printing temperature, layer thickness, and chamber temperature. The value of each parameter can be modified, and the impact on the mechanical characteristics that arise must be investigated. As shown in Fig. 2, the fishbone diagram summarises the parameters that potentially influence the mechanical parameters of FDM technology. In the FDM processing, the components undergo heating and cooling at a high-speed rate, generating a temperature differential and generating residual stress (Casavola et al., 2017; Safronov et al., 2017). This residual stress can cause substantial distortion or fatigue cracks of printed objects, affecting the printed parts' dimensional accuracy and mechanical properties

(Aliheidari et al., 2017). As a result, conducting the analysis and measuring residual stress is critical for FDM quality control (Hadny et al., 2022).

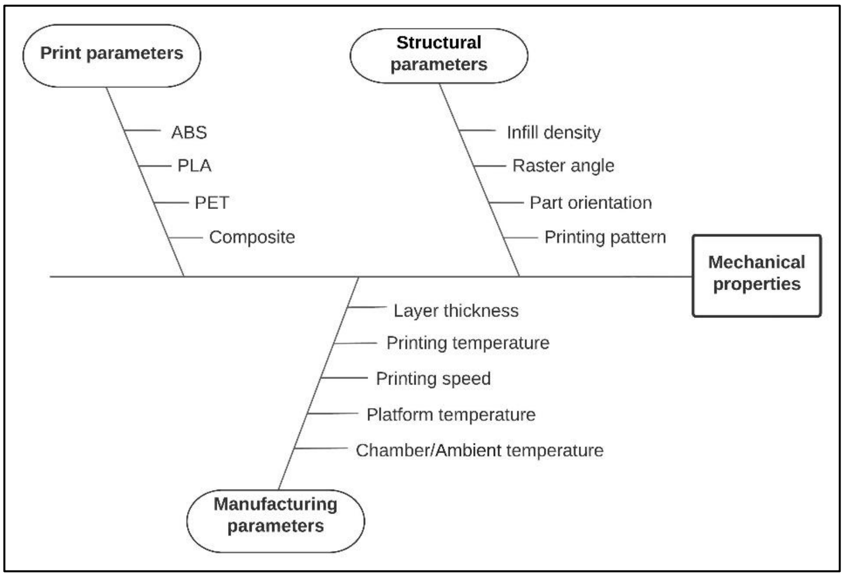

Fig. 2. Fishbone diagram showing the most important parameters that affect the mechanical properties of FDM

Residual stress measurement methods are now divided into two classes based on the test methodology (Withers and Bhadeshia, 2001). Destructive methods, such as hole drilling, contour method, and strain gauge. The destructive method's concept requires eliminating and measuring stress in the component in a specific way. By analyzing the strain or displacement of the surface, the residual stress may be calculated using the elastic mechanics concept. Destructive testing techniques are straightforward to perform, and test accuracy is usually relatively high, but surface damage is occasionally undesirable. The second test methodology is nondestructive testing methods like diffraction, ultrasonic, and Raman spectroscopy. These methods analyze the physical features of the specimen itself with tools integrated to prevent the samples from being damaged (Mousa, 2014). The residual stress of FDM 3D printed components has been researched by many researchers. (Casavola et al., 2017) used the hole-drilling approach to investigate residual stress in an FDM 3D printed plate made of Acrylonitrile Butadiene Styrene (ABS). To prevent local strain gage reinforcement, the deformation of the plate's surface was evaluated using electronic speckle pattern interferometry. (Safronov et al., 2017) examined the deformation and residual stress in rectangular in cross-section parts like beams by adapting the curvature of deformed beam, and the achievement of this method is that components can be evaluated non-destructively. (Kantaros and Karalekas, 2013) investigated residual stresses in ABS components made with FDM using the fibre Bragg grating technique. (Ficzere et al., 2017) studied the effect of printing orientation on residual stress in 3D printed PLA using Optical Photostress analysis.

2. NUMERICAL SIMULATION

2.1 Model description and material

A bridge geometry was investigated in the simulation with dimensions, as shown in Fig. 3. The purpose of choosing this model is that warping and residual stress can clearly affect the geometry. The material used in the simulation was ABS. the simulation was carried out using Digimat-AM software. Digimat-AM uses different types of polymers and composites, and it can provide a good prediction and estimation of warpage and residual stresses of printed parts.

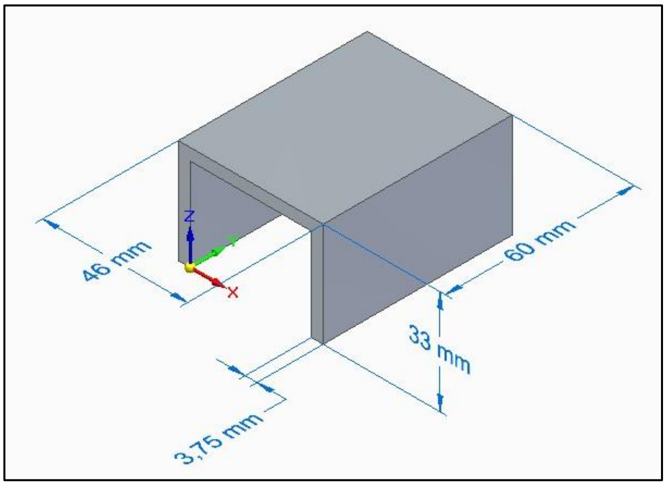

Fig. 3. Dimensions of the used model

2.2 Printing parameters

In this work, six different parameters with three levels of each parameter were investigated to predict the relationship between the residual stress and the parameter, and Table 1 illustrates that. The default set of printing parameters is shown in Table 2.

Table 1
Investigated printing parameters with different levels.

Printing parameter	**levels**			**Unit**
	1	**2**	**3**	
Printing speed	20	40	100	mm/s
Layer thickness	0.29	0.39	0.49	mm
Printing temperature	230	240	260	°C
Bed (Platform) temperature	30	50	90	°C
Infill density	10	40	60	%
Infill pattern	Triangle	Concentric	Grid	

Table 2
Default printing parameters.

Printing parameter	**Value**	**Unit**
Printing speed	60	mm/s
Layer thickness	0.19	mm
Printing temperature	250	°C
Bed (Platform) temperature	70	°C

Infill density	100	%
Infill pattern	Zigzag	

The total simulations are (6 parameters x 3 levels + 1 default) = 19 simulations. Fig. 4 illustrated the structural parameters.

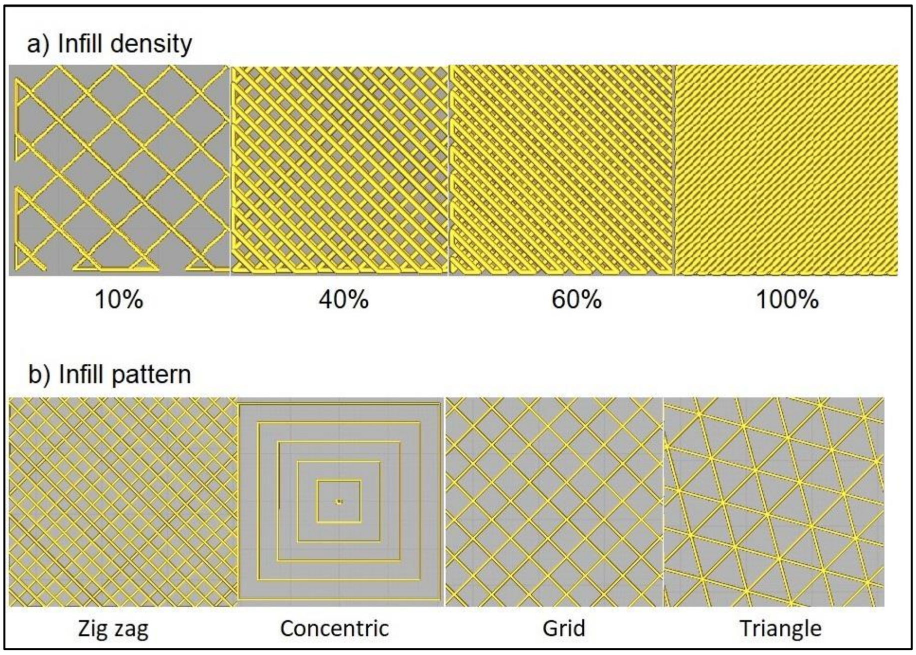

Fig. 4. Structural parameters of printing: a) Infill density, b)Infill pattern

3. RESULTS AND DISCUSSION

Using numerical simulation can give a pretty good insight into the effect of printing parameters on the residual stress. As mentioned before, the printing parameters can be divided into two categories. Results showed that the structural parameters influence the residual stress in the printed part, and Fig. 5 illustrates that. We found that the residual stress will increase by increasing the infill density. In comparison, the printing pattern's slight effect on the residual stress.

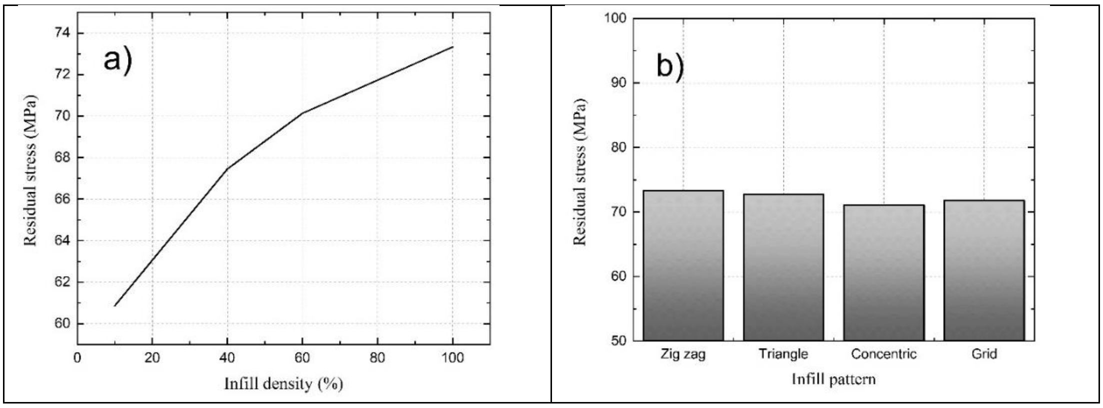

Fig. 5. The effect of structural parameters on the residual stress: a) infill density, b) infill pattern

On the other hand, as shown in Fig. 6, the results showed that the manufacturing parameters have a different relationship with the residual stress. The layer thickness and the printing speed have an inverse correlation with the residual stress. In other words, residual stress will decrease by increasing layer thickness and printing speed. While by increasing the printing temperature, the residual stress will increase too. Finally, the platform temperature does not affect the residual stress.

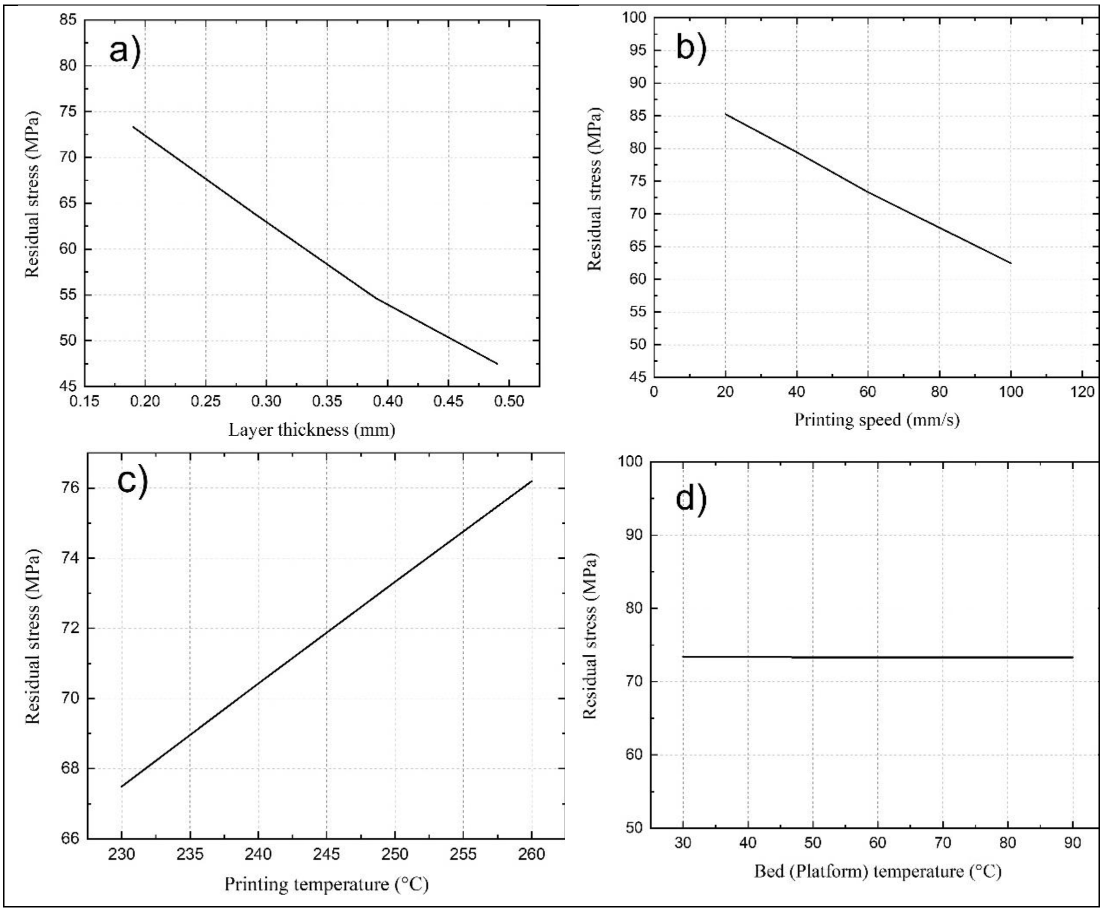

Fig. 6. The influence of manufacturing parameters on the residual stress: a) layer thickness, b) printing speed, c) printing temperature, and d) bed temperature

4. CONCLUSION

Residual stress is one of the most crucial factors that influence the mechanical properties of the components. The investigation and minimization of residual stress are the interest field of most research. This article sheds light on the residual stress in FDM technology by investigating the parameters that affect the residual stress and how they could help minimize it. Printing parts with different printing parameters was done using numerical simulation. We found that the infill density and printing temperature directly proportionate with the residual stress. On the contrary, the layer thickness and the printing speed have an inverse proportion with the residual stress. Finally, the printing pattern hardly affects the residual stress, while the bed temperature has no impact on the residual stress.

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