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Correlation Between Printing Parameters and Residual Stress in Additive Manufacturing: A Numerical Simulation Approach

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Abstract
Fused Deposition Modeling (FDM) is a widely used 3D printing technology that can create a diverse range of objects. However, achieving the desired mechanical properties of printed parts can be challenging due to various printing parameters. Residual stress is a critical issue in FDM, which can significantly impact the performance of printed parts. In this study, we used Digimat-AM software to conduct numerical simulations and predict residual stress in Acrylonitrile Butadiene Styrene (ABS) material printed using FDM. We varied six printing parameters, including printing temperature, printing speed, and infill percentage, with four values for each parameter. Our results showed that residual stress was positively correlated with printing temperature, printing speed, and infill percentage, and negatively correlated with layer thickness. Bed temperature did not have a significant effect on residual stress. Finally, using a concentric infill pattern produced the lowest residual stress. The methodology used in this study involved conducting numerical simulations with Digimat-AM software, which allowed us to accurately predict residual stress in FDM-printed ABS parts. The simulations were conducted by systematically varying six printing parameters, with four values for each parameter. The resulting data allowed us to identify correlations between residual stress and printing parameters, and to determine the optimal printing conditions for minimizing residual stress. Our findings contribute to the existing literature by providing insight into the relationship between residual stress and printing parameters in FDM. This information is important for designers and manufacturers who wish to optimize their FDM printing processes for improved part performance. Overall, our study highlights the importance of considering residual stress in FDM printing, and provides valuable information for optimizing the printing process to reduce residual stress in ABS parts.

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1. Introduction

Additive manufacturing (AM) is a method of combining materials by fusing, binding, or solidifying. It uses 3D Computer-Aided Design (CAD) modeling to construct parts layer upon layer. AM techniques can be described using terms like 3D printing (3DP), rapid manufacturing (RM), and rapid prototyping (RP) (Abdulhameed et al., 2019).AM's prospective features enable it to be employed in creating complex structures for a variety of applications. AM technology is being employed in a wide range of technological applications, with the ability to completely transform the current industrial sector (Dasgupta and Dutta, 2022). It provides a new industrial approach for changing the way manufacturing is done, as it generates a wide range of objects made of various materials quickly (Ficzere, 2022). Nowadays, it is used in many sectors such as aerospace (Blakey-Milner et al., 2021), automobiles (Alzyod and Ficzere, 2021a; Mohanavel et al., 2021), food industries (Le-Bail et al., 2020), and biomedical (Ahangar et al., 2019; Horváth and Ficzere, 2015). It is also being applied in academic research. AM is grouped into four primary types according to the status of the raw material: powder, filament, solid layer, and liquid (Alsardia et al., 2021). Fused Deposition Modeling (FDM), which locate in the filament category(Gibson et al., 2015), has advanced to the point that it is now commonly available for industrial application and commercial marketing. Polymers such as Polyethylene terephthalate glycol (PTEG), Acrylonitrile butadiene styrene (ABS), and Polylactic acid (PLA) are used in three-dimensional printing. It is done by heating up the polymer and depositing it on a plate to create a three-dimensional physical geometry based on the design. The created CAD geometries are sliced into G-code, which specifies printing settings, and then sent to a printer to build the part (Jackson et al., 2022). FDM printers contain three main parts: heater block, nozzle, and build plate. The heater block heats the filament to be in a molten form. This molten material is extruded through the nozzle (extruder) and placed on the build plate. There are two mechanisms of Z-axis movement, moving build plate with fixed nozzle or fixed build plate with moving nozzle. FDM uses two techniques of an extruder, a Direct extruder and a Bowden extruder (Tlegenov et al., 2018). Fig. 1 illustrates the principle of the FDM technique.

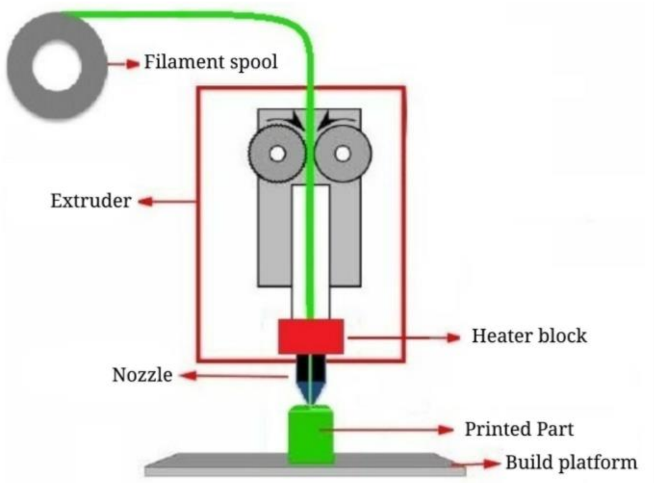

Fig. 1. Schematic of FDM technology

There are two types of parameters utilized in the FDM process: structural parameters and manufacturing parameters. The raster angle, infill density, and part and print orientation are all part of the first group. Printing speed, platform temperature, printing temperature, layer thickness, and chamber temperature are all part of the latter group. It is necessary to forecast how the parts will perform when subjected to mechanical forces to determine their applicability for a specific application. As a result, analyzing the mechanical characteristics of AM components is a trendy area of interest and study, with some of the earliest studies dating back to the mid of nineties (Fodran et al., 1996). As illustrated in Fig. 2, the fishbone diagram outlines the variables that may impact the mechanical properties of FDM technology.

Since then, the impact of process parameters on the mechanical characteristics like tensile and compressive stresses and fatigue strength of test samples has been widely researched for various materials and production environments(Alzyod and Ficzere, 2022; Fatimatuzahraa et al., 2011) studied the effect of raster angle on the mechanical parameters (tensile, flexural, bending, and deflection) using ABS material. (Markiz et al., 2020) studied the relationship between the printing orientation and the tensile strength of ABS specimens. (Baich et al., 2015) investigated the impact of the infill density on the cost and the mechanical properties of ABS parts. (Xiaoyong et al., 2017) investigated the effect of Platform temperature on the mechanical properties of Polyetheretherketone (PEEK) components. (Onwubolu and Rayegani, 2014) studied the effect of layer thickness on the tensile strength of printed parts made of ABS. (Deng et al., 2018) studied the relationship between the printing temperature and the mechanical characteristics of PEEK dogbone parts.

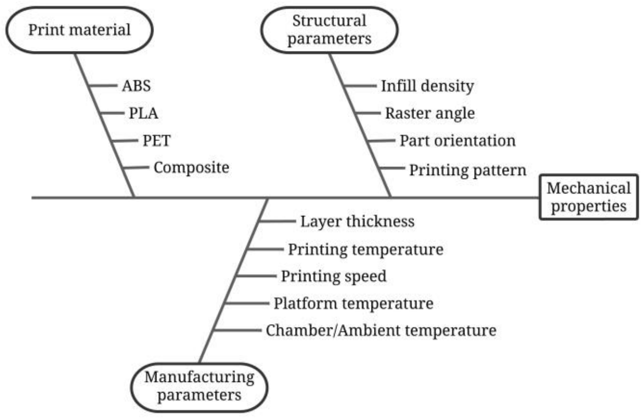

Fig. 2. Fishbone diagram showing the essential petameters that affect the mechanical properties of FDM

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). This residual stress can cause substantial distortion or fatigue cracks of printed objects, affecting the printed parts' dimensional accuracy and mechanical properties (Trško et al., 2020). As a result, conducting the analysis and measuring residual stress is critical for FDM quality control (Hadny et al., 2022).

Residual stress measurement methods are classified into two main types based on their testing approach (Withers and Bhadeshia, 2001). The first type is destructive methods such as hole drilling, contour method, and strain gauge. These methods require a specific approach to eliminate and measure stress in the component. The residual stress can be calculated by analyzing the strain or displacement of the surface using the principles of elastic mechanics. Although these techniques are relatively simple to perform and generally accurate, they can sometimes damage the surface, which is not ideal. On the other hand, non-destructive testing methods such as diffraction, ultrasonic, and Raman spectroscopy are the second type of residual stress measurement techniques. These methods analyze the physical properties of the specimen without causing any damage to the sample (Mousa, 2014). Several researchers have studied the residual stress of FDM 3D printed components, including (Casavola et al., 2017), who used the hole-drilling method to investigate the residual stress in an FDM 3D printed plate made of Acrylonitrile Butadiene Styrene (ABS). They used electronic speckle pattern interferometry to evaluate the deformation of the plate's surface to prevent local strain gauge reinforcement. (Safronov et al., 2017) investigated the deformation and residual stress in rectangular cross-section components, such as beams, by modifying the curvature of the deformed beam. Their approach offered a significant advantage as it allowed for non-destructive evaluation of components. (Kantaros and Karalekas, 2013) studied the residual stresses in ABS components produced using FDM with the fiber Bragg grating technique. This method enabled them to measure residual stresses without causing any harm to the components. Similarly, (Ficzere et al., 2017) used Optical Photostress analysis to examine the impact of printing orientation on residual stress in 3D printed PLA. This non-destructive testing method allowed them to analyze residual stresses without causing any damage to the printed components. Non-destructive methods for measuring residual stress can be useful for obtaining surface-level information about residual stress in a component or structure. However, they may have limitations in terms of accuracy, depth of measurement, equipment cost, and operator expertise.

FDM is a complex process that involves numerous printing variables, making it difficult and time-consuming to investigate the printing conditions for each material using experimental methods. To address this challenge, simulation and modeling approaches can be employed to efficiently assess the impact of processing conditions on the final printed part. By utilizing numerical techniques, researchers can examine the effects of these processing conditions on the crystallization kinetics and thermomechanical behavior of the printed polymer. Integrating simulation and modeling into the investigation of FDM printing conditions provides a more cost-effective and efficient way to study the various factors that affect the quality of the final product. These techniques enable researchers to accurately predict the behavior of the printed polymer under different processing conditions and identify the optimal conditions for each material. This knowledge is essential to improve the quality and performance of additively manufactured parts, as well as to expand the range of materials that can be utilized in the FDM process.

In recent years, there has been a considerable amount of research aimed at forecasting the mechanical properties of 3D printed components using FDM. (Ferreira and Quelho de Macedo, 2017) developed a simulation model for the FDM process, which can calculate stress and temperature during filament deposition. The study showed that printing without a heated build plate resulted in higher stresses due to rapid temperature changes during the printing. (Xia et al., 2018) developed a numerical simulation methodology to examine the physical properties of PLA polymer, including viscosity, density, specific heat capacity, and thermal conductivity. The simulation results were effective in modeling the FDM process. (Zhang and Kevin Chou, 2008) used a Finite Element Method (FEM) model to analyze the mechanical and thermal behavior of a sample and calculate residual stress. The 3D model was also employed to optimize the printing parameters by investigating the effects of various process parameters on part warpage and distortions. Also, (Bertevas et al., 2018) conducted a numerical investigation into the FDM 3D printing of fiber-reinforced polymer composites using a classical microstructure-based fiber suspension model, which was implemented through the smoothed particle hydrodynamics (SPH) method. Their approach allowed them to analyze the influence of various factors such as aspect ratio, fiber distributions, and orientations on the FDM printing process. (Alzyod and Ficzere, 2021b) investigated the residual stress in three materials namely TiAl6V4, AlSi10Mg and 316L stainless steel using Simufact AM software. (Costa et al., 2015) studied the FDM method and evaluated the heat dissipation and warping of a sample during manufacturing, using a 3D extruded filament to account for convection and radiation effects. Their research provides insights into temperature changes throughout different regions of the specimen. In a similar vein, (Cattenone et al., 2019) aimed to optimize the mechanical properties of 3D printed parts by investigating the impact of various parameters using ABAQUS simulation software. Through their study, they aimed to identify the optimal printing conditions for enhancing the performance of 3D printed parts. As per (Kechagias et al., 2022), a comprehensive literature review was conducted along with an experimental study to determine the impact of critical process parameters on the surface quality (SQ) and dimensional accuracy (DA) of Fused FFF parts. The research observed that layer thickness, nozzle temperature, printing speed, infill density, and printing orientation are the most significant factors affecting these properties. In a related study, (Popescu et al., 2018) evaluated a total of 381 research papers that were published during the period of 2008 to 2017 to review the effects of printing parameters on the mechanical properties of FDM parts. The review highlighted that certain process parameters, such as nozzle and bed temperatures, had not been thoroughly investigated.

To address the research gap on the influence of printing parameters on the residual stress response of FDM parts, the current study was conducted. Specifically, this investigation focuses on the impact of six critical printing parameters, namely printing speed, layer thickness, printing temperature, platform temperature, infill density, and infill pattern, on the residual stress response of FDM parts. The residual stress in FDM parts is an important factor that affects their mechanical behavior and can lead to warping, deformation, or even cracking of the parts. Therefore, it is crucial to understand the influence of different printing parameters on residual stress to optimize the printing conditions for producing high-quality parts.

2. Numerical simulation

2.1. Model description and material

The simulation was done using a bridge geometry with dimensions as depicted in Fig. 3. This bridge sample can be clearly influenced by the residual stress. The material used in the simulation was ABS filament, procured from e-Xtream engineering, a subdivision of Hexagon's Manufacturing Intelligence division. The filament in its unfilled, amorphous state was characterized by an isotropic Coefficient of Thermal Expansion (CTE) and possessed a natural color. The simulation was conducted using Digimat-AM software. Digimat-AM is a process simulation program designed for AM of polymers and composite materials. It helps process engineers to forecast the residual stresses, warpage, temperature history, and microstructure changes that occur in a printed component because of process parameters, printing strategy, and material selection. The printing setup can be revised using Digimat-AM simulations before the actual printing.

2.2. Printing parameters

In this study, the investigation of the prediction of the correlation between the residual stress and the printing parameters was done by six different parameters with four levels of each parameter. The six parameters were printing speed, layer thickness, printing temperature, platform temperature, infill density, and infill pattern. The levels of each parameter are illustrated in Table 1. The printing speed limitation is that printing at high speed gives the filament less time to melt in the hotend, which can also be affected by thick layers. The boundary conditions of the printing temperature are based on the manufacturer's recommendations. For the platform levels, the limitation was that printing with a high bed temperature could lead to an elephant's foot.

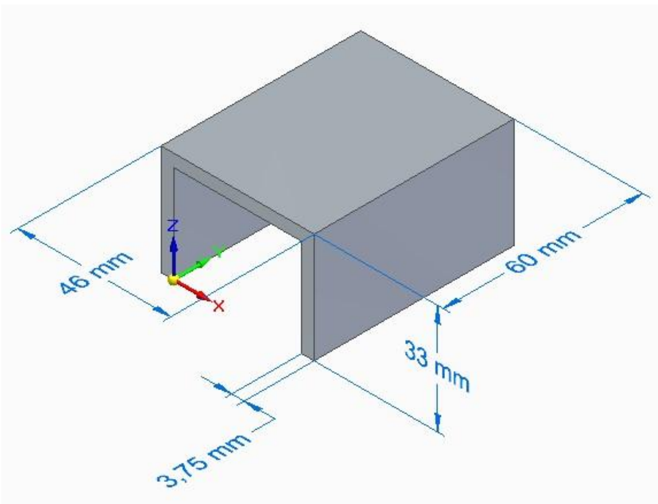

Fig. 3. Dimensions of bridge geometry

Table 1. Levels of printing parameters

Printing parameter	Default	levels 1	2	3	Unit
Printing speed	60	20	40	100	mm/s
Layer thickness	0.19	0.29	0.39	0.49	mm
Printing temperature	250	230	240	260	°C
Bed (Platform) temperature	70	30	50	90	°C
Infill density	100	10	40	60	%
Infill pattern	Zigzag	Triangle	Concentric	Grid	

The total simulation runs were (6 parameters x 3 levels + 1 default) = 19 runs. Fig. 4 showed the structural parameters.

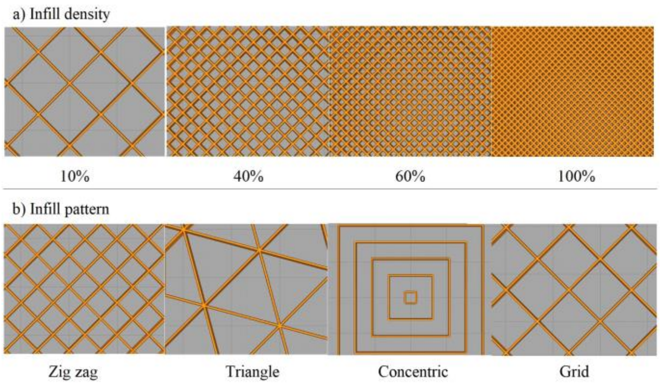

Fig. 4. Structural parameters of printing: a) Infill density, b) Infill pattern

2.3. Digimat-AM simulation

Using numerical solutions in FDM printing can provide significant advantages, such as reducing the need for physical prototyping and saving both time and costs during the research and development process. Numerical simulations can predict a part's final properties, including warpage deflection and mechanical characteristics, without requiring the printing and testing of multiple physical prototypes. This can save time and money. Furthermore, using numerical solutions can optimize the printing process by predicting the impact of printing parameters like printing temperature, chamber temperature, printing speed, and layer thickness on the final properties of a part. This can help identify the optimal process parameters and improve the quality of printed parts. Additionally, numerical simulations can predict mechanical properties like strength and toughness based on material properties and printing parameters, helping to select the appropriate materials and process parameters for a given application. This study used Computer Aided Engineering (CAE) simulations with Digimat-AM software, a tool specializing in process simulation for additive manufacturing. The software allows process engineers to anticipate factors such as warpage, residual stresses, temperature history, and microstructure changes that a printed part may undergo based on process parameters, printing strategy, and material selection. By using Digimat-AM simulations, printing setups can be optimized before physically printing the part, such as by determining appropriate warpage compensation. This allows for efficient optimization of the printing setup prior to physical printing, ultimately leading to cost and time savings during research and development. Digimat-AM offers a six-step workflow to optimize the additive manufacturing process of polymers and composites, including selecting the desired printing process, importing the component geometry, describing how the component is manufactured, translating the settings into an actual FEA simulation, submitting and monitoring the simulation model, and post-processing the simulation results. The beginning step is selecting the needed printing process, printer type, and the type of analysis on the printing process. In this study, the FDM process, a generic printer, and warpage analysis type were chosen. The second step involves importing the geometry, which can be obtained as a .Stl file, and selecting the material that will be used in printing. The third step allows for the description of how the component is manufactured, including various inputs such as toolpath, positioning, order of manufacturing steps, and the boundary conditions. In this study, the part was positioned in the middle of the build plate, 23°C for the chamber, room, and final temperatures, and 0.015 mW/mm2 ºC convection coefficient. The fourth step is the solver, which translates the previous settings into an actual FEA simulation. Voxel meshing of the geometry is proposed, which can't be less than the layer thickness, solution methods can be chosen, and material model parameters can be adjusted. In this study, 0.2 mm voxel mesh, and default solver were chosen. After that, the simulation model can be submitted and monitored until job completion in the fifth step. Finally, the post-processing step provides all the functionalities required to post-process the simulation results, including field visualization of deformation and residual stresses.

3. Results and discussion

Employing numerical simulation can provide valuable insights into the impact of printing parameters on residual stress. Table 2 ()shows the results obtained during the simulation. Regarding the structural parameters, results showed that the infill density greatly influences the residual stress while there is no effect of the infill pattern on the residual stress. The residual stress value increased by increasing the infill density, which happened due to the increase in the heat generation and temperature that changed the structures. Fig. 5 illustrates the relationship between the residual stress and the structural parameters. The results of this study showed that the level of infill density significantly impacted the residual stress in FDM-printed ABS parts. At a low infill density of 10%, the residual stress was measured to be approximately 60 MPa, whereas at a higher infill density of 100%, the residual stress increased significantly to around 73 MPa. These findings indicate that increasing the infill density can result in a notable increase in residual stress, which can have negative implications for the performance and durability of the printed part. With the boundary conditions of infill density from 10% to 100%, Eq. (1) can be applied. In addition, the results also showed that the type of infill pattern used had a negligible impact on residual stress, as the residual stress was found to be relatively consistent across all four infill patterns tested (Zigzag, Triangle, Concentric, and Grid). The measured residual stress values for these infill patterns ranged from 71 MPa to 73 MPa, which is within a very narrow range of values. When the infill density is increased, there is less space for the molten material to fill within the part. This means that the material has less room to move and redistribute during the cooling process. As a result, more residual stress can build up within the part.

$$y = 0.14x + 60.83 \quad (1)$$

In previous studies, researchers have investigated various manufacturing parameters that can affect residual stress in FDM-printed parts. These parameters include layer thickness, printing speed, printing temperature, and bed temperature. From these studies, it has been found that printing speed is the most dominant factor for developing residual stress, followed by layer thickness (Cuan-Urquizo et al., 2019). In this study, the relationship between layer thickness and residual stress have been investigated, and the results were consistent with previous findings. As shown in Fig. 6, it is obvious that layer thickness has an inverse relationship with residual stress. This means that as the layer thickness increases, the residual stress decreases. This relationship has also been observed in another study by (Chen et al., 2021). Specifically, the results revealed that at a layer thickness of 0.19 mm, the residual stress was above 73 MPa, which is a high level of stress that can negatively impact the performance of the printed part. However, by increasing the layer thickness, the residual stress dramatically decreased and dropped by 35% at a layer thickness of 0.49 mm. These findings suggest that optimizing the layer thickness can be an effective way to reduce residual stress and improve the mechanical properties of FDM-printed parts. Furthermore, with boundary conditions of layer thickness between 0.19 mm and 0.49 mm, Eq. (2) can predict residual stress.

$$y = -86.72x + 89.32 \quad (2)$$

Investigation results showed that printing speed has a negative correlation with residual stress. As the printing speed increases, the residual stress decreases. Specifically, it is found that the residual stress linearly decreased from about 85 MPa at a printing speed of 20 mm/s to almost 62.5 MPa at a printing speed of 100 mm/s. This trend is consistent with the findings of another study by (Samy et al., 2021). When the printing speed is increased, the cooling rate of the printed material also increases. This rapid cooling reduces the time available for the material to expand or contract as it cools, leading to lower levels of residual stress. In other words, the faster the printing speed, the less time the material has to contract or expand, resulting in lower residual stresses. Moreover, higher printing speeds can also result in a more uniform temperature distribution across the printed part, which can further reduce the development of residual stresses. This is because a more uniform temperature distribution leads to a more uniform cooling rate, which in turn reduces thermal gradients and the development of residual stresses. Yet, it is important to note that increasing the printing speed beyond a certain point can also have negative effects on the quality of the printed part, such as decreased resolution, poor surface finish, and increased porosity.

On the other hand, printing temperature has a positive correlation with residual stress. As the printing temperature increases, the residual stress also increases. For instance, the residual stress was 67.5 MPa at a printing temperature of 230°C, and then increased to around 76 MPa at a printing temperature of 260°C. Increasing the printing temperature can increase the amount of thermal expansion and contraction that occurs during the printing process, which in turn can lead to higher levels of residual stress. This is because higher temperatures cause the material to expand more before it solidifies, and then contract more rapidly as it cools. Also, higher printing temperatures can also cause the material to flow more easily, which can result in more uneven cooling and solidification. This can also contribute to the formation of residual stresses, particularly if there are significant temperature gradients across the printed part. To summarize, within the constraints of printing speed between 20 mm/s and 100 mm/s and printing temperature between 230°C and 260°C, Eq (3) and Eq (4) could be used to calculate the residual stress, respectively. These equations can help manufacturers optimize printing parameters to achieve desired mechanical properties in FDM-printed parts.

$$y = -0.29x + 90.81 \tag{3}$$

$$y = 0.29x + 0.74 \tag{4}$$

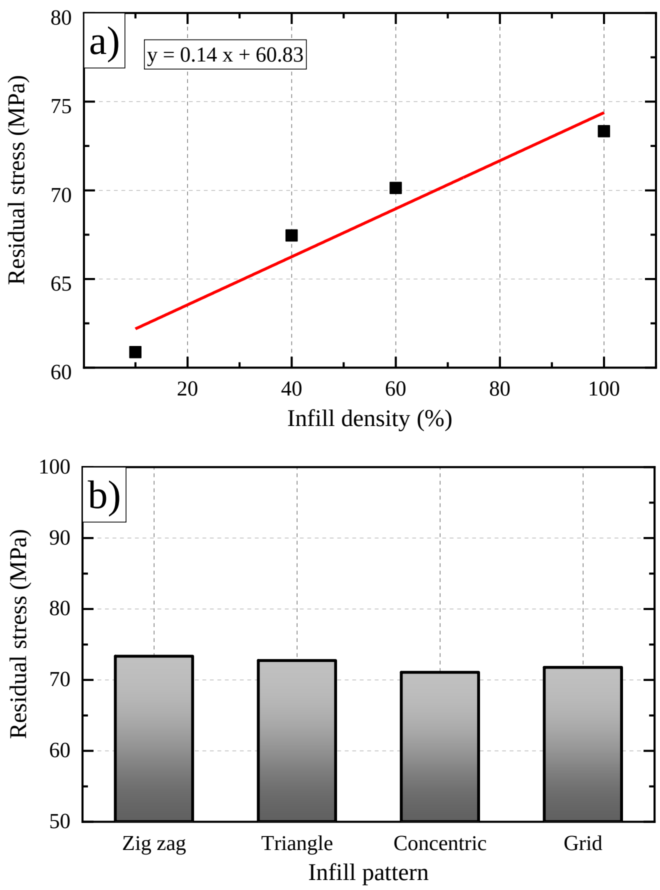

Fig. 5. The relation between the structural parameters and the residual stress: a) infill density, b) infill pattern

Finally, the research found that changing the platform temperature did not have a significant impact on the residual stress level in the printed part. The residual stress level was found to be approximately 73.5 MPa, regardless of the platform temperature used, and Fig. 7 shows the simulation results for the default parameters (run 4).

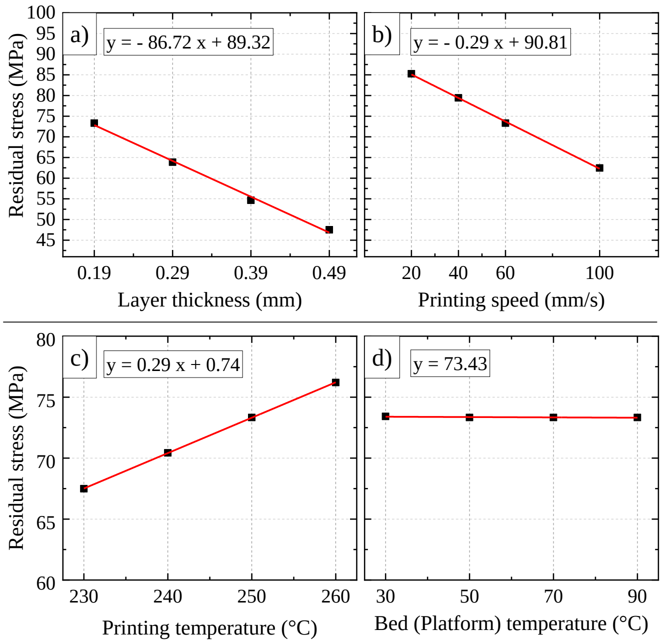

Fig. 6. The effect of manufacturing parameters on the residual stress: a) layer thickness, b) printing speed, c) printing temperature, and d) bed temperature

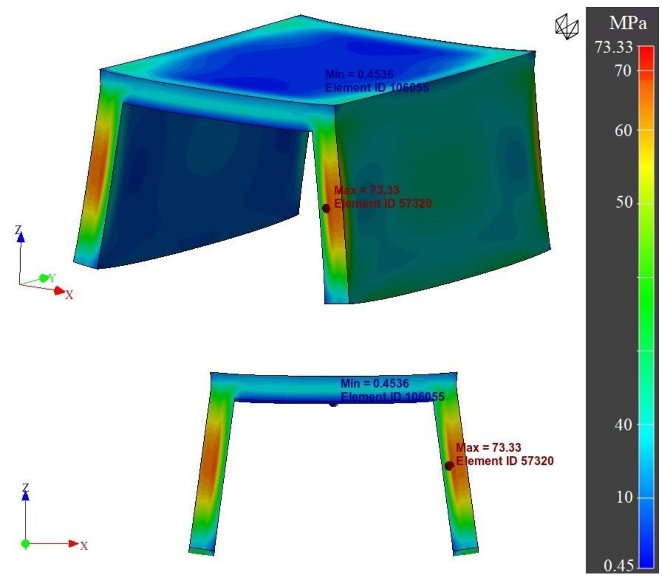

Fig. 7. Simulation result provided by Digimat-AM for run 4 (the default setting)

4. Conclusion

Residual stress is a critical factor that can significantly impact the mechanical properties of 3D printed components. Reducing residual stress has been the subject of much research in the field of additive manufacturing, and this study aimed to investigate the effects of various printing parameters on residual stress and explore ways to minimize it.

Through numerical simulations of 3D printing with different combinations of printing parameters, it was found that the infill density and printing temperature had a direct relationship with residual stress. As these parameters were increased, the residual stress in the printed components also increased. Conversely, decreasing layer thickness and printing speed was found to be inversely proportional to residual stress, with lower levels of residual stress observed when these parameters were reduced. Interestingly, the printing pattern had a minimal effect on residual stress, while the bed temperature had no significant impact. This suggests that optimizing other printing parameters, such as layer thickness and printing speed, may be more effective in minimizing residual stress than focusing on printing pattern or bed temperature.

Generally, this study highlights the importance of carefully selecting and optimizing printing parameters to minimize residual stress and achieve the desired mechanical properties in 3D printed components. By understanding the relationships between printing parameters and residual stress, researchers and engineers can make informed decisions about how to adjust their printing process to achieve the best results.

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Appendix A

Table 2. Part's results from the simulation

Run	Infill density [%]	Infill pattern	Layer thickness [mm]	Printing speed [mm/s]	Printing temperature [°C]	Bed temperature [°C]	Results [MPa]
1.	10	Zigzag	0.19	60	250	70	60.87
2.	40	Zigzag	0.19	60	250	70	67.45
3.	60	Zigzag	0.19	60	250	70	70.13
4.	100	Zigzag	0.19	60	250	70	73.33
5.	100	Triangle	0.19	60	250	70	72.71
6.	100	Concentric	0.19	60	250	70	71.05
7.	100	Grid	0.19	60	250	70	71.76
8.	100	Zigzag	0.29	60	250	70	63.88
9.	100	Zigzag	0.39	60	250	70	54.65
10.	100	Zigzag	0.49	60	250	70	47.5
11.	100	Zigzag	0.19	20	250	70	85.26
12.	100	Zigzag	0.19	40	250	70	79.44
13.	100	Zigzag	0.19	100	250	70	62.46
14.	100	Zigzag	0.19	60	230	70	67.49
15.	100	Zigzag	0.19	60	240	70	70.43
16.	100	Zigzag	0.19	60	260	70	76.2
17.	100	Zigzag	0.19	60	250	30	73.42
18.	100	Zigzag	0.19	60	250	50	73.33
19.	100	Zigzag	0.19	60	250	90	73.33

增材制造中打印参数与残余应力之间的相关性：数值模拟方法

關鍵詞
熔融沉积建模 3D 打印 残余应力
Digimat-AM
ABS

摘要
熔融沉积成型 (FDM) 是一种广泛使用的 3D 打印技术，可以创建各种物体。 然而，由于打印参数多种多样，实现打印部件所需的机械性能可能具有挑战性。 残余应力是 FDM 中的一个关键问题，它会严重影响打印部件的性能。 在本研究中，我们使用 Digimat-AM 软件进行数值模拟并预测使用 FDM 打印的丙烯腈丁二烯苯乙烯 (ABS) 材料的残余应力。 我们改变了六个打印参数，包括打印温度、打印速度和填充百分比，每个参数有四个值。 我们的结果表明，残余应力与印刷温度、印刷速度和填充百分比呈正相关，与层厚度呈负相关。 床温对残余应力没有显着影响。 最后，使用同心填充图案产生的残余应力最低。 本研究中使用的方法涉及使用 Digimat-AM 软件进行数值模拟，这使我们能够准确预测 FDM 打印 ABS 零件中的残余应力。 通过系统地改变六个打印参数（每个参数有四个值）来进行模拟。 由此产生的数据使我们能够确定残余应力和印刷参数之间的相关性，并确定最小化残余应力的最佳印刷条件。 我们的研究结果通过深入了解 FDM 中残余应力与打印参数之间的关系，为现有文献做出了贡献。 对于希望优化 FDM 打印工艺以提高零件性能的设计师和制造商来说，此信息非常重要。 总的来说，我们的研究强调了在 FDM 打印中考虑残余应力的重要性，并为优化打印工艺以减少 ABS 零件的残余应力提供了有价值的信息。