THERMAL ANALYSIS OF FDM PROCESS PARAMETERS AND THEIR EFFECTS ON RESIDUAL STRESS

Hussein Alzyod, *Budapest University of Technology and Economics, H-1111 Budapest Megyetem rkp.3, Hungary, E-mail: hussein.alzyod@edu.bme.hu.*
Peter Ficzere, *Budapest University of Technology and Economics, H-1111 Budapest Megyetem rkp.3, Hungary, E-mail: ficzere.peter@kjk.bme.hu.*
Lajos Borbas, *Budapest University of Technology and Economics, Department of Railway Vehicles and Vehicle System Analysis, and EDUTUS University, Technical Institution, Stúdium tér, Tatabánya H-2800, Hungary, E-mail: borbas.lajos@edutus.hu.*

ABSTRACT
This study focuses on the impact of printing parameters on residual stress in Fused Deposition Modeling (FDM) through numerical simulation. The research examines printing temperature, bed temperature, chamber temperature, and print speed as key parameters. By analyzing the results, it was determined that printing temperature had the most significant contribution in minimizing residual stress (59.3%), followed by chamber temperature (20.5%) and print speed (19.4%). Bed temperature was found to have minimal effect. The study provides valuable insights for optimizing FDM printing processes and reducing residual stress, thereby enhancing the quality and performance of FDM-printed components.

1. INTRODUCTION

Fused Deposition Modeling (FDM), a widely used additive manufacturing technique, has revolutionized the production of complex geometries and functional prototypes [1]. However, ensuring optimal part quality and mechanical performance remains a critical challenge [2]. One key factor that significantly influences the final properties of FDM-printed parts is the presence of residual stress [3], [4]. Residual in FDM refers to the internal stresses within a printed object after the printing process is completed. These stresses arise due to the thermal history and cooling dynamics experienced by the material during the FDM process. During FDM printing, thermoplastic filaments are heated and melted, and the molten material is extruded layer by layer to build the final object. As the material cools down and solidifies, it undergoes thermal contraction, resulting in internal stresses within the printed part [5]. These stresses can be caused by non-uniform cooling, differential shrinkage, and variations in temperature across the layers and interfaces. Residual stress can significantly affect FDM-printed components' mechanical properties and dimensional accuracy[6]. High residual stress levels can lead to warping, distortion, and even cracking of the printed parts. Moreover, residual stress can affect the material's fatigue life, structural integrity, and performance under different loading conditions [7]. The 3D printing process involves the continuous application of heat to the uppermost layer of a printed object as subsequent layers are added sequentially. However, as each newly deposited layer joins the underlying layers, the lower layers begin to cool relative to the temperature of the extruded material. As thermal energy rapidly dissipates from the uppermost layer, it initiates a contraction process. However, due to the confinement imposed by the underlying layers, the top layer experiences limitations in its ability to contract or deform fully. Consequently, the interaction between the tendency of the material to shrink and the physical constraints exerted by the preceding layers gives rise to residual stress, and Figure 1 illustrates that. Consequently, heat is transferred from the top layer of the printed part through three distinct modes. Conduction serves as the initial mode of heat transfer, wherein heat is conveyed from the top layer to the underlying layers via direct physical contact. As the temperature gradient exists between the hotter top layer and the cooler lower layers, heat flows from the former to the latter, facilitating a

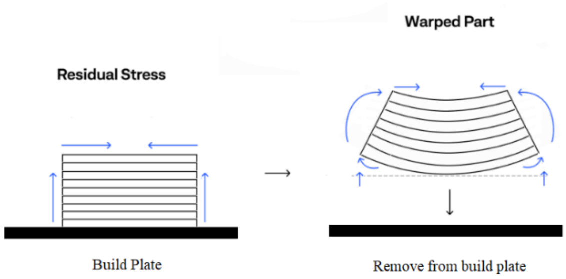

Figure 1. Internal generation of residual stress through thermal gradients in 3d printing

gradual decrease in temperature throughout the part. Convection, the second mode of heat transfer, occurs when the heat generated by the top layer causes the surrounding air to heat up. This heated air rises due to its reduced density, creating a convection current. This upward movement of hot air aids in carrying away heat from the printed object, ensuring effective cooling. Promoting convective heat transfer maintains a stable temperature distribution within the printing environment, mitigating issues such as excessive heat accumulation that could result in deformations or compromised print quality. Radiation constitutes the third mechanism through which heat is transferred from the top layer of the printed part. In this mode, heat energy is emitted from the top surface in the form of electromagnetic waves. These thermal radiation waves propagate through the surrounding air and are subsequently absorbed by nearby surfaces or the air itself. The radiation heat transfer rate is influenced by factors such as the temperature of the emitting surface, the material's emissivity characteristics, and the printed object's geometry. Radiative heat transfer aids in dissipating heat from the top layer, contributing to the overall cooling process. Understanding these various modes of heat transfer in 3D printing is essential for optimizing the process and improving the quality of printed objects. By carefully managing the heat transfer mechanisms, it is possible to achieve greater dimensional accuracy, minimize warping, and enhance the material properties of the printed parts. Adjusting printing parameters, such as layer thickness, print speed, chamber temperature, and material properties, allows for control over the heat transfer processes, thereby addressing concerns related to uneven cooling and residual stresses that may arise during the printing process. These stresses can adversely affect the dimensional accuracy, structural integrity, and mechanical behavior of FDM-printed parts. Therefore, understanding the underlying thermal behavior and its relationship with process parameters is crucial in mitigating the impact of residual stress on the final product. This article aims to numerically delve into the thermal analysis parameters and investigate their influence on the residual stress of the FDM process using ABS material. Four key parameters will be explored: printing temperature, bed temperature, chamber temperature, and print speed. By examining the relationships between these variables and their impact on residual stress, we seek to provide valuable insights for enhancing the quality and performance of FDM-printed components.

2. SIMULATION PROCEDURE OF FDM

2.1 Material, sample, and printing parameters

The ABS filament utilized in this research was acquired from e-Xtream Engineering, Hexagon's Manufacturing Intelligence division. The filament employed was unfilled, amorphous, and possessed a natural color. A 3D cuboid model, measuring 60 mm in length, 30 mm in width, and 10 mm in height, was designed using computer-aided design (CAD) software, as depicted in Figure 2. The rest parameters were set as shown in Table 1.

Table 1. Fixed printing parameters values

Printing parameter	value
Layer thickness (mm)	0.2
Nozzle head (mm)	0.4
Infill density (%)	100
Infill pattern	Zig zag
Raster angle (°)	0
Infill orientation	X-axis
Build direction	Flat

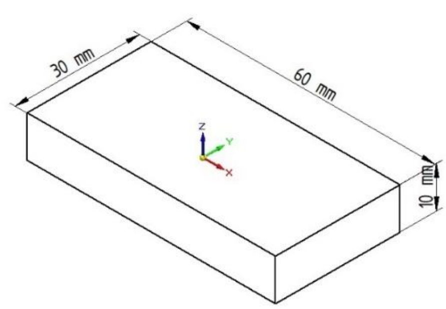

Figure 2. Used sample dimensions

2.2 Design of experiment and optimization methodology

To comprehensively investigate the influence of process parameters on FDM, the adoption of systematic Design of Experiments (DOE) techniques such as Taguchi's orthogonal design, Box-Behnken Design (BBD), Response Surface Methodology (RSM), and Central Composite Design (CCD) is imperative [8]. Employing these methods ensures a well-structured and systematic framework for assessing the impact of multiple input variables on a single output variable, enabling precise characterization of the response surface and identification of optimal parameter configurations [9]. In this study, Taguchi L9 orthogonal array was employed to analyze the four parameters and their levels, and Table 2 depicts these parameters. Means graphs and Signal to Noise (S/N) ratio are tools for minimizing process variability and response values [10].

Table 2. Factors and levels of simulation

Parameter	Unit	Levels		
		1	2	3
Printing Temp. (PT)	ºC	225	230	235
Bed Temp. (BT)	ºC	87	90	93
Printing speed (PS)	mm/s	30	45	60
Chamber Temp. (CT)	ºC	37	40	43

Following the investigated variable, the selection of the S/N ratio is tailored to the study's specific needs. In this research, the focus is on minimizing the residual stress of the samples, making the S/N ratio of the 'smaller is better' type the appropriate choice for evaluation [11], [12].

2.3 Numerical simulation

The investigation employed the Computer-Aided Engineering (CAE) tool Digimat-AM to analyze the additive manufacturing (AM) processes. Digimat-AM is a comprehensive software platform for collecting data on mechanical characteristics and simulating AM of composites and polymers. Its four-stage process, namely definition, manufacturing, simulation, and results, enables the analysis of warpage and residual stresses in printed parts.

3. RESULTS AND DISCUSSION

Incorporating Taguchi L9 Orthogonal Array: Analysis of Simulation Results in Table 3. The experimental investigation delves into the residual stress of ABS FDM printed parts, unveiling significant variations in residual stress with varying printing parameters. Additionally, an in-depth statistical analysis employing ANOVA is performed to ascertain the extent of influence exerted by these parameters on the residual stress exhibited in the printed components, and Figure 3 shows the S/N ratio graph. The significance of printing factors on individual responses was assessed through an ANOVA conducted at a 95% confidence level.

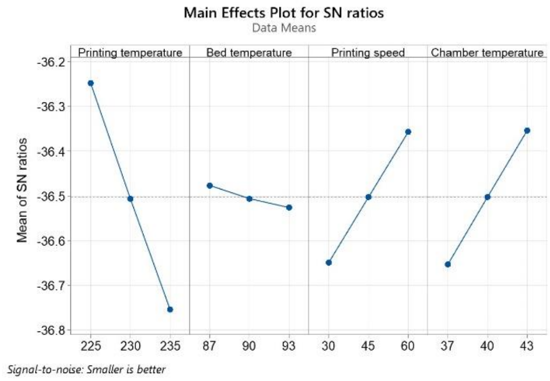

Figure 3. S/N ratio plot for residual stress

Table 3. DOE results using L9

Run	PT	BT	PS	CT	Residual stress [MPa]
1	225	87	30	37	66.97
2	225	90	45	40	64.94
3	225	93	60	43	62.92
4	230	87	45	43	65.54
5	230	90	60	37	66.94
6	230	93	30	40	68.19
7	235	87	60	40	67.46
8	235	90	30	43	68.81
9	235	93	45	37	70.2

The ANOVA results, presented in Table 4, facilitated the calculation of each parameter's contribution percentage in reducing residual stress. Notably, the printing temperature emerged as the most influential factor, contributing 59.3% towards minimizing residual stress. Subsequently, chamber temperature and printing speed contributed substantially, accounting for 20.5% and 19.4%, respectively. Conversely, the effect of bed temperature was insignificant, contributing less than 1%. Consequently, minimizing residual stress can be achieved by adopting specific parameter values: a printing temperature of 225 °C (first level), a bed temperature of 87 °C (first level), a printing speed of 60 mm/s (third level), and a chamber temperature of 43 °C (third level).

Table 4. ANOVA for individual responses

Source	DF	Seq SS	Contribution %	Adj SS	Adj MS	F-Value	P-Value
PT	1	23	59.3	23	23	28777	$7x10^{-9}$
BT	1	0	0.8	0	0	381	$4.05x10^{-5}$
PS	1	7	19.4	7	7	9392	$6.8x10^{-08}$
CT	1	8	20.5	8	8	9937	$6.1x1^{-08}$
Error	4	0	0.0				
Total	8	39	100				

4. CONCLUSION

FDM is a widely used additive manufacturing technique known for its ability to create complex geometries and functional prototypes. However, residual stress remains a significant challenge in achieving high-quality parts. Residual stress in FDM refers to internal stresses within printed objects caused by thermal gradients and cooling dynamics. These stresses can negatively affect mechanical properties and dimensional accuracy. Understanding heat transfer mechanisms like conduction, convection, and radiation is crucial for optimizing printing. Numerical simulation using Digimat-AM software investigated the influence of printing parameters on residual stress. Results showed that printing temperature had the most significant impact (59.3%) in minimizing residual stress, followed by chamber temperature (20.5%) and print speed (19.4%). Bed temperature had an insignificant effect. Specific parameter values were recommended to minimize residual stress, improve quality, and enhance FDM-printed parts. This research provides valuable insights for optimizing printing parameters and managing heat transfer to reduce residual stress and improve overall performance.

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