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NUMERICAL SIMULATION OF FUSED FILAMENT FABRICATION PROCESS AND TENSILE TESTS

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Abstract

Fused Filament Fabrication (FFF) is a prevalent additive manufacturing process that uses thermoplastic materials such as polylactic acid (PLA) in filaments deposited layer-by-layer. This study focuses on the fabrication of components withstanding mechanical loads. However, the FFF parts are subjected to a time-varying thermal profile during manufacturing. Thus, these parts are subjected to geometry distortions and residual stresses due to temperature gradients and varying hardening degrees in adjacent layers, impairing the mechanical performance of 3D-printed structures. Rapid heating and cooling of the polymer feedstock further contribute to non-uniform internal stresses. These residual stresses and geometry distortion determine the research object. Finite element (FE) software ABAQUS is employed to simulate the 3D printing process and tensile test. The FE modelling includes a coupled thermo-mechanical analysis, and a tensile test simulated in two stages. The first analysis stage estimates the residual stresses' effects on mechanical performance through heat transfer, followed by static structural analysis, generating nodal displacement, stresses, and strains. The second stage uses this calculated stress distribution over time as a predefined stress field to define residual stresses acting in the 3D-printed samples for tensile tests. The experimental results are used to validate the tensile model predictions.

Keywords: material extrusion; fused filament fabrication; finite element simulation; thermo-mechanical analysis; residual stresses.

1. Introduction

Additive manufacturing (AM) has emerged as a transformative process in modern production technologies [1], with Fused Filament Fabrication (FFF) being one of the most prevalent methods for producing thermoplastic components. The increasing demand for parts that can withstand mechanical stresses, especially in industries like automotive and aerospace, highlights the need for a thorough understanding of the material properties and the process parameters involved in FFF. The FFF process manufactured parts experience a time-varying thermal profile, which introduces complexities such as geometry distortion and the development of residual stresses due to the polymer evolution from a semi-molten to a solid state during the manufacturing process [2]. These stresses have a detrimental effect on the mechanical performance of the produced parts, making this study area highly relevant.

Several studies have been conducted on the effects of thermal profiles in 3D printing processes, particularly focusing on the mechanical properties of printed parts [3], [4]. Recent advancements in numerical modelling have enabled researchers to simulate printed components' thermal and mechanical behaviours, providing insights into how different process parameters, such as printing speed, nozzle temperature, nozzle velocity, and layer thickness, influence the resulting properties [5]. Moreover, Finite Element Method (FEM) simulations have proven their efficiency in predicting mechanical deformations and stress distributions, furthering the understanding of the 3D printing process's intricacies.
The physical optimization of FFF process parameters is costly, requiring time-intensive trials [6]. Therefore, Predictive simulation tools offer the potential to model the process, enabling parameter optimization to minimize part distortion and achieve the desired shape on the first trial. The FFF process is characterized by complex multiphysical phenomena, including solidification, heat transfer, and mechanical loads, which are closely interrelated with the process parameters and significantly influence the final part performance [7]. A comprehensive simulation procedure requires implementing a constitutive thermo-mechanical model for the extruded material, an accurate representation of process parameters, and experimental validation of predictions at each analysis stage. The FEM, coupled with element progressive activation, facilitates the simulation of the FFF process by utilizing various constitutive models of polymers and incorporating key process parameters such as extrusion temperature, tool-path patterns, nozzle velocity, layer thickness, filament width, etc. [8]. Zhang et al. [9] developed one of the earliest full 3D FEM models for the FFF process simulation, investigating the tool-path pattern on the FFF process through a thermo-mechanical analysis to predict the formation of residual stresses in a regular Acrylonitrile Butadiene Styrene (ABS) plate. The used material modelling was assumed to be linear elastic with temperature-dependent thermal properties. The study demonstrated that the tool-path pattern significantly influences both the distribution and magnitude of the computed residual stresses. The same simulation framework was later utilized in [10] to predict the impact of other process parameters, such as layer thickness, nozzle velocity, and filament width, on the final residual stresses and part distortion. The results demonstrated that the nozzle velocity is the most influential parameter affecting part distortion, followed by the layer thickness. Cattenone et al. [11] conducted simulations to investigate the influence of constitutive models on the FFF process for an ABS bridge-like part. The findings indicated that incorporating a temperature-dependent Young's modulus and yield stress, alongside constant thermal properties, resulted in a mean difference of 12% between the measured and predicted distortions.
This study simulated the FFF process and subsequent tensile tests using Finite Element (FE) modelling. ABAQUS software is employed to conduct a coupled thermo-mechanical analysis, focusing on the residual stresses and their effects on the mechanical performance of the printed components. Experimental tensile tests validate the simulation to ensure the accuracy of the results. Our findings contribute to the ongoing research by providing a deeper understanding of how process parameters affect residual stresses and mechanical performance, with implications for optimizing FFF processes for high-performance applications.

2. Simulation workflow

The FFF simulation workflow was proposed in [11],[12],[13] and illustrated in the schematic Fig. 1. In the preliminary stage, a CAD model defines the part's geometry; after that, the G-code outlines the FFF process parameters. The G-code is analysed to extract the time-dependent filament centrelines of the cross-sectional area of deposited material to compute the activation intervals of each finite element (FE) defining the Event-series data in ABAQUS. The numerical modelling of the FFF process is conducted using thermo-mechanical simulations with the activation intervals using element progressive activation approach, which are summarized in [14]. The Element progressive activation approach defines the printing path through time-dependent coordinates of the filament centreline processed from the G-code. The elliptical cross-section of the filament is assumed to remain constant and is represented by a rectangle. If the centre of the element lies within the defined rectangular boundaries, the element is activated and will be included in the analysis. The thermal model is first used to evaluate the temperature distribution as a function of time. The time-dependent temperature distribution is introduced as a solution-independent boundary condition into the mechanical model to estimate the residual stresses and part deformations. In the final stage, the residual stresses and geometry deformation are incorporated into the tensile test FE model to evaluate its influence on mechanical performance. Simultaneously, the experimental results in [15] were used to validate the model predictions.

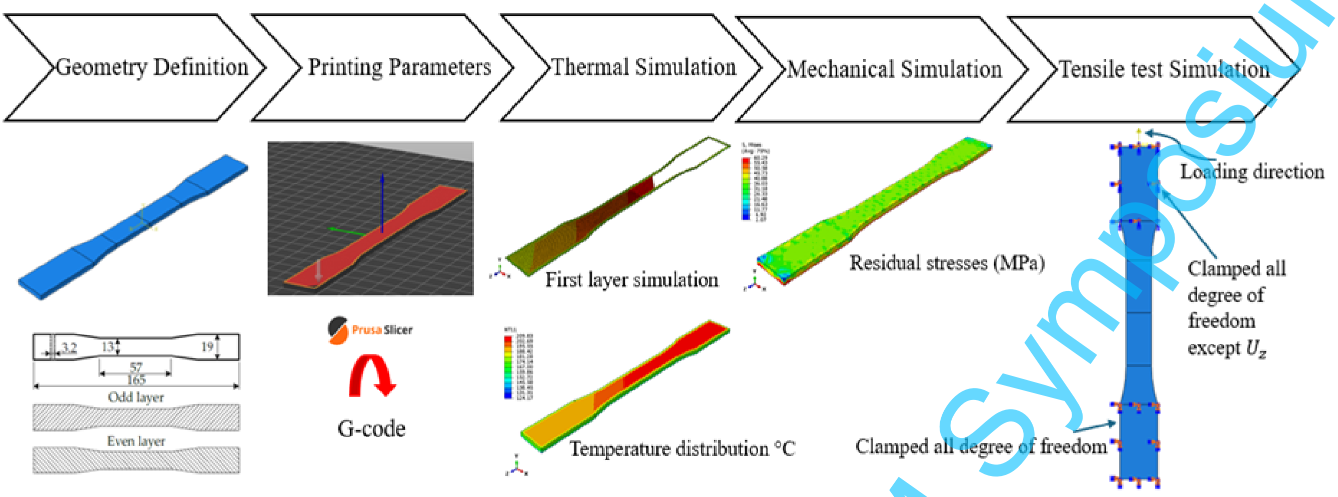


Fig. 1. Schematic workflow of the proposed study.

3. Numerical simulation of the FFF process

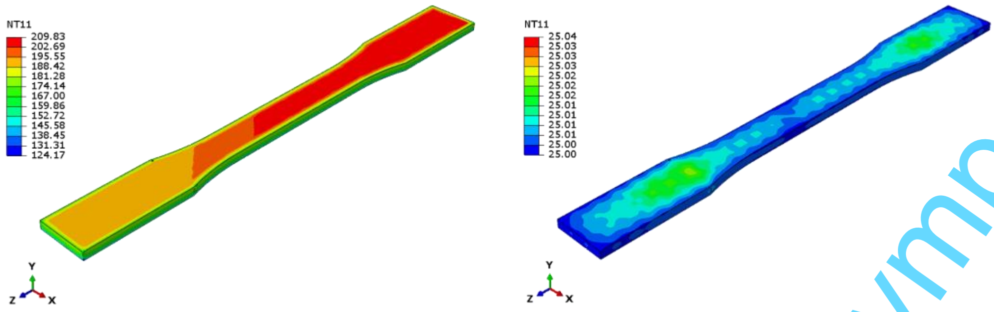
Following schematic workflow Fig.1 of the simulation of the FFF process, the CAD model of the ASTM standard D638-14 determines the part's geometry. afterward, PrusaSlicer 2.3.3 slicing software is used to generate the G-code that outlines FFF process parameters in Table 1. A Python script is developed to re-elaborate the G-code, extracting the activation time of each FE and using it as input to define the event series data in ABAQUS. Full activation of elements was assumed during the element progressive activation while the specific boundary conditions were applied only for the activated elements. PLA is used as feedstock material in this study. Material characterization is performed experimentally to assess post-manufacturing material properties, including manufacturing defects. The temperature dependent material properties were demonstrated in [16],[17]. The selected element type was DC3D8: 8-node linear heat transfer brick and C3D20R:20-node quadratic brick for thermal and mechanical analysis, respectively. The element size along (x, z) axes was set to equal the nozzle diameter and along (y) axe was equal to layer thickness.

Printing Parameters	Typical Value
Extrusion Temperature	210 °C
Build Platform Temperature	60 °C
Print Speed	28 mm/sec
Infill Density	100%
Nozzle Diameter	0.4 mm
Number of layers	11

Table 1. Printing Parameters

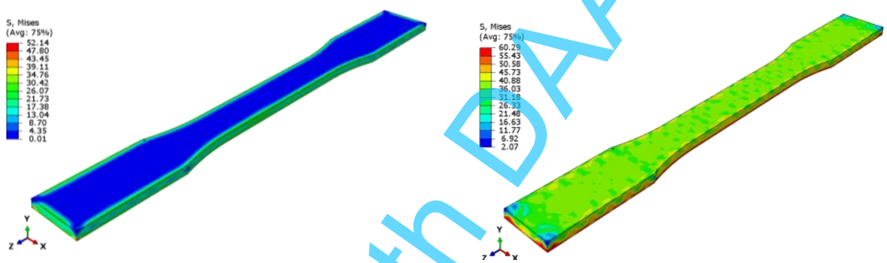
4. Results

The proposed thermo-mechanical model predicted the temperature distribution Fig.2 for the test specimen. The temperature history is introduced as a solution independent boundary condition into the mechanical model to estimate the residual stresses and part deformations which are generated within the 3D printed specimen due to thermal cycling, cooling and process constraints. Higher residual stresses were observed along the specimen edges compared to the other locations. The formation of residual stresses was significant during the cooling process Fig.3. The thermo-mechanical analysis was followed by subsequent tensile test simulation. The first Tensile test simulation was performed excluding the manufacturing defects of FFF process. The second Tensile test model includes the residual stresses and geometry distortion. The later model indicates the impact of residual stresses on the mechanical performance of the 3D printed components. At the same time, the results were validated with the physical test achieving acceptable accuracy Fig.4. Average values of force-displacement results explained in [15] were considered during the validation of the FE model. The physical test demonstrated tensile load-bearing capacity of 1.7 kN at displacement 2.8 mm. The first tensile test model demonstrated higher predictions than the physical test. However, the second model demonstrated a reduction of tensile load-bearing capacity due to the incorporation of residual stresses and geometry deformation of the test specimen.



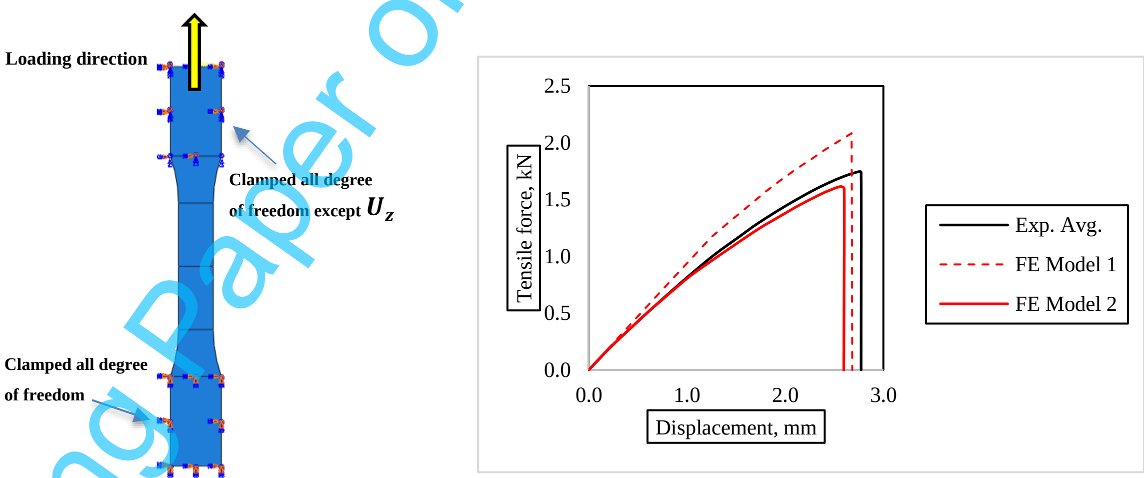
(a) (b)

Fig. 2. Temperature distribution (a) temperature distribution of test specimen at the end of extrusion, (b) at the end of cooling, where NT11 represents the nodal temperature (°C).



(a) (b)

Fig. 3. Residual stresses of test specimen (a) at the end of extrusion, (b) at the end of cooling, where S is in (MPa).



(a) (b)

Fig. 4. (a) Tensile test simulation setup, (b) Force-displacement curve where Exp. Avg. Represents the average typical values obtained from the physical tests [15]. FE Model 1, FE Model 2 represent the first and second tensile test simulations respectively.

5. Conclusion

This study discussed a numerical approach to predict the temperature distribution and residual stresses in PLA parts manufactured using the FFF process. The results demonstrated the potential influence of residual stresses and geometry deformation on the mechanical performance of the final component. To achieve enhanced accuracy, a detailed temperature-dependent material characterization should be considered. This could include the complex thermal and mechanical behaviour of the material at different stages, thus improving the simulation reliability. It was found that the computational efficiency of FE simulation depends highly on proper meshing strategies. In addition, the effects of radiation should be considered during the thermal simulation. However, the simulation approach of the FFF process faces some limitations as follows:

1. Thermal and Residual Stress Modelling: The simulation approach doesn't consider the full complexity of thermal gradients, residual stresses, and solidification effects during and after filament deposition. For intense solidification and volume changes, they are not adequately modelled, leading to incomplete predictions of distortions.
2. Material Defects: The current simulation approach does not fully capture the presence of voids and porosity in FFF parts, which significantly impacts their mechanical performance.
3. Layer Adhesion and Bonding: The interlayer bonding is a critical aspect of FFF part strength. The simulation approach doesn't capture the complexities of interlayer bonding, such as the temperature-dependent adhesion between layers, leading to inaccurate predictions.
4. Viscoelasticity and Melt Flow: The FFF process involves the extrusion of molten thermoplastics that exhibit viscoelastic behaviour. The simulation failed to accurately capture the flow dynamics of the melted filament and the solidification process.

Future research should focus on the effect of porosity and the air gap on the mechanical properties, incorporate realistic boundary conditions and environmental parameters, introduce composite materials such as reinforced thermoplastics, and consider the topology optimization of the FFF parts. Furthermore, incorporating multi-material printing strategies may enhance the performance of components subjected to complex loading conditions, offering new possibilities for advanced applications in additive manufacturing.

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