Thermo-Mechanical analysis of fused filament fabrication process

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Abstract. Manufacturing industry has been revolutionized by 3D printing or Additive Manufacturing (AM) processes introduced in the late 1980s. Subsequent to intensive research, the technology is even accessed by hobbyists. A layer-by-layer deposition of a material produces a prototype in the commercialized 3-dimensional (3D) printing techniques. Among the 3D printing processes, Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) process is the commonly used process for prototyping, manufacturing functional parts, etc. The process involves the extrusion of a molten polymer filament sequentially through a heated nozzle in the required pattern on to a platform. The FDM process primarily depends on the thermal gradient as the deposited molten material cools, solidifies and bonds with the previous layer. This temperature gradient greatly affects the produced parts microstructure and in turn the macrostructure of the final part. Numerous attempts to experimentally characterize the thermal and mechanical properties of structures fabricated with FDM have been reported in the literature. However, few attempts have been made with 2D models to predict the thermal and mechanical behaviour of the FDM printed components. In this study, a 3D thermo-mechanical model has been developed using ANSYS® workbench using the element birth and death effect. The temperature evolution, maximum principal stress and the deformation due to the thermal gradient were calculated using the developed model. The developed Finite Element Analysis (FEA) model was tested with properties of Poly-Lactic Acid (PLA) material. Through the analysis, it was shown that the model can be used as a predictive tool to understand the thermo-mechanical behaviour of FDM printed parts and also the modelling method used has a great influence on the thermal gradient of the printed parts.

1. Introduction
The Additive Manufacturing (AM) technology has rapidly gained popularity since its inception in the late 1980’s. One of the key advantages of the AM process is the zero-waste generation during the fabrication process. The various categories of AM include Stereolithography (SLA), Laser Engineered Net Shaping (LENS), Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF), Direct Metal Laser Sintering (DMLS), Laminated Object Manufacturing (LOM), Electron Beam Melting (EBM) and Digital Light Processing (DLP) [1]. Among the above-mentioned AM processes, the FDM process is the most widely used process due to its ease of use, material availability and affordability. In the FDM process, filaments made of a polymer material usually Acrylonitrile butadiene styrene (ABS) or Poly-Lactic Acid (PLA) is partially melt and deposited on a heated bed. Even though the process is even used by hobbyists, the deposition process is still not completely explored [2]. As the process is primarily driven by the thermal behaviour, the thermal gradient of the
filaments during and after deposition is crucial for determining the dimensional accuracy and quality of the fabricated product. Other parameters such as scanning speed and orientation of material deposition also plays an important role in the final quality of the product [3-5].

As the temperature is crucial in the FDM process, several monitoring processes were developed. A non-intrusive method for FDM machine monitoring was developed by Wu. et al. which detailed the use of acoustic emissions to monitor the FDM machine conditions [6]. Another method for online monitoring of the layered manufacturing processes using an optical camera was also implemented to detect process defects [7]. Experimental measurements using embedded thermocouples were also demonstrated to determine the quality of layer bonding in the FDM processes [8]. However, limitations such as scan quality, S/N ratio and location of the sensors exist in these systems. Meanwhile the use of Infra-Red (IR) thermal imaging systems has gained popularity in comparing with the measurement techniques. But the cost of the IR system is too high which is sometimes even twice the cost of a desktop 3D printer [9].

Considering the drawbacks in the experimental methods, it is essential to develop predictive models to characterize and understand the thermal behaviour of the FDM process. Few numerical simulations using 2D models were established to predict the thermal gradient of the deposited filament in the FDM process. A 2D heat transfer analysis was performed by Rodriguez and Thomas by assuming rectangular cross sections and neglecting the effects of conduction between the filament and the heated bed [10]. Indirect results such as scan quality, S/N ratio and location of the sensors exist in these systems. Several theoretical models without the validation of the thermal behaviour with the experimental results were also found in literature [12–17]. Primarily, the simulations were carried out in ANSYS APDL and APDL coding was used to solve the model. The theoretical models developed also did not address the phase transition heat transfer and the heat loss/generation into the governing equation. FEA simulation using commercially available software packages such as Abaqus and MATLAB were also used to model the FDM process [18–19]. These simulations also lacked the verification of the model with experimental results. For addressing these drawbacks, this research focusses on developing a 3D finite element model considering the effects of conduction, convection and radiation on the thermal behaviour of the FDM deposition process. A commercial software ANSYS® Workbench is used to simulate the material deposition process. The developed thermal and mechanical model is simulated with PLA as print material. Finally, the FEA results is validated with the experimental results of the thermal gradient measured using an IR thermal camera in the previous research works.

2. Thermo-Mechanical modelling

2.1. Finite Element Model

A three-dimensional coupled thermo-mechanical model was created to study the FDM process. The commercially available ANSYS R19.2 was used for the simulation. Initially, the thermal model was solved, and the results of the thermal model were given as input to the structural analysis to determine the effect due to thermal stress. The geometry of the model was generated with a dimension of 15 (length) X 0.4 (width) X 10 (height) mm. SOLID90 element type with 20 nodes was used to generate the mesh of 0.4mm element size. The size of the model was selected to study the results using a single line generation of the part without using infill. The filament part was printed on a bed of size 15 (length) X 10 (width) X 4 (thickness) mm. The bed size was chosen very small to understand the heat transfer behavior between the deposited filament and the bed. The model has 25 layers of material deposition that equals to 10 mm of the part height. Figure 1 shows the meshed solid model of the fabricated part and the heated bed.
The element birth and death concept in ANSYS R19.2 Workbench was used to activate and deactivate a particular element at a given time and load condition. The birth and death concept has been successfully implemented in simulating temperature gradients in welding and melting of material [20–22]. The element birth and death method is applied to the FDM process to better replicate the material deposition process. Figure 2 (a) and (b) show the element birth and death effects utilized in the developed model.

**Figure 2.** Birth and Death of elements during the FDM simulation. 2 (a) Birth of element 1 during load case 1; 2 (b) Birth of element 2 during load case 2.

### 2.2. Thermal boundary conditions and assumptions

The study basically involves two steps – Thermal analysis and a structural analysis. The following boundary conditions were applied to solve the model.

- The initial temperature for each element was maintained at 190°C for the PLA filament printing.
- The first three elements will be in contact with the heated bed. The thermal contact resistance was calculated using the relation explained in [23]. The value was found to be 77.33 Wm⁻²°C⁻¹.
- The value of convective heat transfer between the fabricated part surface to the ambient air was set to 100 Wm⁻²°C⁻¹. The value was calculated using the function for forced convection over a rectangular body [23]. The forced convective value was calculated considering the cooling fan speed over the fabricated part at approximately 2.5-3 m/s [24].
- The effect of radiation was neglected in the simulation as the effect of convective heat transfer is considerable in the FDM process [13]. But it was proven that the effect of radiation should be considered for the FDM process by Natalie Rudolph et al. [15]. So, an emissivity value of 0.95 was considered as suggested in their research work.
- The structural analysis was performed with all the degrees of freedom of the bottom surface of the first layer arrested.
The following assumptions were also made based on the till date research findings in the simulation of material deposition in the FDM process.

- The initial temperature is maintained constant throughout the simulation process.
- The speed of material deposition is equal to the travel speed of the nozzle.
- The extruded material can be modeled as a finite volume with imposed heat energy.

2.3. Material properties of PLA

The simulation was carried out with commercially available WOL3D PLA filament. The material was chosen as it is commercially available and is one of the most commonly used polymer filaments for prototype part fabrication. The material properties for PLA was adapted from [25] and [18]. The values of thermal conductivity and specific heat are temperature dependent and the density values are temperature independent. Table 1 shows the physical, thermal properties and the operating conditions of PLA used for the simulation.

Table 1. Properties of PLA used for simulation.

| Characteristics                   | Unit          | Value  |
|-----------------------------------|---------------|--------|
| Density                           | kg m\(^{-3}\) | 1252   |
| Thermal Conductivity              | W m\(^{-1}\) °C\(^{-1}\) |        |
| 190 °C                            |               | 0.195  |
| 109 °C                            |               | 0.197  |
| 48 °C                             | °C            | 0.111  |
| Specific Heat (C\(_p\))           | J kg\(^{-1}\) °C\(^{-1}\) |        |
| 190 °C                            |               | 2060   |
| 100 °C                            |               | 1955   |
| 55 °C                             |               | 1590   |
| Print Temperature                 | °C            | 190    |
| Build Plate Temperature           | °C            | 60     |
| Ambient Temperature               | °C            | 22     |
| Glass Transition Temperature (T\(_g\)) | °C       | 65     |

3. Simulation results and validation

3.1. Thermal simulation

The overall thermal simulation was carried out for a total time period of 22.5 seconds. The time period was calculated based on the time required to print the part at a nozzle speed of 50 mm/s. A time step of 0.3 seconds for each load step was simulated. Figure 3 (a) and (b) shows the front view temperature distribution of the fabricated PLA part and the heated bed at the first layer and the final layer (10 mm) respectively. The temperature distribution is observed to replicate the actual material deposition process. It is also observed that the heated bed has a minimum effect on the temperature distribution of the fabricated part. This condition is observed since the heated bed is of high density and mass compared to the printed part. The heated bed almost maintains the room temperature during the simulation process. This effect is in agreement with the similar phenomenon observed by Zhou et al. [16]. The final time step shows three distinct layers: the heated bed at 60°C, the bottom layers cooled down to room temperature of 22°C and the last few layers above the glass transition temperature. The temperature distribution is such that the temperature reduces from the bottom layer towards the middle layers of the part and the last layer will have the deposition temperature.
Figure 3. Temperature distribution during the FDM simulation of PLA (Front View), 3 (a) at 0.9 seconds after the deposition of first layer; 3 (b) at 22.5 seconds after the deposition of last layer.

The key parameter observed in the simulation is the Diffusion Time \( t_{\text{diff}} \). Diffusion time is the time taken for the deposited filament to reach the glass transition temperature from the deposited temperature. This factor determines the bonding quality between the layers and in turn the part strength. Figure 4 shows the temperature distribution comparison curves for the first ten layers for the PLA part simulation. From the chart, the average diffusion time was found to be 4.89 seconds. The calculated value is compared with the analytical \( t_{\text{diff}} \) value of 5.27 calculated by Li et al. for the parts fabricated with different process parameters [26]. The values agree with variation of 7.2 %. The comparison shows that the developed thermal model can be used for the simulation of 3D FDM part fabrication process.

Figure 4. Temperature distribution comparison curves for the first ten layers of PLA.

3.2. Structural simulation
The structural simulation was carried out with the base of first layer fixed to the heated bed. The thermal load from the thermal simulation was used as input to the structural simulation. The maximum principal stress and the deformation in X and Y directions were measured from the simulation and compared with the samples printed. Three samples of PLA slabs of same dimensions as the simulation model were printed using INSTA3D FDM printer. The nozzle temperature was maintained at 190°C. The bed temperature was maintained at the recommended temperature of 60°C. All the three samples
are printed with same process parameters and filament. Figure 5 shows the printed samples in comparison with a millimeter measurement scale.

![Figure 5. Samples of PLA slabs printed using INSTA3D FDM Printer.](image)

Figure 6 (a) and (b) show the deformation comparison in X-direction and Y-direction for the PLA samples. The deformation in X-direction is maximum at the top edge showing similarity with the simulation results. Sagging effect is observed in the Y-direction as the part is built layer by layer. The simulation shows similar sagging effect in the Y-direction. The sagging may be attributed to the cooling effect of the bottom layers causing the middle layers to fall in the Y-direction during layer deposition.

![Figure 6. Deformation comparison between simulation and printed parts, 6 (a) in X-Direction; 6 (b) in Y-Direction.](image)

4. Future outlook
The thermo-mechanical model was developed considering the effects of temperature, convection and radiation during the FDM process. The developed framework was proved to be applicable for a simple slab geometry. The model can be further extended for full complex part simulations which has support structures with the understanding of temperature distribution. The current work did not involve the study of adhesion effects between the printed layers, factors such as change in nozzle temperature, infill pattern and the number of walls in the fabricated part. The parametrical study still needs addressing with intensive theoretical and experimental investigations. Further the model can be improved with the inclusion of voids in the deposited filament material.

5. Conclusions
In this research, the thermal behavior of the FDM process was modelled and simulated numerically using ANSYS R19.2; diffusion time, maximum thermal stress and distortion parameters were evaluated. The model demonstrated the applicability of the element birth and death effects to simulate the FDM material deposition process. The developed FDM model can predict the diffusion time with a
bias of 7.2% which is comparable with the results available in literature. The simulation results revealed the following characteristics regarding the simulation of FDM process:

- The element birth and death technique can be used for the simulation of FDM process.
- The effects of radiation should be considered during the thermal simulation.
- The temperature comparison of the deposited layers show that the diffusion time plays an important role in the thermal behavior of the material deposition.
- Sagging effect is observed when the part is printed as single layer thin walls.

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