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# Simulation on Influence of Environmental Conditions on Part Distortion in Fused Deposition Modelling

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***Abstract*****—**Fused Deposition Modelling (FDM) is one of the additive manufacturing techniques that has become highly attractive in the industrial and academic sectors. However, parts fabricated through FDM are highly susceptible to geometrical defects such as warpage, shrinkage, and delamination that can severely affect their function. Among the thermoplastic polymer feedstock for FDM, semi-crystalline polymers are highly prone to part distortion due to polymer crystallization. In this study, the influence of FDM processing conditions such as chamber temperature and print bed temperature on the induced thermal residual stress and resulting warpage are investigated using 3D transient thermal model for a semi-crystalline polymer. The thermo-mechanical properties and the viscoelasticity of the polymer, as well as the crystallization physics which considers the crystallinity of the polymer, are coupled with the evolving temperature gradient of the print model. From the results it was observed that increasing the chamber temperature from 25 °C to 75 °C leads to a decrease of 3.3% residual stress and increase of 0.4% warpage, while decreasing bed temperature from 100 °C to 60 °C resulted in 27% increase in residual stress and a significant rise of 137% in warpage. The simulated warpage data are validated by comparing it with the measured warpage values of the samples using 3D scanning.

***Keywords*****—**Finite Element Analysis, FEA, Fused Deposition Modelling, residual stress, warpage.

## I. Introduction

FDM is one of the additive manufacturing (AM) technologies that can 3D print thermoplastic polymers effectively. Due to their anisotropic nature of semi-crystalline polymers and the non-homogenous printing conditions in FDM, the printed part results in part distortion severely affecting the function of the printed part [1]. Although these challenges are partly influenced by the printing conditions in FDM, the crystallisation morphology of the semi-crystalline polymers is also a driving factor towards part distortion.

Researchers have identified various printing parameters in FDM that can highly affect shrinkage and warpage [2], [3]. However, in the literature, it can be found that processing conditions such as bed temperature and ambient temperature are ignored or reported with converse results. Even though, previously there are studies that have reported that increasing ambient temperature improves bonding between the deposited roads and layers, there are reported conversely [2]. Among the processing conditions in FDM, bed temperature is one of the least focused parameters. This paper aims to investigate the effect of ambient temperature and print bed temperature towards part distortion. The predicted warpage values of the models through the FEA simulation were validated by the measured 3D scanned values of the experimentally printed parts.

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## II. Printing Parameters

Polypropylene has been selected as the material of study with the printing conditions as follows: melting temperature 210 °C, nozzle speed 30 mm/s, infill 100%, raster pattern line (90°/90°) and layer thickness 0.5 mm. Due to the complexity of the simulation, sample with dimensions 50*50*2 mm were simulated and printed. Table I shows the varying printing conditions between the samples of the study. Based on their varying printing conditions, the samples are referred to as bed sample and amb sample, while reference sample is mentioned as ref sample throughout the study. The printing of the samples was carried out in modified Ultimaker 2 under their respective printing conditions.

TABLE I
Processing Conditions of PP

| Sample | Ambient temperature (°C) | Print bed temperature (°C) |
|---|---|---|
| Ref sample | 25 | 100 |
| Amb sample | 75 | 100 |
| Bed sample | 25 | 60 |

## III. Modelling

The developed simulation model consists of solid mechanics, heat transfer and crystallisation kinetics physics. Through the solid mechanics physics, in-house developed tool path program, the effect of gravity on the deposited melt and activation and de-activation of the elements with respect to their material deposition were defined to the model. To simplify the model's contact with the print bed, spring foundation boundary condition was used while maintaining the print bed at constant temperature throughout the printing process [4]. Here, application of spring foundation enables to model to warp while it is being cooled for studying the part distortion behaviour. Since the material properties of semi-crystalline polymer are highly thermal dependent, the thermo-mechanical properties ($\lambda$ thermal conductivity, $\rho$ density and $C_p$ specific heat capacity) of the material of study were coupled with respect to the evolving temperature of the model [5]. The viscoelastic nature of the polymer was considered through shift factor function and Generalised Maxwell model. For crystallisation, the crystallisation kinetics model that was developed by Levy [6] was modified using the kinetics model that was proposed by Nakamura as follows [7]:

$$K(T)=\left(\frac{4}{3}\pi N_o(T)\right)^{\frac{1}{3}} G_o * \exp\left(-\frac{U^*}{R(T-T_\infty)}\right)\exp\left(-\frac{K_g}{T(T_f-T)}\right) \quad (1)$$

The DSC values of parameters in K(T) from Koscher [7] are listed as:

$$N_0(T)=\exp\left(0.156*(T_f-T)+15.1\right) \quad (2)$$

$G_0 = 2.83*10^2$, Kg = 5.5*105($K^2$), U* = 6284 J/mol.K, R is the gas constant, $T_f$ = 210°C, $T_\infty$ = $T_g$-30°C, $T_g$=-10°C, ΔH = $90*10^3$J/kg and n = 3. Nakamura kinetic is widely used for simulating the semi-crystalline polymers behaviour.

## IV. Results and Discussion

In order to investigate the effect of the selected printing conditions on part distortion, an element was selected from the top layer of the printed/simulated samples from the infill at co-ordinates (7.8 mm, 2.1 mm, and 1.5 mm). This element is referred as element m throughout the study.

### *A. Temperature vs. Printing Time*

The printing conditions of FDM process highly influence the temperature gradient of the printed part [3]. In Fig. 1, the temperature distribution of element m from top layer of ref, amb and bed sample after the deposition has been plotted against the overall printing time in order to exhibit the impact of the effect of the printing conditions in this study.

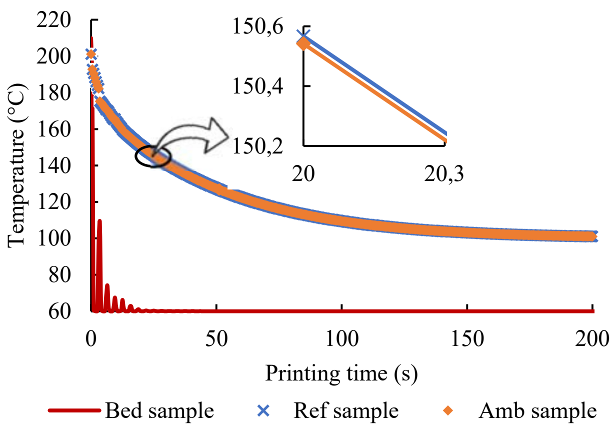


Fig. 1 Overall cooling of element m (top layer) after deposition in ref, amb, and bed sample. An inset plot is presented to show the difference in the cooling curve between sample ref and amb is magnified at 20 s of their print time

From Fig. 1 (inset plot), it can be noted that increasing in ambient temperature from 25 °C to 75 °C slows down the cooling curve of the sample. Increasing the ambient temperature in sample amb will allow the temperature transitioning of the deposited roads to be gradual and slow down the cooling rate of the sample. As a result, the polymer molecules in the semi-crystalline polymer achieve higher molecular orientation compared to sample ref [8]. However, the decrease in cooling rate is not significant as in sample amb, the increase in ambient temperature (75 °C) is still well below the crystallization temperature of the deposited polymer. Due to this, no significant variation in the cooling curve between sample ref and amb is observed while on the other hand, the temperature profile of element m in bed sample from Fig. 1 appears to be significantly affected by the print bed temperature in comparison with the other samples. In bed sample, the print bed temperature was maintained at 60 °C, while in other samples it was maintained at 100 °C. Therefore, in bed sample, when the polymer melt was deposited, the temperature of the melt from 210 °C is forced to cool rapidly due to the ambient temperature (25 °C) and the print bed temperature (60 °C). In bed sample, during the initial stage of cooling, prominent peaks are noticed on comparison to the other samples. This is because, when element m is deposited, the temperature distribution from the neighbouring roads affects the cooling curve of element m by reheating, leading to increase in the temperature profile (which can be seen as peaks in Fig. 1). During the reheating process, based on the thermal inertia received by the deposited roads/layers, the polymer molecules undergo re-crystallisation and cold crystallisation. As semi-crystalline polymers are poor thermal conductors [9], as the layers of the printed sample increases, the temperature from the newly deposited layer does not entirely reach and reheat the subjacent deposited layers leading to cold crystallisation. As depicted from Fig. 1, element m in bed sample is reheated by the neighbouring roads considerably compared to the reheating effect received by the element m in sample ref and amb. In other words, these prominent peaks are not observed in samples ref and amb. In these samples, as element m is deposited, the temperature history of the roads is slow and gradual as the deposition progresses, thus representing a smooth transitioning curve.

### *B. Residual Stress vs Printing Time*

In FDM, as aforementioned due to the non-homogeneous thermal conditions, the printed layers of the FDM part develop internal thermal residual stresses [10]. These stresses are trapped and stockpiled continuously when the parts are cooled leading to part distortion and mechanical failure of the part. Fig. 2 represents the residual stress profile accumulated and released by element m as the printing process progresses.

In this study, when element m (fourth layer) is deposited at 210 °C on the third layer of the sample (which is being cooled), due to the temperature difference, element m cools rapidly from the outside while the core of the melt still retains the heat. Thus, leading to the continuous increase and accumulation of thermal residual stresses represented as peaks in all the samples in Fig. 2.

In Fig. 2, even though the residual stress profile of samples ref and amb originate from the same value, with the printing time it is evident that increase in ambient temperature reduces the in-built residual stress. As explained in Section V *A*., increase in ambient temperature decreases the cooling rate of the sample, allowing the temperature distribution of the part gradually slower. It has been reported by other researchers in literature that increase in ambient temperature has demonstrated in decrease in residual stress of the printed sample [3], [11]. In the present study, increasing ambient temperature from 25 °C to 75 °C has resulted in a 3.3% drop in the built-in residual stress whereas, decreasing bed temperature from 100 °C to 60 °C has shown a significant increase in residual stress of 27%. This is mainly because, in bed sample the print bed was maintained at 60 °C throughout the printing process. Here, when element m was deposited on the third layer, due to the low print bed temperature, the deposited layers are already forced to cool to the print bed temperature. Therefore, due to this temperature difference although the bed sample illustrates a peak during its the initial printing time, the displayed prominent peak is very narrow compared to the peak observed from the other samples. Additionally, the stress peak observed from the bed sample shows smaller peaks which are seen due to the stress built from the neighbouring roads.

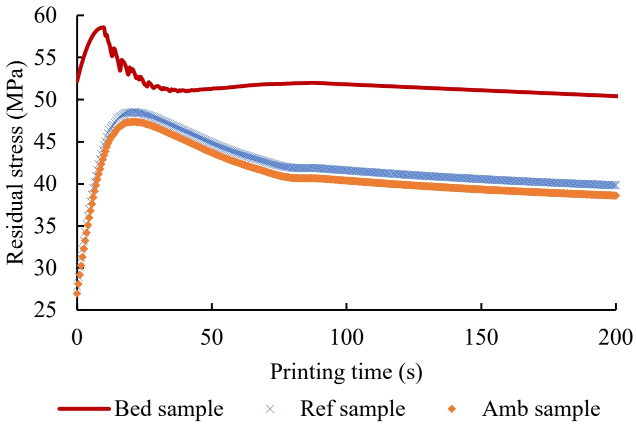


Fig. 2 Built-in residual stress of element m from ref, amb and bed sample plotted against the overall printing time

### *C. Warpage vs Printing Time*

Increasing and continuous accumulation of thermal stress in the FDM printed parts results in warpage [12]. Fig. 3 displays the warpage of element m from sample ref, amb and bed plotted against their printing time.

The warpage trend of element m of the samples in Fig. 3 appears to be flat in the initial stage followed by a gradual increase. The polymer chains in semi-crystalline polymers begin to crystallise once the temperature falls below the crystallisation temperature of the polymer (160 °C in this case for PP). The gradual increase in the warpage trend is observed when the crystallisation occurs in the samples in Fig. 3. Despite of increasing the ambient temperature from 25 °C to 75 °C, amb sample warpage trend depicts no apparent changes. Sample amb has shown 0.4% increase in warpage on comparison with ref sample.

Increasing ambient temperature decreases the cooling rate of the sample allowing the polymer to crystallise slower compared to ref sample. Here, warpage observed in sample amb is influenced drastically by the high molecular crystallisation achieved by the polymer chains over the residual stress [2]. However, from Fig. 3 it can be noted that bed sample exhibits the highest warpage among all the samples. The warpage profile observed from bed sample is driven due to the developed internal thermal residual stresses seen in Section V *B*. Conversely to amb sample, the polymer chains in bed sample are frozen and forced to reach low molecular orientation due to the rapid cooling of the polymer melt, thus illustrating a significant increase of 137% in warpage.

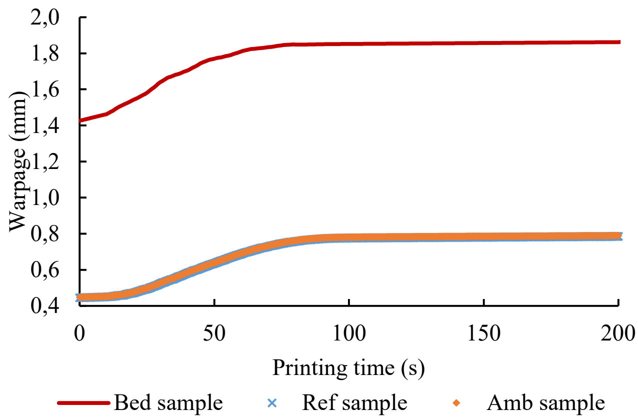


Fig. 3 Element m warpage from ref, amb and bed sample plotted against their overall printing time

### *D. Final Residual Stress vs. Overall Warpage*

The accumulated thermal stress directly influences the resulting warpage of the parts printed in FDM. Fig. 4 shows the relationship between the final residual stress towards the resulting overall warpage of the samples with respect to their printing condition.

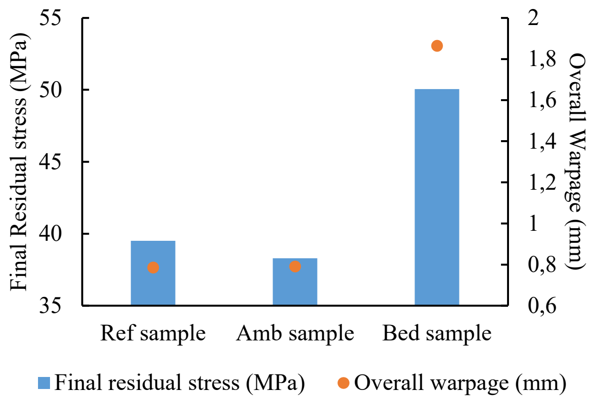


Fig. 4 Final residual stress of element m from ref, amb and bed sample against the overall warpage with respect to their printing condition

From Fig. 4, it is apparent that the residual stress accumulated in FDM parts are directly in relation with the resulting warpage. The residual stress noted from amb sample is evidently less (3.3%) than the stress noted from ref sample. While the warpage is not noticeable, amb sample has showed a 0.4% increase in warpage. Between these two samples, ascribed in the above sections, increasing ambient temperature increases the degree of crystallisation of the polymers leading to increase in warpage despite of the decrease in stress. Furthermore, the relationship between residual stress and warpage can be seen more clearly in bed sample. Compared to the other samples, bed sample residual stress and warpage show a significant increase due to the low print bed temperature (60 °C). Here, the increased residual stress of the sample subsequently leads to increase in warpage due to the rapid cooling of the polymer resulting in an increase of 27% residual stress and 137% rise in warpage.

### *E.Experimental Validation*

The predicted warpage results from the developed model through the simulation was validated by comparing the obtained results with the 3D scan measured values.

TABLE II
3D SCANNED VALUES OF THE EXPERIMENTALLY PRINTED PARTS

| Samples | FEA Predicted Warpage (mm) | 3D scan measured warpage value (mm) | Deviation (%) |
|---|---|---|---|
| Ref sample | 0.787 | 0.80 | +1.7 |
| Bed sample | 1.86 | 1.98 | +6.5 |

It can be seen that the developed model predicts the warpage of the simulated printing conditions with the deviation of less than 6.5%.

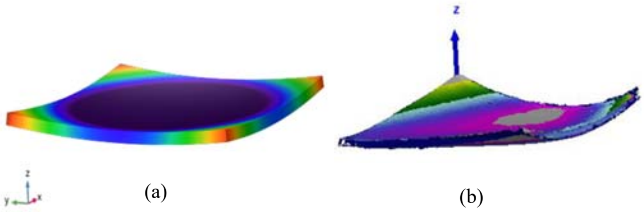


Fig. 5 Comparison of the simulated and 3D scanned warpage of bed sample

Fig. 5 represents the comparison between the simulated and the 3D scanned measured warpage of bed sample. It can be noted that in both Figs. 5 (a) and (b), the warpage is observed is significantly higher in the corners due to the decreased print bed temperature.

## V.CONCLUSION

In the presented transient 3D thermal study, influence of printing conditions such as print bed temperature and ambient temperature on part distortion was investigated. The developed model has considered viscoelasticity, crystallinity, and the thermal dependency of the material properties of the polymer. Furthermore, an in-house developed tool path program was incorporated with the element activation and de-activation technique.

From the study, it can be concluded that, increasing ambient temperature decreases the cooling rate of the sample and reduces the internal residual stress. But it can result in increase in warpage of the printed part. While on the other hand, bed temperature should be maintained closer to the crystallisation temperature of the semi-crystalline polymer. Lower print bed temperature can lead to significant increase in thermal stresses and drastic increase in the resulting warpage.

## ACKNOWLEDGMENT

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