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Thermo-mechanical model for a selective thermoplastic electrophotographic process for dimensional defects

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Abstract
Additive manufacturing is a revolutionary method that relieves industries from the geometrical restrictions of their products. In this area, the Selective thermoplastic electrophotographic process (STEP) is a breakthrough approach that can obtain fast and high-volume production. Despite the STEP's excellent characteristics and achievements, the final products present dimensional defects which significantly impact their mechanical qualities. This study presents a prediction model of deformation behaviour by a finite element-based thermo-mechanical model. Additionally, a dimensional study was conducted on various STEP manufactures products. The work presents an analysis of the results of the dimensional measurements, highlighting the position of the products on the building plate. The dimensional evaluation of the STEP's products supports the thermo-mechanical model results.

Additive manufacturing, thermo-mechanical model, dimensional defects, selective thermoplastic electrophotographic process

1. Introduction

Selective thermoplastic electrophotographic process (STEP) is a novel additive manufacturing process. It is a brand-new polymer-based additive manufacturing method introduced by Evolve Additive Solutions, Inc. This new technology might be invaluable addition to injection moulding production by producing completely dense, multi-material. The STEP technology is mainly composed of two fundamental modules, electrophotographic and transfusion modules. The manufacture occurs by fusing 2D layers created by the electrophotographic module into a 3D structure. STEP's 2D-to-3D deposition method involves heating both the incoming 2D layer and the component's structure. Next, the incoming 2D layer is fused to the final component using pressure. Finally, the transfusion module is used for deposition.

Some research in the STEP machine for process digitalization, such as multiphysics modelling, data analysis, sensorics collecting and fingerprints, supports its exploration, comprehension and optimization. Based on the knowledge, the finished product was determined to have dimensional faults that may be connected to the transfusion module of the system and negatively affect its mechanical properties.

This paper proposes a thermomechanical model using finite elements that predicts the behaviour of deformation [1], [2], [3]. The model incorporates multi-material samples consisting of component and support material, bringing the model closer to the actual printing process. Moreover, the model simulations are calibrated using measurement data in order to provide an accurate depiction of defects. Using a 3D scanner, the three dimensions of the printed products obtained from the STEP process are measured and recorded. A brief statistical analysis of these results will be provided, highlighting various defects along the three dimensions.

2. Methodology

2.1. Simulation

In this work, the finite element method (FEM) is used to simulate the deformation of printing samples shown in Figure 1. Based on the knowledge of the STEP machine, the defect is induced by the pressure and heat in the transfusion module could be concluded. The simulation follows the actual manufacturing sequence, i.e., idle, pre-heating, transfusion, and cooling. Afterward, the printed build is detached from the machine and cooled to room temperature.

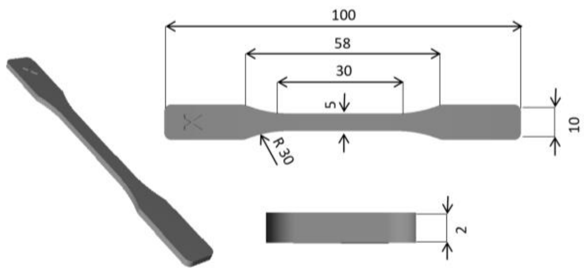

Figure 1. Dimensions of ISO 527 type 1BA sample

The model consists of heat transfer and mechanics theories. Regarding the thermal part, heat conduction, convection, and radiation shown in Equation (1) and Equation (2) are taken into account.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \rho \Delta H_{met}\frac{\partial r_{liq}}{\partial T} + \dot{Q}''' \quad (1)$$

It's worthy mention that $\rho \Delta H_{met}\frac{\partial r_{liq}}{\partial T}$ represents the energy caused by melting and solidification.

$$-k\frac{\partial T}{\partial z} = h_{amb}[T - T_{amb}] + \varepsilon\eta[T^4 - T_{amb}^4] \quad (2)$$

Equation (3) of the mechanical model uses Hooke's general rule to calculate stress, strain, and deformation.

$$\sigma_{ij} = \frac{E}{1+v}\left[\frac{1}{2}\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right) + \frac{v}{1-2v}\delta_{ij}\delta_{kl}\right] e_{kl}^{el} \quad (3)$$

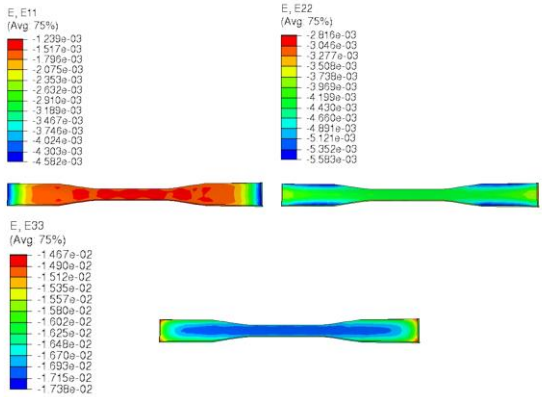

Figure 2. Simulated strain in three directions

For the thermal model, the simulation was validated with the thermal cameras mounted on the machine and the predictive thermal profile was consistent with the sensorics. The printed tensile test samples were used for the validation of the mechanical part of the model, see Section 3.

2.2. Sample measurement data

To investigate the dimensional flaw, the study considered eight batches of seven products each for a total of 56 products. Subsequently, the products were cleaned by removing the support material and measured using a 3D scanner, ATOS ScanBox.

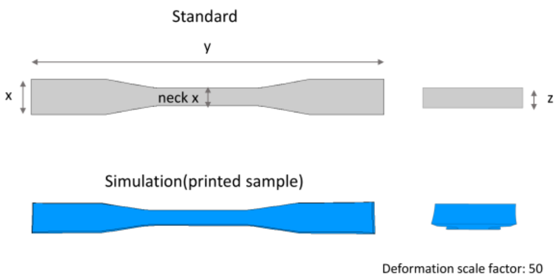

Figure 3. Standard sample vs. printed sample by simulation

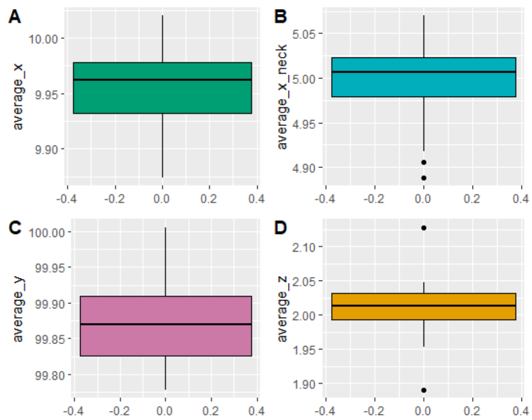

Figure 4. Measurement result for all the dimensions of the STEP's produced products. Figure A: boxplot related to the measurements along the x axis. Figure B: boxplot of the measurements along the $neck\ x$ axis. Figure C: boxplot of the measurements along the y axis. Figure D: boxplot of the measurements along the z axis.

Multiple measurements were collected along the x, y and z axes, as depicted in Figure 3. One measurement was taken along the y-axis, 18 measurements were taken at various positions along the z-axis, and 15 measurements were taken along the x-axis, including 5 for the neck area. In Figure 4 are collected the measurement of the dimensions along the three axes of the printed products. Consequently, these measurements are compared to the one of the thermo-mechanical models.

3. Result and discussion

Based on the process thermo-mechanical model, we get the dimensions of the printed sample and compare them with the original CAD file. The 3-dimensional defects could be calculated as shown in Figure 2. In Table 1 are collected the original measurements, model results and STEP's products analysis results. In order to make the dimensions defects more visible, we apply scale factor 50 to the deformation. Furthermore, Figure 2 shows the nonuniform strain distribution. It indicates that two ends of the sample have higher contraction ratios in the x and y directions. On the other hand, the middle part of sample contracts more in the z direction than the others.

Table 1. Dimensions of sample for ISO standard, simulation, and measurement

Dimensions	Nominal (mm)	Simulation (mm)	Measurement mean (mm)	Measurement std dev (mm)
x	10	9.96	9.95	0.0387
neck x	5	4.97	4.998	0.0388
y	100	99.82	99.87	0.0578
z	2	1.97	2.01	0.0441

According to Table 1, the simulated printed dimensions closely match the average STEP's measurement result. Based on the simulation, the dimensions defects are because of the thermal-induced residual stress. Besides, the residual stress may cause other defects as well, e.g., warpage. The connection between manufacturing parameters and the quality of products could be obtained and the study also provides an opportunity for product optimization to fit the desired tolerance 10 to 20 microns. Therefore, the optimal temperature of the process will be our next goal.

4. Conclusion

The paper suggests a thermo-mechanical numerical model for the STEP transfusion module that is preliminary verified using part quality measurement to better examine the procedure and enhance the quality of the final result. In this research, a thorough manufacturing parametric investigation is also offered. With the help of this modelling strategy, a reliable digital twin of the STEP process could be created and afterwards incorporated into the STEP process itself, acting as a source of feedback for real-time adjustment of the input process parameters to produce a defect-free final product.

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