10th Brazilian Congress on Manufacturing Engineering
August 05th-07th, 2019, São Carlos, SP, Brazil

SHAPE DISTORTION OF FUSED DEPOSITION MODELING PARTS EVALUATED BY FINITE ELEMENT ANALYSES

Sérgio Henrique Evangelista
Alexandre Tácito Malavolta
Mariano Eduardo Moreno
José Benaque Rubert
Universidade Federal de São Carlos – UFSCar – Departamento de Engenharia Mecânica - Rod. Washington Luís, km 235 - São Carlos - SP - Brazil - CEP 13.565-905.
toddyprof@ufscar.br, malavolta@ufscar.br, mmoreno@ufscar.br, benaque@ufscar.br

Abstract. *Additive manufacturing (AM), popularly embracing expressions such as 3D printing, has become an important process to create components or prototypes before final release to commercialization or even to create a final functional product. A popular AM method is the Fused Deposition Modeling (FDM), a material extrusion technology which is characterized by a pre-heating that increases the material temperature to its melting point so that it can be extruded through a nozzle in a controlled manner. An important design consideration when using FDM is to account for the macroscopic mechanical behavior of the final printed part, e.g., its geometric distortion. In this context, it is investigated the problem of geometric distortion of a specimen made of acrylonitrile butadiene styrene (ABS), an AM material which is a common thermoplastic polymer used in FDM processes. The procedure is based on a sequential set of uncoupled thermal and thermomechanical finite element analyses (FEA) combined to an element birth-and-death strategy available in the software ANSYS®. The problem is analyzed under several loading and boundary conditions in order to evaluate the progressive effect of residual stresses accumulated from previously deposited material. The obtained results are discussed and compared with analytical and numerical data presented by other researchers. This investigation shows that the proposed tool can evaluate the distortion in terms of geometric shape pattern, while the critical displacement values are quite different from the experimental data. Despite of that and compared to other authors, over than 80% reduction on the processing time is possible with this approach.*

Keywords: *Additive Manufacturing, FDM, FEA, Shape Distortion, Thermo-mechanical analyses.*

1. INTRODUCTION

Additive manufacturing (AM) has become an important process to rapidly create components before final release to commercialization or even to create final functional products. According to Gibson, *et al*. (2015) there are many ways to classify the additive manufacturing technologies. The classification for single step additive manufacturing processes applied to polymers is reproduced in Fig. 1. A complete overview of additive manufacturing processes is standardized by references as ISO/ASTM 52900(E) (2015).

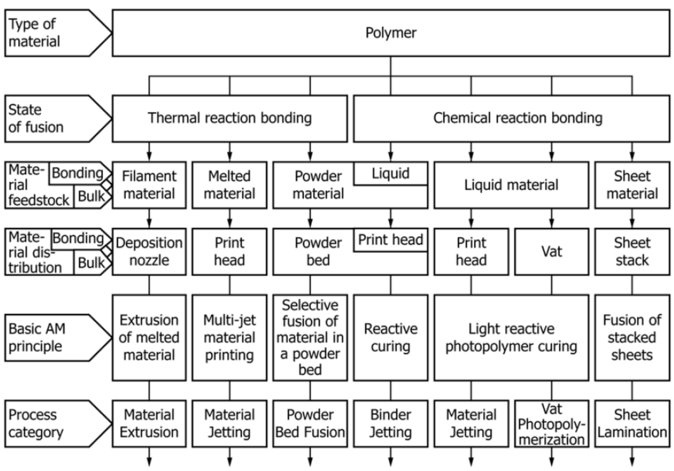

Figure 1. Single step Additive Manufacturing processes for polymers ISO/ASTM 52900(E) (2015).

The heated filament-based materials are characterized by a pre-heating that increases the material temperature to its melting point so that it can be extruded through a nozzle in a controlled manner. A common method of heated filament-based materials is the Fused Deposition Modeling (FDM) material extrusion technology.

An important design consideration when using FDM is to account for the distortion behavior of the final printed part. This problem is mainly originated due to the residual stress resulting from the thermal gradients during the heating and cooling phases of the deposited material.

Many authors have studied the distortion problem in FDM components. Wang, *et al.* (2007) proposed a mathematical model to predict the warp deformation in FDM process and evaluated the main influencing factors including the number of deposition layers, the stacking section length, the chamber temperature and the material linear shrinkage rate. Zhang and Chou (2007) showed a kind of finite element model using element activations to simulate the mechanical and thermal phenomena in FDM to predict the distortion due to residual stresses considering different tool-path patterns. The numerical results are compared with experimental measures of prototypes and the main conclusions suggest that the FDM parts are sensitive to the tool-path pattern. Recently, Li, *et al*. (2018) investigated the distortion of polylactic acid (PLA) specimens by using a bilinear elastic-softening cohesive model. Their experimental procedure aimed to validate the theoretical residual models and the respective results indicated that the layer thickness is dominant in determining the distortion compared with deposition velocity. Yang and Zhang (2018) studied the temperature and stress field on FDM process by using a finite element model with the technology of “birth-death element” to describe the distribution and change of temperature and stress fields for four different scanning filling paths. The results show that the most uniform stress distribution and the smallest deformation are associated with honeycomb scanning filling path.

In this context, the main purpose of this study is to investigate the distortion behavior of an ABS (acrylonitrile butadiene styrene) thin plate on the FDM process by considering a specific tool deposition path. A finite element model has been developed in order to evaluate its thermal and mechanical influences as an uncoupled set of analyses. The proposed study is focused on a simplified model to predict the distortion behavior in a reduced computer processing time when compared to the above cited authors whose experimental results are used to compare and validate the proposed approach.

2. METHODOLOGY

The proposed approach uses techniques of birth and death of elements and a combination of structural and thermal analyses arranged in such a way to represent the material deposition rate following a predetermined path according with typical values for FDM processes using ABS as deposition material. The mechanical and thermal properties of ABS are summarized in Tab. 1, whose values were adapted from Zhang and Chou (2007) for further results analyses.

Table 1. Structural and thermal properties for ABS, according to Zhang and Chou (2007).

Properties	Unit	ABS values
Young’s Modulus	GPa	2.4
Poisson Ration	-	0.4
Density	kg/m^3	1200
Thermal Expansion Coefficient	μm/(m.K)	80
Heat conductivity	W/(m.K)	0.19
Specific heat capacity (from 20°C to 280°C)	J/(kg.K)	1620
Melt temperature	°C	280

The hypotheses for this study are that the filling rate is 100% and that the continuous deposition of material can be represented by a sequence of 8-node brick elements aligned according to the desired deposition path. No degradation of properties will be considered in order to compensate such hypothesis. In this preliminary study the shrinkage that occurs due the ABS cure will be neglected, despite of the fact that some possible consequences will be discussed later.

The analyzed subject is a plate discretized with 40 elements (40 mm length) by 10 elements (10 mm width) by 4 layers (1.016 mm thickness for each layer). In the studied case the deposition is performed continuously, mainly according to the width direction with parallel tracks forming a base layer, going up and forming a second layer and so on successively. Parallel track deposition is performed on each layer for the short raster case as shown in Fig. 2. On the next layer the same deposition path is followed in an inverse way.

The FEA mesh is created in the software ANSYS® by considering the full part and then the commands of birth and death of elements are used to simulate the deposition path. Initially all elements are in death condition. The first element is then set to birth condition and is carried out a sequence of uncoupled transient thermal analysis and structural analysis. The thermal analysis considers the cooling of the element from its melt temperature (280 °C) and applies as boundary condition the convection of 86 W/(m^2.K) to chamber ambient (75 °C) and a fixed temperature for the deposition table (75 °C). The structural analysis considers the temperature gradient as input and calculates the residual stresses with the imposition of zero displacement at the nodes that represent the base plate constraints. The second element is then set to birth condition and a new sequence of analyses is carried out with the results of previous analysis being imposed as an initial condition. The procedure is repeated element by element with the elements birth sequence being determined by the desired deposition path, already shown in Fig. 2. Once all the elements are active and the deposition simulation is finished there are still additional steps in order to accomplish for the reduction of the specimen temperature to room temperature and evaluate the distortion when releasing the specimen from the base table. A workflow for these FEA studies is presented in Fig. 3 as a brief description of tasks to be performed at each step.

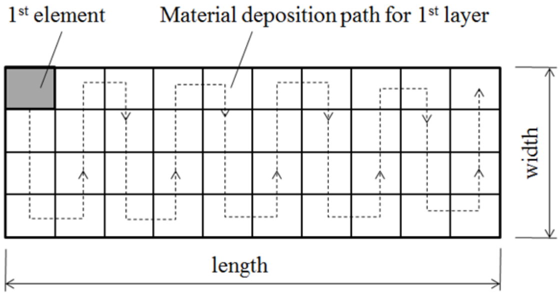

Figure 2. Analyzed deposition path.

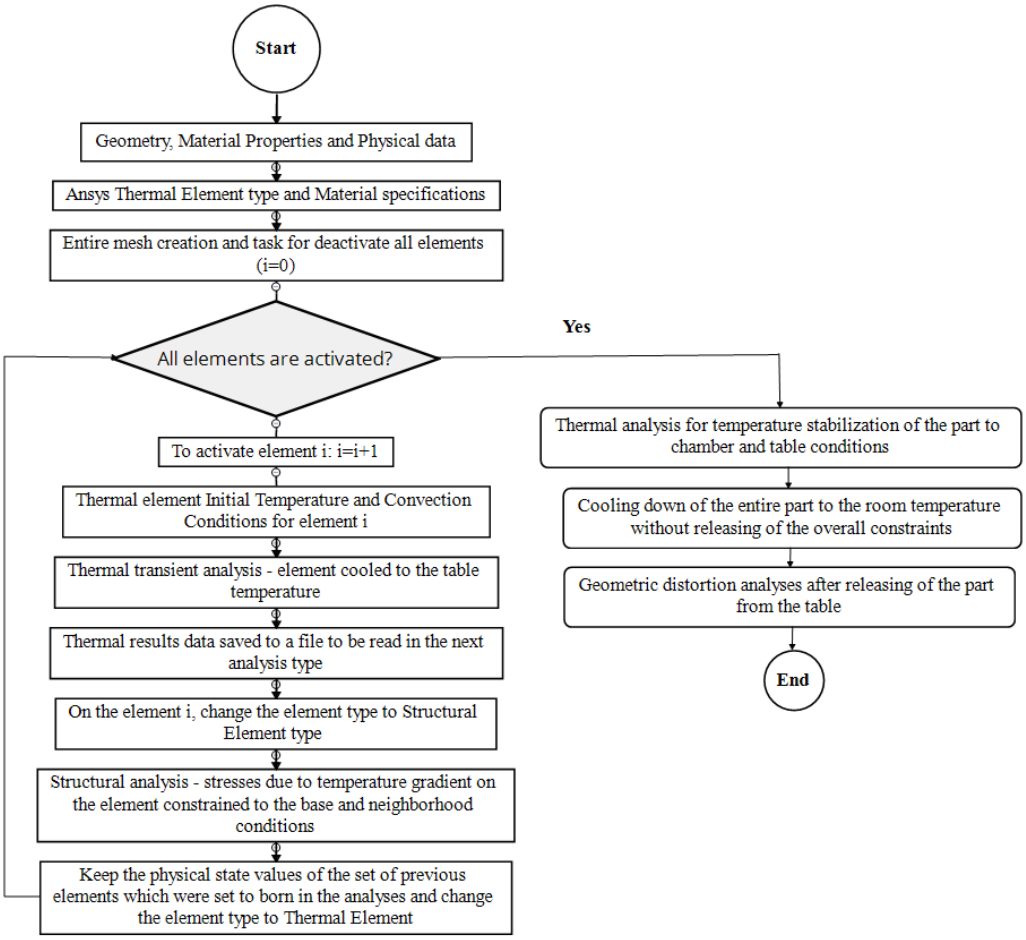

Figure 3. FEA analysis workflow for FDM thermo-structural simulation.

Other general conditions were established as proposed by Zhang and Chou (2007). However, all numerical simulations obeyed linear material behavior laws and were performed in a computer with an i7 processor and 16GB RAM using the academic license of Ansys®. The steps showed in Fig. 3 has been written as subroutines using APDL language (Ansys Parametric Design Language), so they can easily be altered to other similar geometries and paths in order to study their influence in this manufacturing process. The entire workflow comprises of more than 3200 FEA runs in approximately 300 minutes of total processing time.

The numerical results of interest are the displacements and shape distortion due to the uncoupled thermal and structural effects during the FDM process and some Zhang and Chou (2007) experimental results are used to verify the reliability of the proposed model and provide comparison pattern to guide further development.

3. RESULTS

Figure 4(a) shows the calculated results of out-of-plane displacements, according to the proposed methodology and Fig. 4(b) shows the experimental results obtained by Zhang and Chou (2007).

The final results from this methodology were calculated according to the step of geometric distortion analyses after releasing of the part from the table. It is important to consider that this final calculation step represents all previously mentioned effects for each iteration run, such as thermal cooling phenomena for each deposition, its thermo-mechanical effect and so in an interlaced manner. In a progressive fashion, the residual stresses evolved, which are responsible for the observed displacements after table releasing. For the sake of suitable comparisons, the constraints applied to the FEA model were set to represent the same constraints established by the authors for their experiments. Specifically, the zero-displacement reference was set to be the top left corner, as seen in the Fig. 4.

As it can be observed, the FEA results produced a similar fringe pattern as the experimental ones. The deviations from the linear diagonal pattern show up only near to the right tip of the part, as seen in Fig 4(a) and in Fig. 5, while in the experiments this type of curved deviation occurs on the most area of the printed part, as seen in Fig 4(b). The concavity produced by the distortion is better seen in Fig. 5 where the displacements are 10 times magnified for visualization purpose.

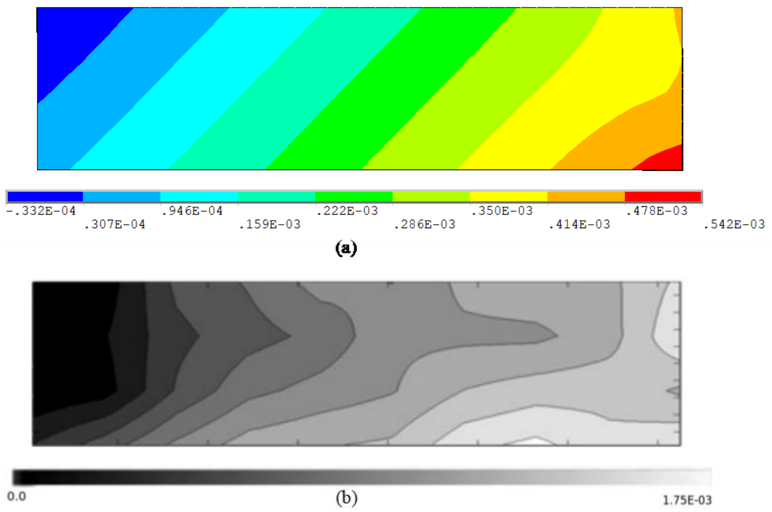

Figure 4. Out-of-plane displacement contour plots (units m): (a) FEA; (b) Experimental from Zhang and Chou (2007).

It is important to observe that the calculated displacement values are quite different from experiments, about 3.5 times lower. However, Zhang and Chou (2007) have reported similar inconsistencies between their numerical and experimental data and they credited this fact to limitations on the analyses, such as material behavior models, reliable boundary conditions and contact bonding. It must be emphasized that the adopted hypotheses in this work unfolded in a simplified analysis process when compared to the above cited authors, which permitted obtain a total processing time of

300 minutes in this work when compared to more than 35 hours in their work for the same geometry. However, they input some restrictions to consider the phase change for the material, which is a limitation for this study. Possibly, other limitations put some penalization on this work, such as a lack of any approach or data input for: material properties degradation, shrinkage effect and the initial printing for the external frame as a boundary for the overall print pattern. Nevertheless, it is considered that this investigation paved the way for future developments for this study, mainly as an orientation to consider every technical limitation for the model.

In order to verify the reliability for the proposed model, future experiments on AM parts shall be carried out to consider other deposition paths and different geometric aspects. Measurements on those tests must be planned to mitigate possible experimental errors and to permit a suitable description of distortion in terms of out of plane displacements. Moreover, a single theoretical sensibility analysis was performed to verify the distortion behavior of the part submitted to a melt point value of 240 °C, which is quite different from the value obtained from Zhang and Chou (2007) for this work. On the comparisons, a reduction of the modeled melt point from 280 °C to 240 °C implied in a reduction on the critical value of distortion, from 0.542 mm to 0.459 mm. This aspect confirms a linearized nature on the structure of the current model.

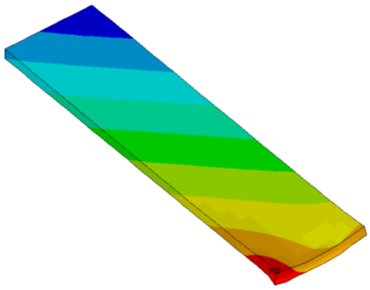

Figure 5. Geometrical distortion predicted by FEA analysis workflow.

For the sake of further investigations, the adopted simplifications of this work are underlined and rewritten to establish a new set of further studies: phase changing and shrinkage effect on the cured material, material properties as a function of temperature and other state variables, presence of voids and imperfections, the influence of boundary conditions from the printer table over the first printed layer, an improved model to represent the interlayer attachments, the modeling of an external deposited frame and other aspects.

4. CONCLUSIONS

It was evaluated the shape distortion in a component manufactured by FDM processes. A case study identified as short raster was successful to describe the distortion form and aspect by considering the out-of-plane displacements. However, the obtained displacement magnitudes were in disagreement with the experimental results used as validation parameter. Nevertheless, a reduction of more than 80% on the computer processing time was obtained on this linearized approach. A trade-off analysis may be useful for the cases when quick predictions of the overall distortion are needed in order to orient the process planning for new printed parts.

These conclusions point to further model and experimental tasks that are being implemented in order to achieve significant improvements on the strategies to simulate the parts behavior obtained by additive manufacturing processes.

5. REFERENCES

International Organization for Standardization / American Society for Testing and Materials, 2015. *ISO/ASTM 52900(E)*: Standard Terminology for Additive Manufacturing: General Principles: Terminology. Geneva (Switzerland): West Conshohocken (US), 9 p.

Gibson, I., Rosen, D. and Stucker, B., 2015. *Additive Manufacturing Technologies: 3D printing, rapid prototyping, and direct digital manufacturing*, Springer, New York, 2nd edition.

Li, H., Wang, T., Li, Q., Yu, Z. and Wang, N., 2018. “A quantitative investigation of distortion of polylactic acid/PLA part in FDM from the point of interface residual stress”. *International Journal of Advanced Manufacturing Technology*, Vol. 94, p. 381-395.

Yang, H. and Zhang, S., 2018. “Numerical simulation of temperature field and stress field in fused deposition modeling”. *Journal of Mechanical Science and Technology*, Vol. 32, p. 3337-3344.

Zhang, Y. and Chou, Y.K., 2006. “Three-dimensional finite element analysis simulations of the fused deposition modelling process”. *Journal of Engineering Manufacture, Proceedings of the Institution of Mechanical Engineers Part B*, Vol. 220, p. 1663-1671.

Zhang, Y. and Chou, Y.K., 2007. “A parametric study of part distortions in fused deposition modelling using three-dimensional finite element analysis”. *Journal of Engineering Manufacture, Proceedings of the Institution of Mechanical Engineers Part B*, Vol. 222, p. 959-967.

Wang, T.M.., Xi, J.T. and Jin, Y., 2007. “A model research for prototype warp deformation in the FDM process”. *International Journal of Advanced Manufacturing Technology*, Vol. 33, p. 1087-1096.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.