MULTI-SCALE MODELING OF ADDITIVE MANUFACTURING: FROM PROCESS SIMULATION TO DESIGN VALIDATION

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Abstract

Additive Manufacturing of polymers is transitioning from rapid prototyping to a true industrial production technique. While it brings valuable opportunities to the industry, such as drastically decreasing the time-to-market of new products or enabling lightweight, multi-material and multi-functional designs, it also comes with a series of challenges for the engineers. The reliability of the mechanical properties of the final part still has some uncertainty and is not fully supported by standard engineering tools. Dimensional accuracy is not always met and cannot be predicted prior to printing. To cope with these issues, the engineering workflow which is daily applied for traditional manufacturing processes needs to be replicated and adapted to the Additive Manufacturing.

Specifically, Additive Manufacturing of polymers and composites shows a very strong influence of the manufacturing on the material and global component behavior and its modeling constitutes a true multi-scale challenge. In this paper, multi-scale material modeling techniques – which are essential to handle the several scales involved in Additive Manufacturing – are presented and applied to 3D printing of polymers (unfilled and reinforced). Insights on how the process simulation of FDM/FFF or SLS method can be solved via coupled thermo-mechanical models are presented. The numerical simulation follows the real printing workflow, takes into account the process setup and the material behavior, allows to predict the deformed shape of the part and residual stresses and offers warpage compensation techniques. Industrial applications of process simulation are shown to demonstrate the validity of warpage predictions.

Finally, a strongly coupled process-structure methodology is shown that predicts the as-printed mechanical behavior. This approach links the material anisotropy and the process-induced microstructure to the as-printed part performance and its validity is demonstrated against experimental tests. The part strength sensitivity to the printing direction is also highlighted in several applications. This integrative workflow, which accounts for the full manufacturing history of the part, enables the design validation and the optimization of the performance of AM designs.

Process simulation

The main goals of AM processes simulations include predicting the final distorted shape of a part, the residual stresses distribution and the process-induced microstructure (such as porosity and fiber orientation – for reinforced plastics). However, the development of the AM process simulation has to cope with several challenges:

1. The complex thermomechanical loadings that occur during the layer-by-layer deposition of the material.
2. Additive manufacturing is a true multiscale challenge (Figure [1]): the infill is made of the superposition of beads inducing some specific mesostructures defined by the printing pattern (toolpath) that will drive the macroscopic mechanical behavior – typically inducing anisotropy due to the inter-beads porosity.
3. The thermal history of the material deposition generates differential shrinkage between adjacent beads or layers that shapes the part.

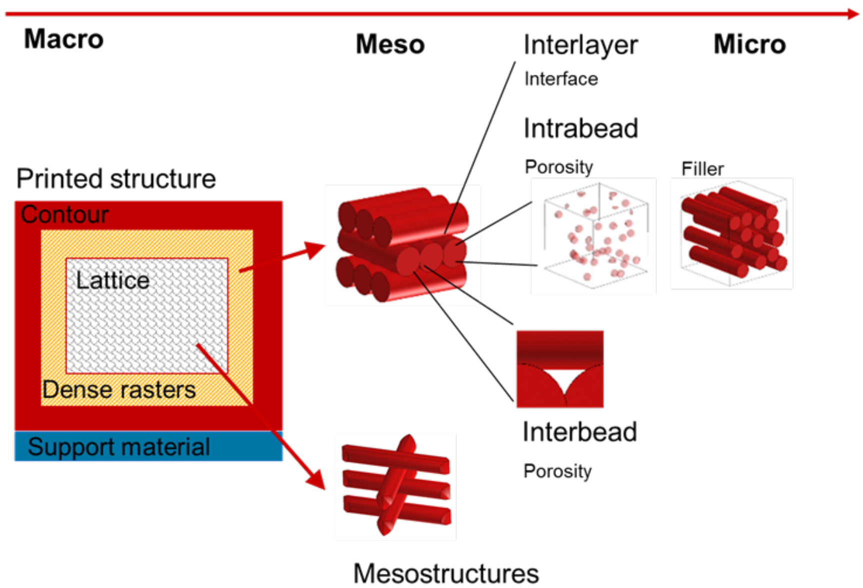

Figure 1: Additive manufacturing is a multiscale challenge (illustrated for the FFF process)

Overall, modeling the printing process requires Users to account for the material state evolution and model the stress build-up as well as the stress relaxation, which can occur over time. Numerical predictions of warpage need to account for the process parameters, which can be a function of the type of AM technology considered – the material characteristics and the printing strategy (part orientation, toolpath, supports …).

Based on a multi-scale FEA simulation, the layer-by-layer progressive build of the part is reproduced, residual stresses can be obtained as well as the final deformed shape of the part. Process simulation has the unique advantage to provide an efficient workflow for warpage compensation by allowing the User to export a counter-warped geometry (.STL file) resulting from a first warpage analysis, and then using it as a compensated geometry. By the end of this workflow, the geometry to send to the physical printer is identified, such that physical printing should yield the right geometrical accuracy.

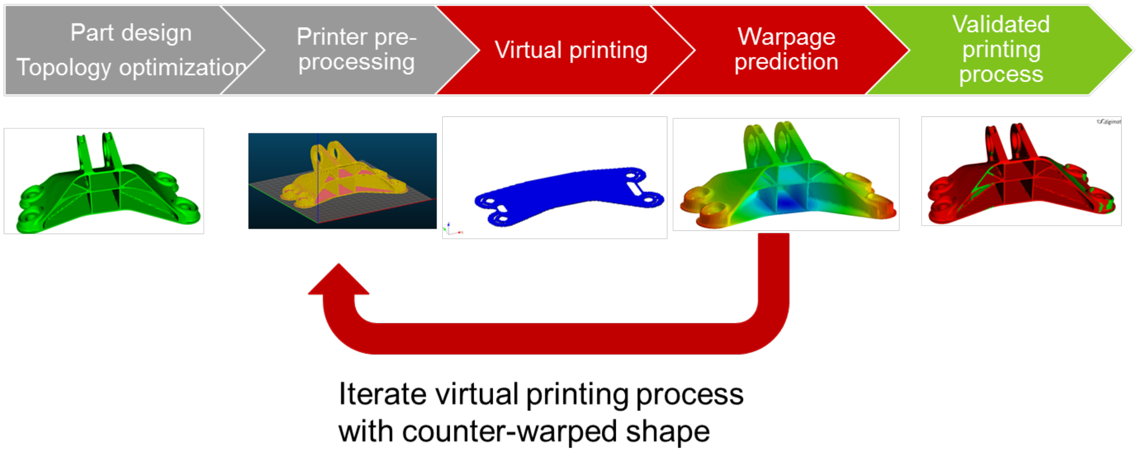

Figure 2: Complete workflow for optimal printing

Part performance

Design validation of additively manufactured parts requires to simulate the printed part performance (stiffness, strength, etc) as a function of the as-printed material and the process setup. This requires a strong coupling between process and structure, which is typically ensured by the usage of a multi-scale material model which is itself dependent on the process parameters, such as the printing direction or toolpath.

In this section, we will illustrate the workflow with the objective to predict the non-linear structural behavior of a dumbbell with influence of the process parameters (toolpath) and a non-linear anisotropic material model of FFF-printed ABS material. The results of the structural analysis with a 90° toolpath are shown in Figure [3]. In particular, the influence of the toolpath on the Von Mises stress is shown as well as the different mechanical response of the contour with respect to the infill.

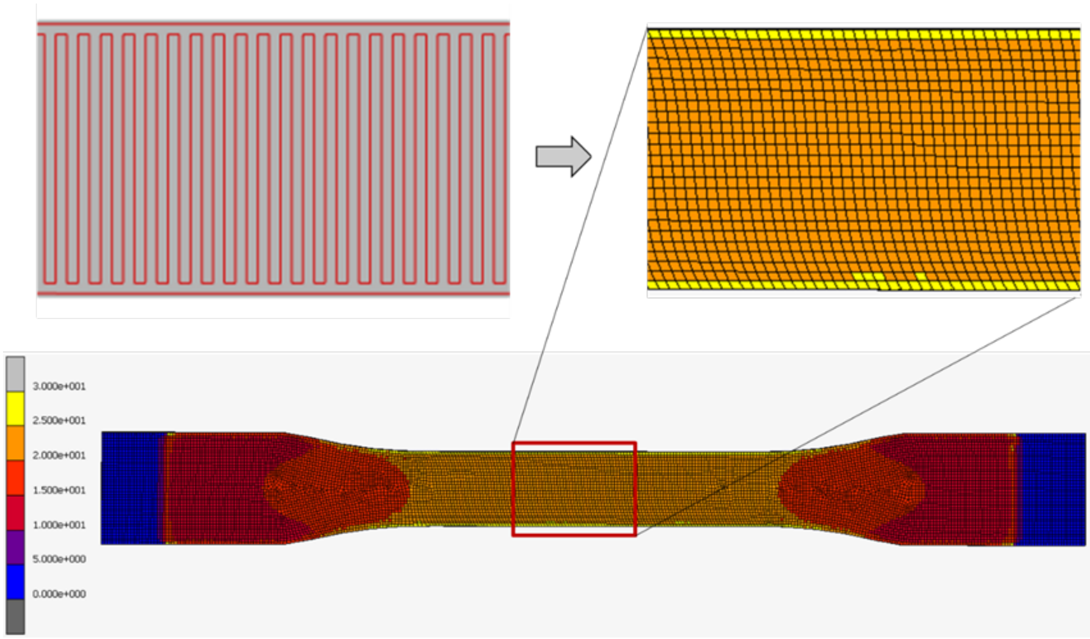

Figure 3: Von Mises stress [MPa] of the dumbbell tensile test

The FFF structural analysis taking into account the process setup (printing direction and toolpath) and the nonlinear anisotropic elasto-plastic material behavior helps thus understand the mechanical behavior of the dumbbell.

Summary

e-Xstream Engineering offers a holistic simulation chain for the additive manufacturing of plastics and composites with solutions for material engineering, process simulation, and part performance. This integrative approach is needed to accelerate the adoption of AM by the industry and promote new innovative structural designs needed to save energy and weight.

This paper has covered the AM process simulation based on a multiscale simulation approach. Methodology and applications for AM process simulations of both SLS and FFF technologies were covered with a particular focus on warpage prediction and compensation. Additive manufacturing material engineering applications based on mean-field and full-field homogenization schemes were presented. Finally, structural engineering of SLS and FFF parts was conducted, highlighting the impact of the manufacturing setup, as the printing direction and toolpath.

Bibliography

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