MULTI-SCALE MATERIAL MODELING AND PRINT SIMULATION FOR "FIRST TIME RIGHT" ADDITIVE MANUFACTURING

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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, 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. An industrial application of process simulation is shown to demonstrate the validity of warpage predictions.

Finally, a strongly coupled process-structure methodology is presented that predicts the as-printed mechanical behavior. This approach links the material anisotropy and the process-induced microstructure to the as-printed part performance. The part strength sensitivity to the build direction is also highlighted. 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, as demonstrated on an automotive engine air manifold.

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1. INTRODUCTION

Additive manufacturing (AM), by definition opposed to subtractive methods, regroups a number of manufacturing processes allowing to create parts from 3D numerical CAD model by building up the components in layers by depositing material, hence not requiring specific mold tooling design. Low volume, complex parts can be produced at fixed cost in less time. As lightweighting becomes a top design priority for the automotive and aerospace markets, the capability to reduce the number of parts by manufacturing an assembly directly is a promising source of gain. Lattice structures are also increasingly interesting the industry seeking the optimum mix of mechanical performance and low density. Such design opportunities offered by AM technologies can successively lead to weight reduction of several tens of percent.

Other advantages of the AM technology include:

- *More integrated/functional parts;*
- *Product lifecycle: reduced costs and time to market;*
- *Onsite - On demand production / Customization;*
    - *End-of-life products;*
    - *Medical & dental;*
    - *Aerospace and defense.*

Until recently, the application of 3D printing was limited to rapid visual prototyping. Additive manufacturing of plastics is experiencing a paradigm shift as the industry is now looking into the technology as a full production technique to achieve not only a tailored design but also, new lightweighting solutions which are not viable with other manufacturing methods.

While the advantages of AM technology are appealing for the industry, additive manufacturing is still a recent technology and requires multiple trials and errors to reach the right consistency and expected performance. The printed part may show important warpage due to thermally induced distortion, thus dimensional tolerance may not be ensured. Process control and optimization is also a matter of concern: a large number of parameters drive the manufacturing and the part-to-part variability is high. New high performance materials need to be developed specifically for the AM industry.

To unveil the full potential offered by AM technology, predictive simulation tools are required by process engineers and end-users. This paper will address the current research and developments of e-Xstream engineering with the goal to provide the industry with a holistic simulation approach for additive manufacturing of plastics and composites, covering process simulation, material engineering and structural engineering of both SLS and FDM.

2. EXPERIMENTATION

2.1 Process simulation

An increasing number of AM technologies are applicable to plastics and reinforced plastics. The most widely used in the industry today are the Selective Laser Sintering (SLS) process and Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF). In SLS, powdered material is sintered using a laser heat source. In FFF, plastic filaments are melted, extruded, and deposited through a moving head.

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 crystallinity 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: the bonding between the layers is induced by microscopic thermal and mechanical phenomena that will drive the macroscopic mechanical behavior – typically inducing anisotropy.
3. The thermal history of the printing process generates differential shrinkage between adjacent layers that shapes the part.

Overall, modeling the printing process requires to account for the material state evolution and model the stress build-up as well as the stress relaxation, which can occur over time. The numerical simulation follows the real printing workflow, takes into account the most important process parameters, which can be a function of the type of AM technology considered, the material characteristics and the printing strategy. 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.

In the next paragraph, a warpage compensation strategy is further considered to minimize part distortion.

2.1.1 Warpage compensation

The objective of this section is to illustrate the workflow performed to compensate for the warpage of a part. We will distinguish, on the one hand, shrinkage (contraction of the part due to the progressive cooling between the extrusion/sintering temperature and room temperature) from warpage (differential shrinkage e.g. between successive layers) and, on the other hand, the as-designed geometry from the as-printed geometry, i.e. the final distorted shape of the part once the printing process is completed. Most printers actually integrate this distinction by preforming the geometry following a printer/user-defined scale factor. However, this functionality is limited to shrinkage compensation.

A solution to circumvent warpage consists of compensating the geometry to be printed, by specifying it such that after warpage, the as-printed geometry is sufficiently close to the as-designed geometry. The proposed workflow for warpage compensation consists in allowing to export a counter-warped shape based on the results of a first warpage analysis, and then using it

as a compensated geometry. By running a new simulation on the compensated geometry, it can be checked that the as-printed geometry becomes similar to the as-designed 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 as-printed geometry.

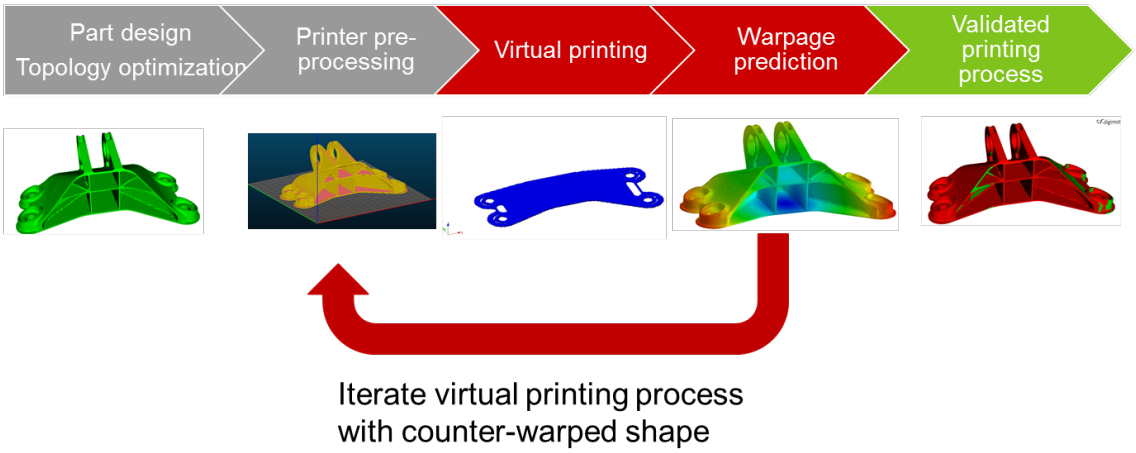


Figure 1. Complete workflow for optimal printing.

2.2 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.

2.2.1 Part performance of FFF printed designs

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 Fig 2. 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.

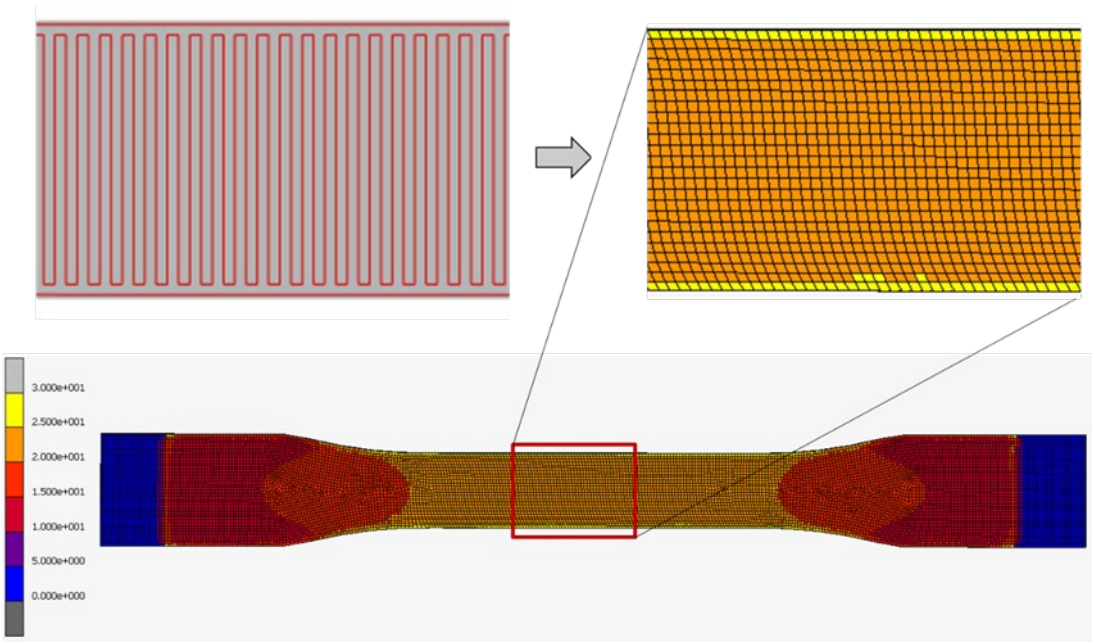


Figure 2. Von Mises stress [MPa] of the dumbbell tensile test.

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

3. RESULTS

This section proposes an application and validation of the numerical simulation on a structural and process simulation of a Charge Air Cooler. The objectives are:

- *define the build direction that maximizes the part performance;*
- *validate the design accuracy in this best build direction;*
- *highlight the warpage compensation workflow.*

3.1 Optimization of the part performance of the Charge Air Cooler

In this section, we will illustrate the workflow with the objective to predict and optimize the non-linear structural behavior of the Charge Air Cooler. The mechanical simulation of the part under a burst pressure test is performed. The build direction of the part is analyzed to determine the best angle maximizing the pressure at break of the part. To predict the ultimate strength of the part, a non-linear finite element analysis coupled with the Digimat multiscale material model is performed to simulate the progressive pressure increase. As soon as the failure indicator has reached a value of 1 in any element of the FEA (Fig 3), we assume the ultimate strength of the part is met. The maximum pressure that the part can sustain has been computed for several print

orientations (Fig 4). The 0° angle has been identified for maximizing the mechanical properties while a second angle (70°) shows the weakest configuration of the part.

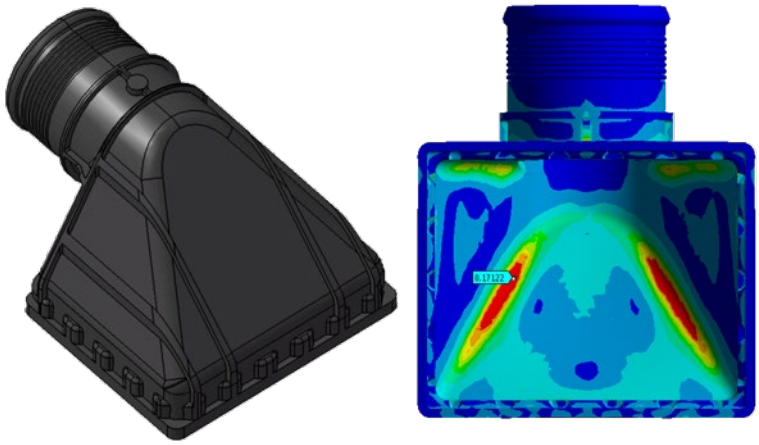


Figure 3. Failure indicator of the part under pressure. (Photo courtesy of Solvay)

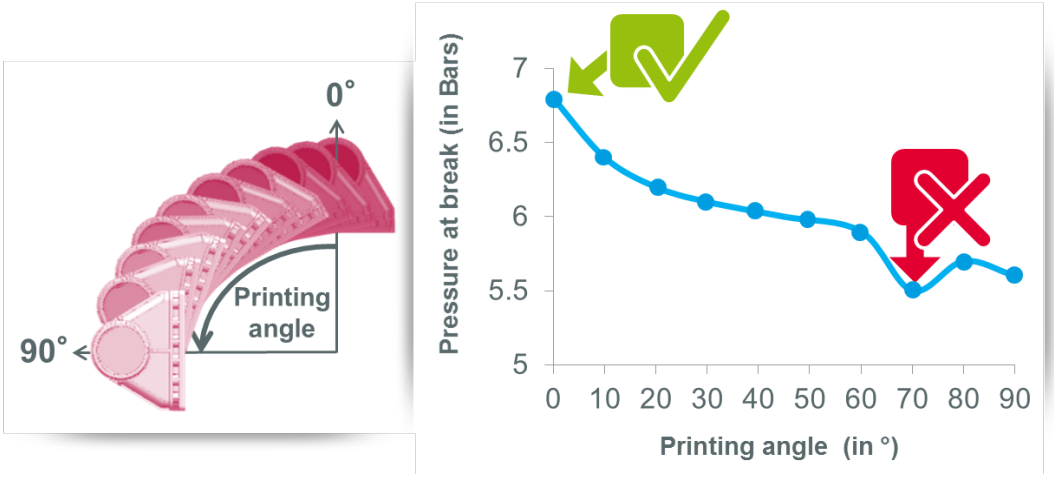


Figure 4. Part performance as a function of the build direction. (Photo courtesy of Solvay)

3.2 Process simulation and warpage compensation of the Charge Air Cooler

The sintering of a Charge Air Cooler is simulated. The material used is Sinterline® PA6 reinforced with 40% GB. The AM processes simulation reveals that the selected building direction generates high warpage (0°). The warpage of printing can then be compensated by optimizing the print shape for this given orientation.

To improve the dimensional accuracy, based on the first warpage simulation, the as-designed geometry is deformed by applying to the nodes of the initial STL geometry the opposite of the resulting displacements. The geometry is reconstructed and can be exported (i.e., STL file of the compensated geometry). Performing a second process simulation using this compensated geometry yields the expected part dimensional accuracy (Fig 5).

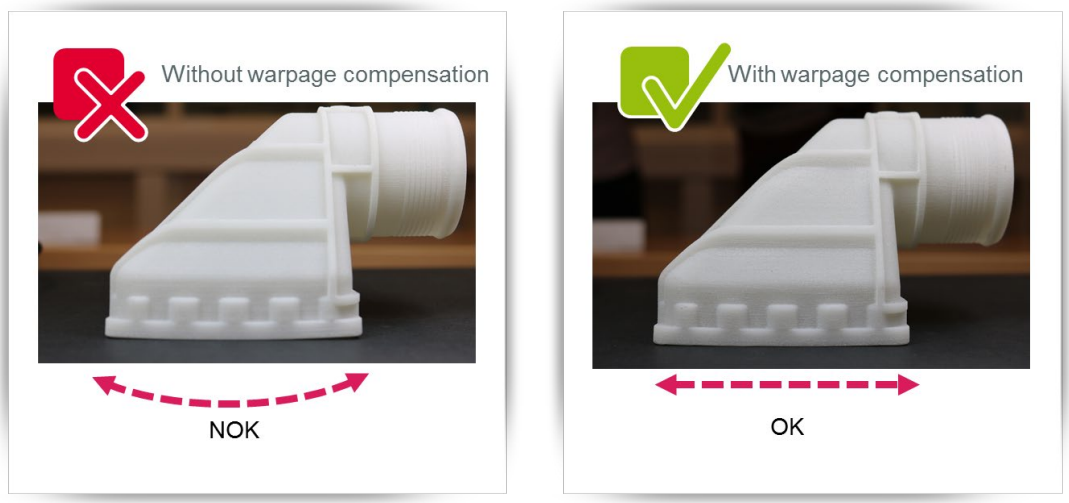


Figure 5. Optimized part dimensions accuracy for 0° building orientation. (Photo courtesy of Solvay)

4. CONCLUSIONS

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. Finally, structural engineering of SLS and FFF parts were conducted, highlighting the impact of the manufacturing setup, as the build direction and toolpath.

In summary, Digimat Additive Manufacturing answers the 3 key challenges the AM ecosystem is facing to increase the adoption of the AM technology: demonstrate the reliability achieved by the technology, enlarge the material portfolio and provide standard design validation tools.

The first concern of end-users and printer OEM is the reliability of the printed part. Thanks to Digimat-AM, printing issues can be anticipated as the warpage is predicted and the dimensional accuracy can therefore be corrected. By delivering ‘print right the first time’ capability, Digimat allows to save time and material.

Finally, design engineers will now rely on accurate, efficient and predictive FEA to complete the engineering workflow which is daily applied for traditional manufacturing processes. Part performance predictions allow to validate the design and optimize its performance, decreasing the need for physical productions and testing.

5. REFERENCES

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