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Process simulation for large scale additive manufacturing using thermosetting material

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Abstract

Additive manufacturing (AM) technologies are these years experiencing a larger amount of traction in terms of applications due to an ever increasing development of printing material properties. Properties, which in the past have been neglected, due to the manufacturing speed requirements, are now getting the attention needed to be widely accepted for industrial productions based additive manufacturing. While the thermos-plastic materials have been preferred in large scale plastic AM it leaves a gap in the AM toolbox, that is the thermos-setting materials, which typically provides cheaper, high fatigue, no creep properties required for many applications. This work will look into some of the requirements for the adaptation of low-cost thermosetting materials in material extrusion-based AM processes in the larger scale. Some of the key challenges discussed during this work are; the open process window criteria versus form stability of the printed material, the curing profile and its influence on the AM process and how to connect this to properly prepare geometries for thermo-setting printing on a larger scale.

Big Area Additive Manufacturing, process analysis, thermo-set AM, thermo-chemical model, finite volume discretisation.

1. Introduction

In recent years additive manufacturing have been used for the production of an increasing amount of final products [1], and it is slowly leaving the label of only being applicable for rapid prototyping. A reason for this change is found in the increased focus on material properties. As the properties increase so does the application span, and even though plastic AM processes are still lacking to show similar material properties to e.g. injection moulding, see e.g. [2], continuous efforts reduce the existing gaps day by day. Some of the key challenges faced in the area of additive manufacturing are process parameter control that influences e.g. the adhesion in between the added material; another is the basic concept of additive manufacturing being more of a 2.5D process than a 3D process due to the layer by layer build-up, hereby leaving at least one axis weakened and restricts optimised processing to account for force pathways through the material. Furthermore when going up in scale and looking into composite AM, this has also heavily been influenced by thermo-plastic materials, in systems such as: Thermwood LSAM, Cincinati BAAM, Stratasys Infinity and Envisiontech SLCOM1, leaving the parts produced expensive and susceptible to fatigue and creep. A way to increase the fatigue properties could be to look into thermosetting AM, which in the smaller scale is seen in vat photo-polymerisation systems like Continuous Liquid Interface Process (CLIP) and stereo-lithography. Going up in scale these systems quickly becomes too expensive, due to e.g.; the need of large vats with expensive material, complex integration of numerous laser systems to increase the deposition rate, and the increased weight of the parts produced making the part harder to move around. This is why the following work will focus on the material extrusion based AM technique, while the ease of scaling is more manageable and it enables the use of conventional thermosetting materials.

Today only a few efforts have been seen in big area AM of thermo-setting materials, while the added reaction during the process increase the complexity of processing. This means the processing sequence is expanded from a mere thermo-mechanical problem to a chemical-thermo-mechanical problem also increasing the complexities of e.g. the flow control. In this study some of these complexities are discussed and a program is developed to point out some of the critical areas of the process during the path planning stage. In the process a G-code evaluation tool is looking into the generated pathways of the processing plan to analyse which areas might become troublesome in terms of stress and reaction cycles. The aim is eventually to validate the process plan before going to the build phase and thereby reduce expensive trial and error approaches, when looking into the manufacturing of new products.

In literature material extrusion-based thermo-setting printing have been performed in the smaller scale by Brett G. Compton [3], wherein the flow control problem have been handled by altering the thixotropic properties of the liquids. Hereby the material is easy to handle and mix, while still having the important high modulus properties when deposited, so that the material can still hold itself, until the curing have properly settled the material. On a medium scale, Michele Tonizzo et al. from PIU-lab Atropos in Italy enters the spotlight with their material extrusion based robots arm that deposit thermosetting material with continuous fibres using fast UV-initiated curing processes to attach the applied layer to the previous layer.

In literature numerous simulations have been performed to describe different aspects of the material extrusion based processes (see [4] for further details). Typically these simulations have involved specific analysis of one or a few process factors within the AM process. In the numerical simulation these have typically been based on heavy finite element analysis, which become computational intensive for larger components. Additionally these simulations have also primarily focused on thermo-plastic approached and are hence not equipped to handle the thermo-chemical nature of the thermo-setting process. This is where this work separates itself from previous efforts, while it aims at providing an overall evaluation tool of the planned pathways in the process giving thermochemical insights, looking into the areas which might make processing more difficult and make a fast finite volume thermo-chemical analysis in these areas to see the consequences before continuing to the build phase. This is achieved by a Matlab program containing a sequence to: (1) extract the g-code information; (2) time the different movements; (3) show when the flow is stopped to move the machine to a new position before continuing the depositions; (4) show the open window criteria and (5) finally end up with a 2D-finite volume thermo-chemical model to calculate the thermal process history and evaluate the thermal degeneration of the part due to the proposed process pathway.

2. Methodology

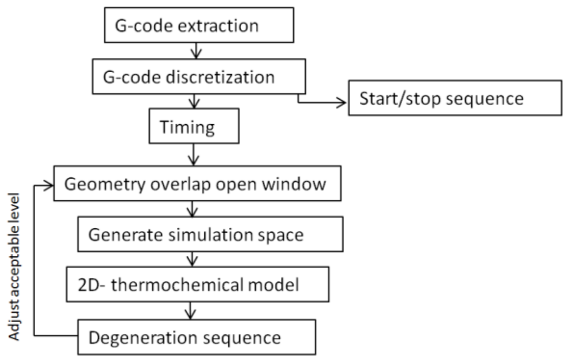

Figure 1. Overview chart of the Matlab analysis tool.

First step in the process feasibility Matlab code is to extract the movement descriptions of the g-code [figure 1]. From here this G-code description is discretized in a finite mesh of control volumes. Then the code parts into two fraction, one showcasing the start/stop sequence of the code, another showing the open window criteria, which takes the finite mesh of control volumes and time when the deposition happens in each of these volumes from that a map is created showing parts, which is outside the open window criteria. These specific areas are then extracted and a 2D-finite volume mesh is created to make a thermochemical analysis of these areas to see the effects of the deposition pattern in this given area, see figure 2.

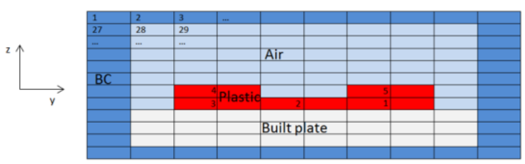

Figure 2. Example of the 2D- discretization of a simulation space that goes into the thermo-chemical model. The black lines separate the different volumes; Dark blue = boundary volumes, light blue= air volumes, White= built plate volumes, red=plastic deposited during the process, wherein the numbers show the sequence at which they are applied.

2.1. The thermo-chemical simulation

The thermo-chemical 2D-finite volume simulation used for this program is based on previous work [4], wherein the governing equation for heat conduction through solid material is used as the principle heat transfer mechanism. This equation is based on Fourier's law and the first law of thermodynamics (conservation of energy) [5] and is shown in equation 1.

$$\frac{\partial T}{\partial t} * \rho * c_p = \frac{\partial}{\partial x}\left(\kappa * \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa * \frac{\partial T}{\partial y}\right) + \dot{Q} \qquad (1)$$

Here T is temperature, ρ is the density, c_p is specific heat capacity, κ is thermal conductivity and $\dot{Q}$ is a volumetric heat source term.

By taking this 2D-approach it is assumed that the deposition can be taken as instantaneous deposition and the heat transfer in the 3 dimension, which is the printing direction, can be neglected. For the solution of the finite volume discretization a fully implicit approach have been applied. The chemical curing has been simulated using the process described in [6], wherein an incremental heat term, seen in equation 2, is added to equation 1.

$$\dot{q}_{i,j}^{t} = \rho * H_r * \left(\frac{d\chi}{dt}\right)_{i,j}^{t} \qquad (2)$$

Where $\dot{q}_{i,j}^{t}$ is heat at time t and position [i, j], ρ is density, H_r is the total reaction enthalpy, χ is curing degree and t is time.

In here the reaction kinetics of the polyurethane is simulated with second order reaction kinetics, see equation 3, which in previous studies have been shown to describe this branch of polymer reaction sufficiently [5].

$$\frac{d\chi}{dt} = a * (b - \chi)^2 \qquad (3)$$

Where $\frac{d\chi}{dt}$ is cure rate, a, b are constants and χ is cure rate.

For a detailed explanation of this simulation see [4].

For the current study a test-geometry (see figure 3) has been chosen to illustrate the different functions of the program and show the results and insights the program provide. For the slicing procedure of the geometry the freeware Slic3r was used.

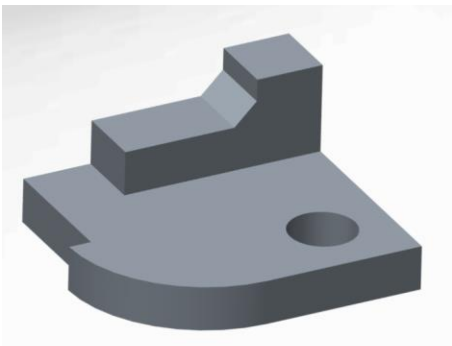

Figure 3. Test geometry for the analysis of this study.

3. Results and discussion

3.1 The Start-stop sequence

The first output of the created program is the map of deposition stops during the manufacturing process, see figure 4. This insight is important for the thermo-setting AM, while each stop and reduction in the deposition flow needs to be adjusted in the reaction kinetics either by adjusting the amount of catalyst added or the temperature in the nozzle and mixing area. Additional in the case of static mixing sudden stops in the flow will affect the mixing, that might reduce the quality of the produced part. The reduction of flow-stops and significant alterations in the flow patterns hence needs to be a priority in the slicing of the parts. In figure 4 it is seen that typical slicing using the Slic3r result in a complex pattern of stops in depositions adding to the processing complexities and is hence not ideal for a thermo-setting process.

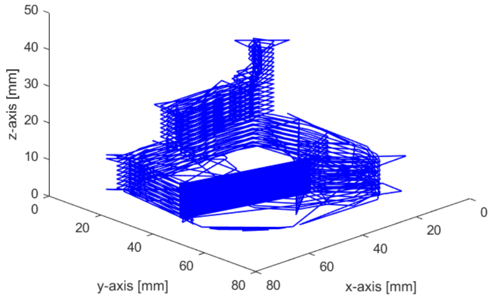

Figure 4. The start-stop sequence, here the blue lines indicate the road travelled without extruding material.

3.2 The open window criteria

Next step in the program is the open window criterion, which is one of the most important aspects of the thermo-setting process, while it is one of the main drivers for the quality of the produced part. To take an example; if the deposited layers are placed too quickly on top of each other the result will be an increased temperature generation, this speeds up the curing process locally. The result of this increased speed could result in increased stresses locally leading to distortions. Furthermore the elevated temperature could lead to polymer degradation. On the other hand, if the layers are placed with a too large time-gap in between them, this might result in lack of interlayer adhesion, while the previous layer have finished its reaction and it can hence not react into the new layer. The consequence of this will be poor part properties due to a reduction of chemical bonding in between the layers. Another consequence of too slow depositions might be increased crack initiations in the parts, while the thermal cycle of the newly applied layer might induce further stresses into the cured layer. Furthermore it leads to large temperature gradients in between layers that might lead to increased distortions as well. For a process evaluation it is hence important to map out the open process window of the used material to secure the optimal process being performed. Figure 5 shows an example of such an analysis, wherein it is seen that the bottom layers takes longer, which is illustrated by the black colour. This gives insights to the need of either restructuring the planned process pathway, or a requirement of thermal or catalytic process control during the build. It shows certain areas of high black (to slow) and high red (to fast) concentrations, which then can be further investigated by the 2D finite volume model.

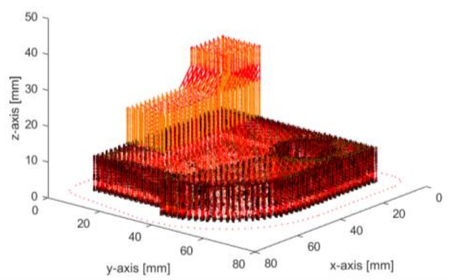

Figure 5. The open window sequence. Black dots indicate the areas in which the time between layers is exceeding the desired time.

3.3 Thermo-chemical simulation

When issues of selected areas are pointed out, a simple 2D thermo-chemical model is used to showcase some of the consequences in these areas. Besides a thermal profile (see example figure 6, left), the code also provides knowledge into the thermal process degradation (see example figure 6, left), and the curing degree of the material when the new layer is applied to secure proper adhesion. This part of the code is still in its early stages, which is why only arbitrary degradation patterns are shown in the example to indicate, which areas have received the highest temperature for longer periods of time. To increase the accuracy of the model it is hence required to perform extensive research into the specific system to receive all the material properties needed for the simulation. Furthermore the exact curing profile under different temperatures and with various catalytic amounts is required. Additional further calibration experiments should be performed, but for now the model is usable for initial process pathway investigations, to see if the planned process will be possible, or if some sections are situated outside the open process window.

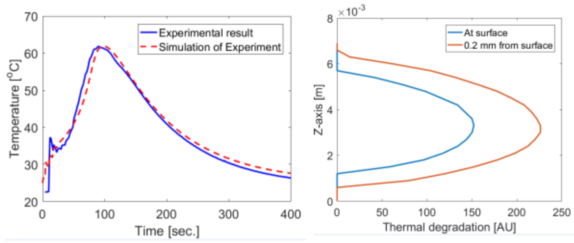

Figure 6. The thermo-chemical sequence. Left: an example of an initial test print using polyurethane, where the thermal profile of the process is compared to a simulation. Right: an example of a degradation profile indicating the highest thermal stress in the middle sections of the prints.

4. Summary, conclusion and future work

In this work a Matlab feasibility tool was made to illustrate some of the areas which need to be handled when looking into thermo-setting additive manufacturing. Being an initial study the developed simulation tools still needs further experimental validation and calibration to increase the simulation accuracy. In its present state the model shows how different geometries prepared for additive manufacturing will be affected during processing. It provides insights to the proposed process plan and finds critical areas in which actions needs to be taken for an optimal printing process of e.g. thermo-setting materials. Through this paper different issues, while printing in thermo-setting materials have been discussed, these include; material flow stops during the process, the open process window, which is set by the curing profile, the difficult thermo-chemical relation that also controls the flow profile and the final mechanical properties of the part. The created model in this study aims to address these issues in an overall sequence, and is hence not meant for in depth accurate analysis of the process, but more as a tool for fast iterations of the process plan, until a final in depth finite element analysis of the process will be performed. Further developments of this Matlab model will include; additional model calibration of the thermo-chemical finite volume analysis through thermo-setting experiments, a thermal gravimetric analysis (TGA) of the used materials to improve the thermal damage sequence, and a further investigation of the open process window, to accurately show, which areas that will not be fit for the thermo-setting processing and hence show the pathways that needs to be altered before the build.

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