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On thermal modeling of Additive Manufacturing processes

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ABSTRACT

A two-dimensional Finite Difference (FD) model of the thermal history of parts manufactured in powder bed fusion Additive Manufacturing (AM) processes is presented. The temperature of the part is calculated in each time-step taking into account the moving laser heat source, the melting phase change and functions of both temperature and porosity are used for the material thermal properties. Also, an algorithm for node birth and distance adaptation over time is utilized, minimizing computational time and memory. A validation of the results of the model is included.

Introduction

Additive Manufacturing (AM) is defined as "the process of joining materials to build objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing processes, such as traditional machining" [1]. The main difference between Rapid Prototyping is that AM specifically aims to the manufacturing of end user parts rather than just prototypes [2]. AM processes have more than 25 years of history [3] and the interest in them is steadily increasing due to the design freedom [4], the potential of producing near net shape structural components and the environmental and ecological promise they offer.

In most of the AM processes, parts are manufactured layer by layer, using a source of thermal energy to fuse the different layers together. As a result, anisotropic material properties and residual stresses are common, because of the non-homogenous thermal and cooling phenomena that take place [5]. Except from the uncertainty of the mechanical properties, other important issues are the low productivity and poor surface quality, the optimization of which is difficult because of limited modeling approaches to the topic [6].

The residual stresses and distortions, which are caused by the non-homogenous thermal phenomena (heating and cooling) [7] that take place in AM, deteriorate the mechanical properties and the dimensional accuracy of the parts. As a result, the thermal history of a part's manufacturing procedure is essential, because it determines its microstructure, mechanical properties and final dimensions. To this effect, the thermal modeling of the AM processes can be utilized for the optimization of those important Key Performance Indicators (KPIs), without the requirement for time-consuming and costly experiments and it is the first step to establishing relationships between the KPIs or Quality Performance Measures (QPM) of a part and the variables of the process (Fig. 1).

There are many different approaches to the modeling of the thermal history of parts, manufactured by AM processes. Most of the existing studies utilize numerical methods, due to the complexity of the phenomena that take place. More specifically, the modeling of heat transfer of AM metal deposition, via Finite Elements (FE), takes place in the work of Ref. [8], along with an error minimization. A temperature field simulation of the Selective Laser Melting (SLM) process, also by using the FE method, is presented in Ref. [9]; the same numerical method is utilized by Ref. [10] for the simulation of the temperature distribution and the melt pool size, when the bulk of powder is heated by a laser source. The FE method has also been used by Refs. [10–14]. Different modeling methods have been followed by some studies, like that of Ref. [15], in which a computational tool has been developed by assembling models of many interacting particles in the small scale. Also, the laser energy was correlated to the Total Area of Sintering (TAS) via a convex hull based approach by Ref. [16]. Heat transfer modeling for the SLM process has been carried out via discrete grid models [17], which take porosity into account. In the works of Refs. [18,19], the finite volume method has been used for the thermal

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Nomenclature

Δt	Time duration of a time-step
Δx	Length between two nodes in the x-axis
Δz	Length between two nodes in the z-axis (standard, non-adaptive meshing)
Δz_a	Array storing the distances between the adaptive nodes of the mesh
π	Pi constant
ρ	Material density
ρ_a	Density of air
ρ_m	Density of fully dense solid material
ρ_{pr}	Density of porous solid material
A	Apparent heat capacity coefficient
c	Heat capacity of the material
c_a	Heat capacity of air
c_{ap}	Apparent heat capacity of the material (function of temperature)
c_l	Heat capacity of the liquid phase of the material (function of temperature)
c_m	Heat capacity of fully dense solid material
c_n	Heat capacity of the solid and liquid phases of the material (function of temperature)
c_{pr}	Heat capacity of porous solid material
c_s	Heat capacity of the solid phase (function of temperature)
c_t	Total heat capacity (solid, liquid phases and apparent heat capacity) of the material (function of temperature)
D_l	Diameter of the laser spot
d	Adaptive mesh node distance non-uniformity exponent
f	Volumetric fraction of porosity
h	Convective heat transfer coefficient
I	Laser beam intensity
I_0	Laser beam intensity at the beam axis and at the focal level
k	Thermal conductivity of the material
k_m	Thermal conductivity of fully dense solid material
k_{pr}	Thermal conductivity of porous solid material
L	Latent heat of the material
L_L	Layer thickness
L_n	The length, taking into account the addition of a new layer, in the z direction in which the meshing will be created using the adaptive algorithm
L_o	The length, without taking into account the addition of a new layer, in the z direction in which the meshing will be created using the adaptive algorithm
l_d	Distance from the laser beam axis
m	The x coordinate of a node
N_L	Number of nodes in the z direction in the thickness of a layer of a part
N_l	Number of nodes in the x direction in the length of the diameter of the laser spot
N_t	Total number of time-steps
N_x	Total number nodes in the x-axis
N_z	Total number nodes in the z-axis
n	The z coordinate of a node
n_h	Number of time-steps a node is being heated
n_s	Number of time-steps needed for the addition of a new layer of powder
P	Laser power
r	Radius of the laser beam spot
T	Nodal temperature
T_1	Lower temperature boundary of the mushy area of the apparent heat capacity method
T_2	Upper temperature boundary of the mushy area of the apparent heat capacity method
T_b	Temperature of the building platform of the AM machine
T_{env}	Environmental Temperature
T_m	Melting temperature of the material
T_{pre}	Temperature of the new layers of powder that are added over time
t	Time
t_h	Time a node is being heated
t_s	Time needed for the addition of a new layer of powder
v_l	Laser head scan speed
x, z	Cartesian coordinates
z_n	Final positions of the nodes of the adaptive mesh in the z-axis
z_o	Previous positions of the nodes of the adaptive mesh in the z-axis

modeling of the SLM process; in the latter, the densification of the material (WC/CU composite powder) and the induced surface tensions are also simulated. A different approach has been followed by Ref. [20], in which the OpenFOAM software has been utilized for the modeling of the process dynamics of the laser beam melting AM process.

However, due to the speed of the process and the high complexity of the spatial and temporal dynamic thermo-mechanical phenomena that take place, the computational cost, time and memory needed for the numerical modeling of AM processes tends to be very high, especially when combined with the need of the simulation of the entire thermal history [7]. As a result, most of the models simulate only a short time-span of the manufacturing of a part and not the whole process. However, such approaches are unable to provide the necessary information for the calculation of the thermal induced stress fields and deformations, because the entire thermal history, including the cooling down rates, is necessary for this. It has to be pointed out that such information is very important for the design and manufacturing engineers, in order to take the necessary actions, like changes in the design that will enable a more homogenous cooling, creation of supports that will minimize the distortions and simultaneously offer force cooling, or change the process parameters in a way that will minimize or even prevent such unnecessary phenomena (thermal distortions, non-homogenous mechanical properties).

Addressing the gap in the existing state of the art, this study emphasizes in the creation of a practical and fast to run, yet accurate in its predictions, model of the thermal history of a part which is manufactured in a powder bed fusion AM process. This model's simulation was not created through a ready to use software, but it was custom made instead, so as to be tailored to the complex and dynamic problem at hand. This decision was made, because such a solution provides better adaptability, easier coupling with other fields (e.g. mechanical) and offers increased connectivity with other modules, such as optimizers. The FD method has been used in this study because of advantages such as strict formulation and ease concerning user inputs [21]. In order to keep the computational time and cost, as well as the accuracy loss, to a minimum, a two-dimensional (2D) space combined with a non-uniform mesh has been used, which is dense in the regions where complex dynamic phenomena take place, while it becomes coarser in places that less dynamic temporal and spatial changes occur. A further increase of the accuracy is achieved by assuming temperature dependent material thermal properties; namely thermal conductivity, specific heat capacity and density. In

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