Multi-scale approach for fast predictions of Additive Manufacturing processes

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Abstract

A multi-scale approach method for fast predictions of additive manufacturing processes is developed in order to deal with the high computational cost which present the current high-fidelity codes available to solve the coupled thermo-mechanical problem. The new scheme is separated in three different scales: microscopic, mesoscopic and macroscopic. Firstly, in the microscopic scale a thermal problem is solved obtaining the heat input for the mesoscopic problem. Secondly, a thermo-mechanical elasto-plastic simulation is realized in the mesoscopic scale, with a large element size, returning the so-called inherent strains which are injected in the macroscopic scale to compute the residual stresses and distortions of the additive manufactured part. The validation of the code is pending, therefore, the future work consists of checking that the accuracy and computational time of the new method is suitable for its practical use in industry.

1 Introduction

Additive Manufacturing (AM), also known as 3D printing or Rapid Prototyping (RP), is a relatively novel technique to build up industrial components, layer upon layer, directly from the 3D model data. This method is growing due to the advantages which presents comparing with the usual subtracting manufacturing. These advantages are, among others: freedom of design, reduction of material and energy or rapid cooling.
The accurate numerical simulation of this technique could mean a significant saving in prototyping and experimental tests. The main drawback of the current code implementation available is the high computational time which requires the calculation. Many researchers have used the finite element method to study metal deposition processes or different kind of additive manufacturing technologies ([1], [2]) which properly solved the problem but it is not feasibly applicable to industry purposes. Therefore, the simulation of the thermo-mechanical problem which drives the additive manufacturing process is achieved paying a high computational cost. The decreasing of the thickness of the layers and high-fidelity of the solutions are forcing the search of simplification methods to provide a useful tool for industry.

The objective of the work is the implementation of a simplified code which performs the simulation of the additive manufacturing process in a reasonable time and with a suitable accuracy in order to be employed in industrial applications. To achieve this goal, a multi-scale approach trying to artificially decouple the thermo-mechanical problem is developed ([3]).

The multi-scale approach considers three different stages: microscopic, mesoscopic and macroscopic scale. In each of them, a different problem is solved. Starting from the microscale, the output obtained in each model is injected as input in the larger scales. Finally, the solution is a sort of smart combination of each simulation model: heat source model, hatching model and layer model.

2 Methodology

The coupled thermo-mechanical problem, which is commonly solved by means of different multi-physics finite element software ([1]), is solved in a multi-scale approach by developing three different simulation models, one for each considered scale. On each scale, a non-linear material model is implemented, as well as, temperature dependent material properties ([3]).

2.1 Heat source model (microscopic scale)

The heat source model is employed in order to calibrate the heat input. This calibration is defined by means of the heat source and the energy absorption parameter η of the material. The approximation of the energy absorbed by the material is performed by means of the experimentally measured micro-cross-sections and the parameters of a Goldak heat source ([4]). Figure 1 represents the correspondent simulation model and boundary conditions.

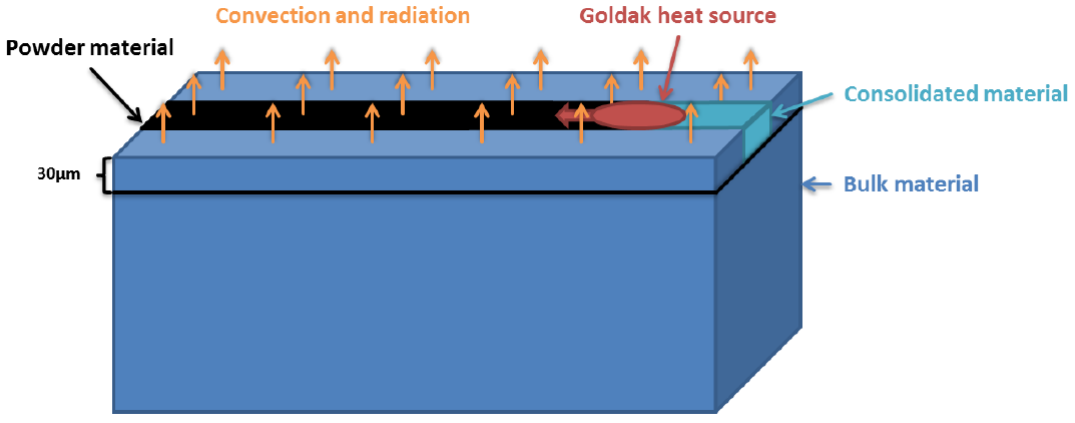

Figure 1: Boundary conditions of the heat source simulation model ([3])

For the simulation of the activated powder which appears in the image, an effective powder material is considered which very low heat conductivity is computed by means of the Zehner-Schlünders equation ([5]). The heat capacity and the density are considered equal to those of the solid material due to the fact the volume does not change (conservation of mass). The rest of material properties are changed to those of the solid material when the powder reaches the melting temperature. For the resolvability of the thermal problem, standard radiation and convection boundary conditions are taken into account.
A brief explanation about the heat transfer analysis which must be solved in this thermal finite element analysis is presented ([1]). First of all, it must be considered that both the solidification and cooling phases are controlled by the balance of energy equation. This governing equation reads as follows:

$$\dot{H} = -\nabla \cdot \mathbf{q} + \dot{Q} + \dot{D}_{mech} \tag{1}$$

where $\dot{H}$ is the enthalpy rate (per unit of volume), $\mathbf{q}$ is the heat flux, while $\dot{Q}$ and $\dot{D}_{mech}$ represent the heat source (per unit of volume) and the thermo-mechanical dissipation rate (per unit of volume) respectively. The source term, as it is commented previously, is introduced in the system by means of a Goldak model ([4]). The enthalpy $H(T, f_l)$ is a state variable defined as a function of the temperature, T, and the liquid fraction, f_l. Therefore, the enthalpy rate in (1) results in:

$$\dot{H}(T, f_l) = \frac{\partial H}{\partial T}\dot{T} + \frac{\partial H}{\partial f_l}\dot{f}_l = C\dot{T} + L\dot{f}_l \tag{2}$$

where $C(T) = \frac{\partial H}{\partial T}$ is the temperature dependent heat capacity and $L = \frac{\partial H}{\partial f_l}$ is the latent heat release during the phase-change process. Durign the phase transformation the material volume, V, can be split into liquid and solid phases as: $V = V_L + V_S$. The evolution of the liquid fraction $\dot{f}_l$ defines the phase change, that is, how the latent heat is absorbed or released during the transformation.

The heat flux (per unit of surface) $\mathbf{q}$, is computed as a function of the temperature gradient through Fourier‘s law as:

$$\mathbf{q} = -k\nabla T \tag{3}$$

where k(T) is the temperature dependent thermal conductivity. Due to the high conductivity of the metallic materials, the thermal diffusion process is the main mechanism to form the welding joint.

Finally, it is necessary to compute the weak (integral) form of the energy balance equation (1):

$$\int_V \big[(C\dot{T} + L\dot{f}_L)\delta T\big]dV + \int_V \big[k\nabla T \cdot \nabla(\delta T)\big]dV = W^{ext}_{ther} \tag{4}$$

where δT are the variations of the temperature field, compatible with the Dirichlet boundary conditions (test functions), and W^{ext}_{ther} denotes the external work of the thermal loads:

$$W^{ext}_{ther}(\delta T) = \int_V \big[(\dot{D}_{mech} + \dot{Q})\delta T\big]dV + \int_{S_q} \big[(\vec{q} + q_{cond} + q_{conv} + q_{rad})\delta T\big]dS \tag{5}$$

The approach to compute the heat fluxes in (5), in the case of electron beam welding ([1]) are the following. The convection flux, q_{conv}, can be neglected. The radiation flux, q_{rad} is computed using Stefan-Boltzmann‘s law. And finally, the conduction flux is driven by a Newton‘s law scheme.

2.2 Hatching model (Mesoscopic scale)

The hatching model takes into account the trajectory of the laser spot. A thermo-mechanical elasto-plastic simulation model is developed. The heat input to solve this problem is directly introduced from the microscopic scale by means of the energy absorption coefficient η. The key point of this model is that the element size is large compared to the laser spot dimensions and therefore, the total estimated energy is distributed within the cubic element. Figure 2 shows the finite element model and boundary conditions. The output which is desired to obtain of this model are the so-called inherent strains.

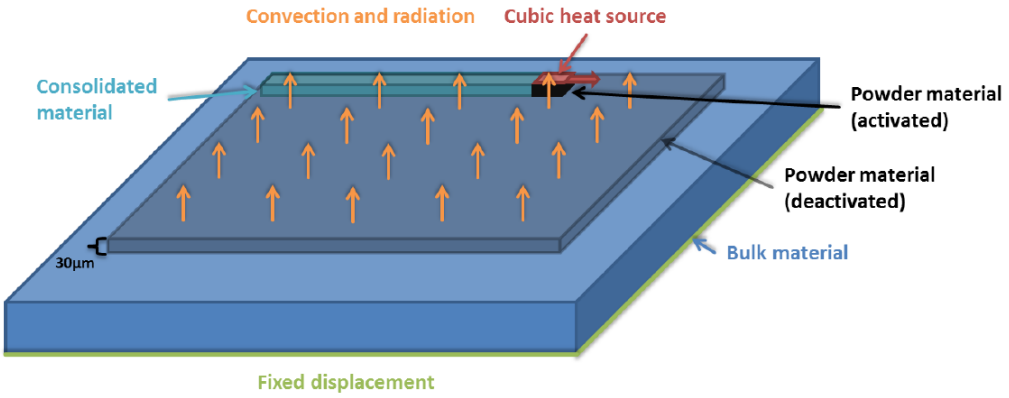

Figure 2: Boundary conditions of the hatching simulation model ([3])

At the beginning, all elements representing the powder later are deactivated and, therefore, they can not physically interact with other elements. When the heat source starts its movement, the elements at the current position are activated. As far as the integration points in powder material elements reach melting temperature, the properties are changed to those of the bulk material. The mechanical properties of the powder are: the yield stress is zero (representing inelastic behaviour), the thermal expansion is zero (powder is loose) and Young modulus is something above zero (it can not be exactly zero due to back-stress calculation for plasticity). Furthermore, standard convection and radiation boundary conditions are also taken into account. A fixed displacement boundary condition is applied on the bottom of the substrate plate.

2.3 Layer model (macroscopic scale)

The distortion in Additive Manufacturing parts is widely proved that tends to be a macroscopic phenomenon, which is mostly dependent on the hatching strategy and the geometry of the manufactured part ([6]). Although stress and temperature of a certain point in a layer are affected by approximately 10 previous layers, displacement values alter until the end of the built-up process. All additive manufacturing parts are extremely large compared to the size of the micro-weld and each weld seam experiences an identical or comparable thermo-mechanical history. This fact is used to reduce the time consuming transient thermo-mechanical for the prediction of geometrical distortion to a fast solution of the mechanical problem on the basis of the method of inherent strain. For this purpose, the strains determined in the hatching model model are applied as inherent strain in the macroscopic layer model. The similar approach has been successfully applied and validated for the calculation of welding distortion of large parts ([7]). Figure 3 shows the simulation model that is used for the fast calculation of distortion of additive manufacturing parts.

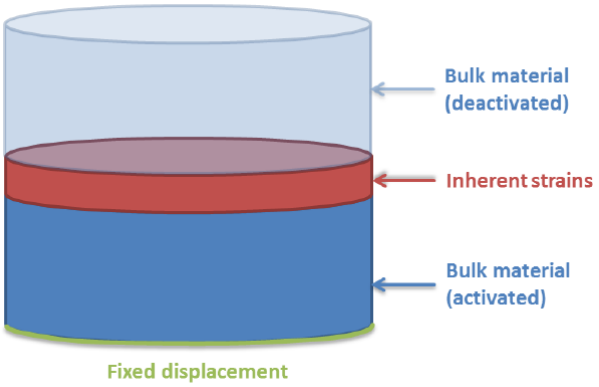

Figure 3: Boundary conditions of the layer simulation model ([3])

The elements are deactivated at the beginning and the built-up process is represented by layer wise activation method. In each activated layer, the inherent strains calculated in the hatching model are applied. The computation and the implementation of the inherent strains method is widely explain in [(8)].

3 Future work

Results are not obtained yet, therefore it is complicated to conclude this paper with clear statements. In a close future, the final implementation of the method and its validation comparing the results with the data available employing high-fidelity simulations of additive manufacturing is to be done. In case the method was proved to be fast enough for practical applications, the possibility of providing it with more accuracy by reducing the simplifications would arise. Summing up, the intention is to find a balance between accuracy and computational time in order to apply it to real cases in industry.

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