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HORIZON 2020

SPECIFICATIONS FOR THERMAL AND STRESS ANALYSIS

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Authors:	Tommaso Zerbi, Stefano Ellero
Quality Controllers:	Michele Chiumenti
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Consisting of

SINTEF	STIFTELSEN SINTEF, Department of Applied Mathematics, Oslo, Norway
Fraunhofer	Fraunhofer IGD, Interaktive Engineering Technologien, Darmstadt, Germany
DFKI	Deutsches Forschungszentrum für Künstliche Intelligenz GmbH DFKI Innovative Factory Systems, Kaiserlautern, Germany
CNR-IMATI-GE	Consiglio Nazionale Delle Ricerche Istituto di Matematica Applicata e Tecnologie Informatiche, Genova, Italy
CIMNE	Centre Internacional de Metodes Numerics en Enginyeria Civil Engineering, Barcelona, Spain
ARCTUR	ARCTUR Racunalniski Inzeniring Doo, R&D, Nova Gorica, Slovenia
BOC	BOC ASSET Management GmbH, Innovation Group, Wien, Austria
Missler	Missler Software Missler Software Service Department, Ramonville St Agne, France
Jotne	Jotne EPM Technology AS, Aeronautics, Space and Defense, Oslo, Norway
STAM SRL	STAM SRL, R&D Department, Genova, Italy
TRIMEK SA	TRIMEK SA, R&D, Altube-Zuia (Alava), Spain
Tronrud	Tronrud Engineering AS, 3D Printing, Hønefoss, Norway
NOVATRA	NOVATRA, Varennes Saint Sauveur, France

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1 EXECUTIVE SUMMARY

The scope of this document is to summarise the main specifications and requirements needed to perform numerical simulation of the production process by Additive Manufacturing (AM). The simulation of the AM process is based on thermal/stress analysis on the manufactured part itself, and is part of the CAxMan design-simulation-manufacturing workflow.

Firstly, an introduction to the whole Work Package 4 is presented, with relevant modules of the output aimed in this part of the CAxMan project, and a focus on the Task 4.1 “Specifications”. Then, three different possible strategies for the definition of the working domain with the activation procedure of the discrete elements composing the model are described.

The core of the document lists all the requirements needed to be given as input to the software tool in order to perform a reliable thermal and/or mechanical simulation of the production process.

Finally, the possible approaches for numerical simulation and future analysis to be performed are mentioned.

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3 INTRODUCTION

The Metal Deposition process occurring during an AM procedure causes a wide range of temperature evolution in the metal powder and in the bulk metal after laser melting. This is due to the highly focused power beam to which the powder layer is submitted during the scanning sequence, in order to obtain the solid part, and also due to the cooling phase after the power beam.

Work Package 4 “Thermal and stress analysis” aims to develop a numerical simulation tool of the Metal Deposition, in order to analyse the previously mentioned temperature evolution and the subsequent stress field generated by the thermal exchanges, finally estimating the residual distortions induced in the manufactured metal part.

The final objective of the whole Work Package is to develop a useful simulation tool enabling the optimization of a design, allowing a minimization of structural issues deriving from these stresses and allowing the design of efficient supporting structures in the part.

The intended simulation tool will be based on a modular software framework, whose structure is shown in Figure 1.

FIGURE 1: WP4 OUTPUT SOFTWARE TOOL MODULES

Figure 1 underlines the three-step structure of the simulation software tool constituting the aimed output of Work Package 4. This comprises:

- A pre-processing module, being a graphical module able to collect all the necessary information to run the numerical simulation. Here the user can specify the process parameters as well as the material data to feed the constitutive models characterizing the material behaviour. The needed parameters are:
  - Domain: CAD geometry representing the part and support structures, or an open space where the AM process will take place;
  - Finite Element (FE) mesh: a discretization of the defined domain into finite geometrical shapes, taking into account the scanning sequence defined, the size of the welding pool and the layer thickness specified;
  - Process Parameters for the AM process;
  - Boundary conditions for thermal and mechanical analysis;
  - Material data: what characterizes the behaviour of chosen material in the entire temperature range;
- A solver module, the software kernel in which the simulation calculations are performed, according to the input specifications collected in the pre-processing phase;
- A post-processing module, where it is possible to view the results obtained from the simulation.

In particular, the present document addresses the Task 4.1 “Specifications”, going through the preliminary requirements to access the numerical simulation. Finally, the possible strategies and approaches for the inputs definition are pointed out, as the domain, such as different physical-model approaches for the numerical simulation itself.

4 STRATEGIES FOR DOMAIN DEFINITION

In this chapter three different possible strategies for defining the working domain are outlined, each of them requiring different data as input to perform the operation. The aim of this phase is to define the FE composing the part to be manufactured (and the relevant support structure) in the virtual space of a software tool. The individuated domain will be used as the boundary for the subsequent stress and thermal simulation.

The first two described strategies are based on the complete knowledge of the scanning sequence used for the material deposition; in the first case the simulation can be run without the solid geometry (3D CAD model), while this information must be available in the second strategy; the third analysed definition mode is a quicker, simplified method, based on the activation of the whole layer composing the 3D geometry, one by one.

4.1 SCANNING SEQUENCE-BASED DOMAIN DEFINITION

The first possibility consists in the definition of a simple virtual box having such dimensions which can contain the geometry to be built-up using the AM process. The size of the box depends on the actual size of the part including the supporting structures used during the material deposition process.

As a further step, the simulation package will perform the slicing of this volume to get a layered domain split according to a pre-defined layer thickness. This thickness corresponds to the actual thickness of the material layer sintered by the heat source during the manufacturing process.

The meshing algorithm will generate the FE discretization required for the FE analysis. Finally, the scanning sequence predefined for the machine (CLI data in ASCII format is the current option) must be used in order to activate the elements belonging to each layer of the domain.

As a result, the final shape of the part produced by AM depends on the material sintering induced by the heat source over the existing powder bed. Similarly, from the numerical point of view, it is possible to start with a large number of elements defining the powder bed for each layer, to be activated (sintered) according to the same scanning sequence of the real process.

Hence, the geometry of the model as well as the definition of the supporting system is not necessary. The mandatory input data is the actual scanning sequence and the layer thickness set for the AM machine.

4.2 3D CAD GEOMETRY-BASED DOMAIN DEFINITION

The second strategy is based on the knowledge of 3D CAD geometry of the part to be simulated, and the geometry of the supporting structure must be available too.

The corresponding volumes defining both the part and the supporting structure must be sliced to get a layered model. Each layer is defined by the polyline that is the intersection of the original model (STEP or STL triangulation of the surface) with the horizontal plane representing the current powder bed level. The volume between two horizontal planes defines the layer.

The meshing procedure will generate the FE mesh necessary for the numerical simulation of the sintering process. Also in this case the scanning sequence (hatching sequence) corresponding to the sintering process must be available to activate the element belonging to each layer.

4.3 WHOLE LAYER-BASED DOMAIN DEFINITION

The third and last proposed domain definition procedure is a simplified alternative to the 3D CAD geometry-based one (i.e., the second approach).

Here, after the model volume has been sliced into a layered model, each entire layer can be activated at once, as if the material was sintered layer by layer in the real AM procedure.

This simplified method can be convenient either when the scanning sequence is not available, or to speed up the simulation strategy in case of a high number of layers, or to decrease the computational requirement for the simulation.

5 REQUIREMENTS FOR SIMULATION PACKAGE

In order to perform a correct domain definition and thermal-stress simulation, the simulation tool needs to receive some input parameters.

In this chapter the required inputs for the domain definition are listed and referred to the strategy choice, together with physical, thermal and mechanical parameters. These characterize the used manufacturing material and are mandatory for the correct thermal-stress simulation.

5.1 DOMAIN DEFINITION INPUT REQUIREMENTS

The three different approaches described in Chapter 2 require different input data in order to be correctly performed.

In the first case (Section 2.1) the user must input the scanning sequence, represented by a CLI (Common Layer Interface) file in ASCII format, together with the meshing algorithm to generate the FE discretization of the volume. The layer thickness defined and set for the AM process is required too.

If the strategy described in Section 2.2 is chosen, the 3D CAD geometry is necessary for individuating the simulation domain. In addition, a slicing tool should be used to split the original domain into a sequence of layers. A meshing algorithm which can discretize the virtual layer is needed as well and the scanning sequence is mandatory.

In the last case (Section 2.3), the 3D CAD model is needed as a STEP or STL file, but here the scanning sequence is not necessary to perform the simulation. The slicing tool is also mandatory for this simplified method.

5.2 PROCESS PARAMETERS

Some parameters are needed to characterize the real AM process, with particular reference to the metal deposition phase. These must be input to the simulation software tool together with the input data listed in Section 3.1, as their values directly affect the material behaviour during the laser sintering and the cooling phase.

In particular, the following physical parameters are mandatory:

- Heat source power [W]
- Laser beam diameter [mm]
- Laser penetration [mm]
- Dimensions of the sintered powder bed: width and thickness [mm]
- Overlapping during scanning sequence [%]
- Powder density [kg/m^3]
- Scanning speed [mm/min]
- Back speed [mm/min]

5.3 BOUNDARY CONDITIONS

In order to perform the numerical simulation of the AM process, it is necessary to specify the boundary conditions for both thermal and mechanical analyses. These conditions depend on the following data:

- Chamber temperature during processing [°C]
- Temperature-Dependent (TD) Heat Transfer Coefficient (HTC) by conduction [W/m^2 °C]
- Temperature-Dependent (TD) Heat Transfer Coefficient (HTC) by convection [W/m^2 °C]
- Heat Transfer Coefficient (HTC) by radiation in terms of material emissivity

All these thermal data are required together with the mechanical constraints due to the clamping system:

- Over points (x-prescription, y-prescription, z-prescription)
- Over lines (x-prescription, y-prescription, z-prescription)
- Over surfaces (x-prescription, y-prescription, z-prescription)

5.4 MATERIAL DATA

The material behaviour in the entire working temperature range is influenced by some intrinsic material parameters, which are then further required data:

- Required for the thermal analysis:
  - Density
  - Specific heat
  - Thermal conductivity
- Required for the phase change analysis:
  - Latent heat
  - Liquidus temperature
  - Solidus temperature
  - Solid fraction
- Required for the stress analysis:
  - Elastic modulus
  - Poisson's ratio
  - Elastic viscosity (rate dependent elasticity)
  - Yield stress
  - Saturation stress (ultimate stress)
  - Isotropic hardening curve (linear or exponential hardening)
  - Kinematic hardening
  - Plastic viscosity (creep)
- Required for coupling:
  - Thermal expansion coefficient
  - Thermal shrinkage (phase change)
  - Reference temperature

6 THERMAL-STRESS ANALYSIS IN CAXMAN

Concerning the thermal-stress simulation analysis, three possible approaches can be identified having different focuses:

- A fully thermal analysis, allowing the selection of the best scanning strategy among several candidates. The objective is to find out the optimal scanning sequence to minimize the thermal field induced by the sintering process. High temperatures generate high thermal deformations and, consequently, higher plastic strains that transform into large distortions and residual stresses. The hatching sequence can also be optimized to prevent the development of inelastic deformations in a single orientation. Nevertheless, this approach is difficult to follow, because the phenomena occurring at metallic microstructure should be studied, and this level of detail in the material study is out of the scope of the CAxMan project.
- A coupled thermo-mechanical simulation, which is extremely computationally expensive but provides the most accurate results. The full size simulation may be run only on parallel HPC infrastructure. A simplified approach is to simulate several (e.g. 10) layers per time, not taking into account the specific scanning sequence, thus reducing the number of steps.
- A fully mechanical simulation can be used to study the residual stresses in the manufactured part induced by the deposition of a sequence of layers with predefined plastic deformations. Those plastic deformations must be estimated in term of the laser power adopted and the predominant orientation of the hatching sequence.

As described above, several approaches are available to define the domain and to perform the numerical simulation of stress evolution and thermal exchanges during the AM procedure. The needed evaluations to select the most appropriate domain definition and simulation approaches will be made in the following of the CAxMan project.

Mainly, the selected demonstrators (NUGEAR by Stam and injection mould by Novatra) will be analysed in their geometrical features (shapes, thicknesses, angles, needed support structures, etc.) in order to understand which of the previously mentioned strategies will be optimal to perform the software simulation.

7 CONCLUSIONS

In order to develop a useful simulation tool, a number of requirements are to be fulfilled. Some data will be collected on the AM process itself and on the metal powder to be used within the CAxMan project.

Further studies on the demonstrators, the partners' knowledge and competences, and the available input data, will lead the Consortium to the selection of the most suitable strategies for the domain discretization, elements activation and simulation approach.

All the data collected in this project phase will be used as input for the next WP4 tasks, which will be aimed at the implementation of the simulation and analysis software tool for the optimization of the AM process.

8 REFERENCES

[1] M. Chiumenti, X. Lin, M. Cervera, W. Lei, Y. Zheng and W. Huang, Numerical simulation and experimental calibration of Additive Manufacturing by blown powder technology. Part I: thermal analysis, (2015) Submitted to Rapid Prototyping Journal.

[2] M. Chiumenti, M. Cervera, A. Salmi, C. Agelet de Saracibar, N. Dialami and K. Matzui, Finite element modeling of multi-pass welding and shaped metal deposition processes, Computer Methods in Applied Mechanics and Engineering, 199 (2010) 2343-2359.

[3] M. Chiumenti, M. Cervera, N. Dialami, B. Wu, J. Li and C. Agelet de Saracibar. "Numerical modeling of the electron beam welding and its experimental validation" (2015) Submitted to Computers and Structures.

[4] M. Chiumenti, C. Agelet de Saracibar and M. Cervera, On the Numerical Modeling of the Thermo-mechanical Contact for Casting Analysis J. Heat Transfer 130, 061301 (2008).

[5] C. Agelet de Saracibar, M. Cervera and M. Chiumenti, On the Constitutive Modeling of Coupled Thermo-Mechanical Phase-Change Problems, International Journal of Plasticity, 17 (2001) 1565-1622.

[6] M. Cervera, C. Agelet de Saracibar and M. Chiumenti, Thermo-Mechanical Analysis of Industrial Solidification Processes, International Journal for Numerical Methods in Engineering, 46 (1999) 1575-1591.

[7] C. Agelet de Saracibar, M. Cervera and M. Chiumenti, On the Formulation of Coupled Thermoplastic Problems with Phase-change, International Journal of Plasticity, 15 (1999) 1-34.

[8] M. Cervera, M. Chiumenti, Q. Valverde and C. Agelet de Saracibar, Mixed linear/linear simplicial elements for incompressible elasticity and plasticity, Comp. Meth. in Appl. Mech. and Eng., 192, 5249-5263 (2003).

[9] M. Cervera, M. Chiumenti and C. Agelet de Saracibar, Softening, localization and stabilization: capture of discontinuos solutions in J2 plasticity, Int. J. Num. Anal. Meth. in Geomechanics, 28, 373-393, (2004).

[10] M. Chiumenti, Q. Valverde, C. Agelet de Saracibar and M. Cervera, A stabilized formulation for incompressible plasticity using linear triangles and tetrahedra, Int. J. of Plasticity, 20, 1487-1504, (2004).

[11] M. Chiumenti, X. Lin, M. Cervera, W. Lei, Y. Zheng and W. Huang.