Steady state numerical calculation of the melt-pool shape

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Abstract. A two dimensional steady-state melting problem is numerically simulated. This task arose during the Selective laser melting (SLM) additive process technology modelling project. Initial problem is formation of residual stresses and, as a consequence, appearance of accumulated deformations (inherent strains) and distortion of final production shape. As solution of this initial problem I suggest development of own appropriate software tool. Development process was divided on 5 stages. Stage 1 is to model the geometric size of the molten bath. A comparison of the results obtained with in OpenFOAM (laserConvBC) and results from similar article.

1. Introduction

Selective laser melting (SLM), also known as direct metal laser sintering (DMLS) or laser powder bed fusion (LPBF), is a rapid prototyping, 3D printing, or additive manufacturing (AM) technique designed to use a high power-density laser to melt and fuse metallic powders together. In SLM, the three-dimensional model of the manufactured part is divided into layers with a thickness from 20 to 100 microns. In each layer, a local heat source (laser beam, etc.) melts metal powder particles and forms "tracks" (welded tracks, welds) which are located at a certain distance from each other. The process of manufacturing parts of SLM includes the heating, melting and solidification of the material by a moving heat source, such as a laser, layer by layer. As a result, different parts of the production component get different reheat and cool cycles. Spatially modified thermal cycles lead to the formation of residual stresses and, as a consequence, to appearance of accumulated deformations (inherent strains) and distortion of final production shape.

2. General problem statement

General problem is software tool development that implements a multiscale approach based on the finite element method, which provides faster determination of residual stresses and distortions for SLM production components. Residual stresses and distortion determination approach includes the calibration of the heat source, the analysis of scanning strategies (shading), the generation of the so-called “mechanical layer equivalent” and its integration into the accelerated structural analysis.
A similar approach was recently implemented in the commercial software such as Simufact Additive by MSC Software. As the practice of using the Simufact Additive has shown, the simulation results are in very good agreement with experimental measurements. The usage of commercial software with closed source code brings following limitations: closed source code, complexity/impossibility of detailed model correction.

3. General problem solution stages

Stages of the proposed software development are follows:

- Stage 1. Solving the problem of temperature distribution in the molten bath in a stationary setting. Depending on the shape and curve of the energy distribution of the laser beam, the melt bath geometry is modeled by solving the heat equation with the substrate/melted layer boundary conditions, unmelted powder, inert gas environment and based on the finite volume method. The solution is the stationary state equation and should give a three-dimensional description of the melting isotherm.
- Stage 2. Solving the temperature distribution problem in the alloyed layer in a quasi-dynamic formulation depending on the technological parameters (speed and beam scanning step), descriptions of the geometry of the moving melt bath and the temperature in the melt bath found in the first stage. This allows us to describe the front of the transition from almost zero conductivity (outside the conduction front) to conductivity immediately ahead of the melt front and to determine the boundaries of the "equivalent mechanical layer" for the next stage.
- Stage 3. Solving coupled thermal problems and structural analysis problems in the top row of finite elements of an “equivalent mechanical layer” containing a fused layer of material. Determination of accumulated deformations in the "equivalent mechanical layer".
- Stage 4. Solving the problem of structural analysis for finite volumes of other lower layers. Calculate accumulated deformations load from the “equivalent mechanical layer”. Calculate the elastic response from the applied load.
- Stage 5. As a result of the solution, the thermal displacements of the finite volume model are determined. Inverting these offsets applied already to the nodes of the STL-file of the geometric model of the production component, i.e. Pre-adjusting the model for negative values of these displacements before generating the control program for building a part, it is possible to level the effects of thermal stresses.

This paper describes the results of Stage 1. In this stage, I simulated the temperature distribution and the melt pool borders, during particles melting with a laser beam.

4. Temperature distribution in the molten bath. Problem description

This paper presents the results of a simulation of the temperature distribution with OpenFOAM library and a comparison of the obtained results with similar works [1, 2], that used commercial tools COMSOL, Ansys and shows proper agreement with experimental results. Several existing studies [3, 4, 5, 6] have employed basic heat-transfer model to investigate the thermal behavior in SLM of metal powders such as stainless steel and titanium alloys and have proposed techniques to simulate the addition of layers with time.

Figure 1 shows the OpenFOAM 3D finite volume model. The powder layer (1E-6 x 1E-6 x 5E-8 m) was meshed with 1.8E6 (300 x 300 x 20) hexahedron elements.

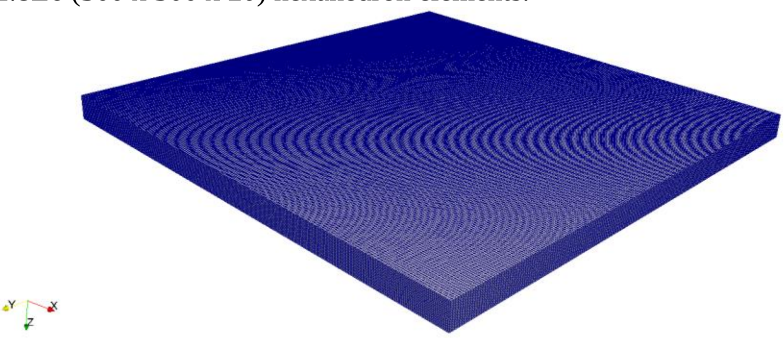

Figure 1. Finite Volume Model.

The following assumptions are made in this simulation:

- The composite powder bed was assumed to be homogeneous and continuous.
- The heat flux from the laser beam was modelled as Gaussian-distributed heat flux and was given directly on the top of the composite powder bed.
- The simulation did not take into account heat loss at the phase transition

- The laser spot was assumed to have a circular shape.
- The convective heat transfer coefficient between the environment and the powder bed was assumed to be a constant.

5. Boundary conditions

Boundary conditions are shown in the Table 1.

Table 1. Boundary conditions.

Value name	Designation	Value
Initial temperature, [K]	T_0	300
Heat Transfer Coefficient for heating, [W/m^2/K]	HTCheating	150
Scanning speed, [mm/s]	heatingTime	1000
Laser power, [W]	power	350
Spot size X, [m]	sigmaX	7E-8
Spot size Y, [m]	sigmaY	7E-8
Constant heat conduction, [W/(m*K)]	kValue	10
Material thermal diffusivity (Aluminium powder), [m^2/s]	DT	5E-06

6. Computational results and analysis

Figure 2 shows the OpenFOAM simulation results, Figure 3 shows simulation results of COMSOL [**1**]. Parameters such as the size of the molten bath and the temperature distribution were compared (see Table 2).

It is assumed that in order to fully melt an alumina particle, the maximum temperature induced by the laser radiation should be higher than the melting point of alumina (2040° C).

Table 2. Results comparison.

Value name	COMSOL model	OpenFOAM model	Difference (COMSOL=100%)
Molten bath length, [µm]	165	190	+15%
Maximum temperature, [° C]	3380	3000	-11%

OpenFOAM results shows enough proper agreement with COMSOL model [1] results. Small differences are caused by different implementation of computational models in OpenFOAM and in COMSOL.

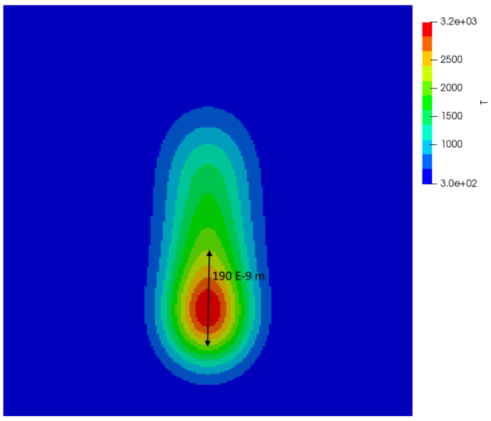

Figure 2. OpenFOAM laser convection simulation. Temperature distribution (K).

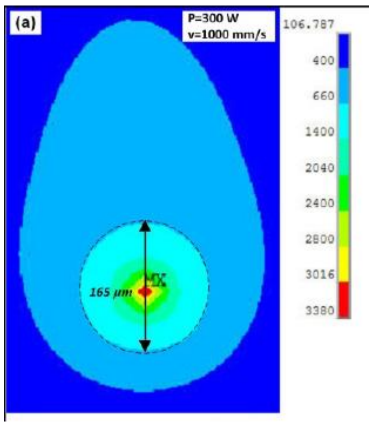

Figure 3. COMSOL laser convention simulation [1]. Temperature distribution (°C).

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7. Conclusion

The current paper shows a good agreement between the results obtained during the simulation in OpenFOAM and in COMSOL [1]. Note that the results of the work [1] showed proper agreement with experimental results. Thus, the OpenFOAM model [7] can be used for further residual stresses model development.

8. References

[1] Peyre, P. Analytical and numerical modelling of the direct metal deposition laser process / P. Peyre, P. Aubry, R. Fabro, R. Neveu, A. Longuet // Journal of Physics D: Applied Physics. – 2008. – Vol. 41(2). – P. 025403. DOI: 10.1088/0022-3727/41/2/025403.

[2] Han, Q. Three-dimensional finite element thermal analysis in selective laser melting of Al-Al2O3 powder / Q. Han, R. Setchi, S. Evans, C. Qiu // Solid Freeform Fabrication: Proceedings of the 27th Annual International Solid Freeform Symposium, 2016.

[3] Labudovich, M. A three dimensional model for direct laser metal powder deposition and rapid prototyping / M. Labudovich, D. Hu, R. Kovacevic // Journal of Materials Science. – 2003. – Vol. 38. – P. 35-49.

[4] Han, Q. Synthesis and characterisation of advanced ballmilled Al-Al2O3 nanocomposites for selective laser melting / Q. Han, R. Setchi, S. L. Evans // Powder Technol. – 2016. – Vol. 297. – P. 183-192.

[5] Khaimovich, A. Optimisation of Selective Laser Melting by Evaluation Method of Multiple Quality Characteristics / A. Khaimovich, I. Stepanenko, V. Smelov // IOP Confirence Series: Materials Science and Engineering. – 2018. – Vol. 302(1).

[6] Khairallah, S. Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones / S. Khairallah, A. Anderson, A. Rubenchik, W. King // Acta Mater. – 2016. – Vol. 108. – P. 36-45.

[7] LaserCase OpenFOAM case sources [Electronic resource]. – Access mode: https://github.com/j-avdeev/LaserCase (02.12.2018).

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