Ullah, Rizwan; Lian, Junhe; Wu, Jiaojiao; Niemi, Esko

Effect of Finite Element Mesh Size and Time-Increment on Predicting Part-Scale Temperature for Powder Bed Fusion Process

Published in:
Achievements and Trends in Material Forming- Peer-reviewed extended papers selected from the 25th International Conference on Material Forming, ESAFORM 2022

DOI:
10.4028/p-16auf3

Published: 01/01/2022

Document Version
Publisher's PDF, also known as Version of record

Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 341-348
doi:10.4028/p-16auf3

Submitted: 2021-12-17
Revised: 2022-02-03
Accepted: 2022-02-18
Online: 2022-07-22

Effect of Finite Element Mesh Size and Time-Increment on Predicting Part-Scale Temperature for Powder Bed Fusion Process

Rizwan Ullah[1,a], Junhe Lian[1,b], Jiaojiao Wu[1,c], Esko Niemi[1,d]

[1]Advanced Manufacturing and Materials, Mechanical Engineering Department, Aalto University, Finland

[a]rizwan.ullah@aalto.fi, [b]junhe.lian@aalto.fi, [c]jiaojiao.wu@aalto.fi, [d]esko.niemi@aalto.fi

Keywords: FE simulation, Powder bed fusion, thermal history, mesh and time lumping, residual stress prediction

Abstract. Simulating powder bed fusion processes (PBF) can reveal temperature evolution in transient mode. Accurate temperature prediction using finite element (FE) method demands both mesh and time increments to be very small; thus, requiring a high computational cost. To avoid this, in part-scale simulation, coarse meshes representing multiple powder layers added at once, are usually used which results in fast solving of FE models. Powder layers and time increments are lumped in such a configuration, which results in a deviation of the temperature history. This research proposes a methodology to predict the nodal temperature (NT) due to the combined effect of space and time lumping for part-scale FE thermal simulation for PBF processes. It shows its effects in predicting both the local temperature history and the average far-field temperature.

Introduction

With the increased impact of additive manufacturing (AM), simulating AM processes to predict the properties of AM materials [1] is also gaining more interest. Powder bed fusion (PBF) process is one of seven ISO/ASTM approved AM technologies in which thermal energy is used to selectively melt powder material, which after cooling solidifies and hence produces new shapes [2]. Powder material (often in 20-60 μm size) is spread layer after layer, using a recoater/spreader which takes material from powder feedstock at one side of the build chamber and spread it on build-platform/substrate. Laser sintering (LS) is a PBF process utilizing one or more laser source/s as heat input to melt and fuse powder particles at the surface. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Direct Metal Laser Sintering (DMLS) are often referred to same LS processes used for producing metal parts. A limited number of metal powder materials are now available to be processed using LS, including steels, aluminum alloys, cobalt-chrome, copper, nickel alloys, and titanium alloys.

Usually, in AM processes, very localized and fast-moving heat source/s activate the material so rapidly and resulting in extreme temperature evolution with time. These fluctuating temperatures are of prime interest as they affect solidification, solid phase transformation, and even intrinsic heat treatment processes that all are decisive for the microstructure of the materials. These microstructural features do not only include phases, grain-level, and dislocation-level characteristics, but also some more critical ones, such as AM defects [3] and residual stresses [4].

A lot of effort is put into studying temperature evolution during PBF processes, using commercially available finite element (FE) packages [5–7]. Recent studies [8–10] have validated the use of the Abaqus plugin which simplifies laser path manipulation. For such a case, simulation is usually conducted in two sequentially coupled steps:

- A transient heat transfer analysis, or thermal simulation to predict temperature evolution with time
- Structural simulation, driven as a result of thermal load applied from thermal simulation to predict stresses, strains, deformations, etc.

In the thermal simulation, typical parameters that can influence peak temperature prediction are laser speed, power, absorption coefficient, hatch distance [11], laser spot diameter, thermal properties

of materials, baseplate material, ambient temperature, and most importantly selection of mesh size and time increment for the analysis. The simplest case is the one where very fine mesh size (considering at least one powder layer thickness per element, e.g., 20-70 μm) is used and time increment is chosen as small as 0.1-2 milliseconds (ms) or even smaller.

FE model is solved using time and space discretization. Time increment (user-specified) represents the frequency at which partial differential equations are solved and so time resolution of the predicted output field, depends on time increment. Additionally, output resolution depends on mesh size. Nodal distance in meshing can be selected independently (referred here as mesh size). Smaller nodal distance would result in a larger number of elements that can fit in the same volume and similarly more nodes that would be solved in FE-solver during simulation. Consequently, with very fine mesh and small time increments, enhanced accuracy of the solution is possible, thus forming a high-fidelity simulation.

In LS, cooling rates are extremely high (10^5 °C/s) [12] during the melting and cooling process. In this context, a high-fidelity simulation can only capture peak temperature evolution accurately. However, this type of modeling requires significant computational resources, due to its micrometer-level mesh and microsecond-level time increment. On the other hand, low-fidelity simulations assume larger elements added at once thus representing multiple powder layers in FE simulation, also known as layer lumping [13]. In this configuration, time increments are typically larger (more than 1 second). This time can also be set as inter-layer deposition time (including laser irradiation time and newly deposited layer cooling time). This modeling approach is particularly useful for the part-scale domain, to speed up the simulation. Such simulation can only capture far-field temperature evolution. Eventually, the goal is to balance the computational effort and high-fidelity accuracy.

Thermo-mechanical FE simulations can be run using Abaqus and AM Modeler (Abaqus released plugin). In previous research [14], residual strains were predicted for the NIST benchmark (AMB2018-01) [15] using the Abaqus plugin. However, the selection procedure for determining initial temperature (750 °C) was unclear for structural simulation [14], when mesh and time lumping are considered for part-scale simulation. Therefore, the aim of this study is to fill this gap and propose the methodology to determine peak temperature compensation in a lumped model as a result of laser melting, which later on can be used as initial temperature [16] for structural simulation to accurately predict residual stresses for powder bed fusion processes.

Methodology

FE Model setup:

In this study, a thermo-mechanical FE simulation model is developed for a rectangular plate with dimensions of 14 mm long, 2 mm wide with varying height using the commercially available FE package, Abaqus. In the FE model, a rectangular plate is placed on a substrate (dimensions: 16 mm long, 4 mm wide, and 5.2 mm high). The substrate is partitioned as shown in Figure 1 and meshed using 1 mm global size for 5 mm height while an additional 0.2 mm is meshed using 0.2 mm seeds. Abaqus ‘tie’ type constraint is used to connect plate and substrate so that heat transfer can occur between plate and substrate. The initial temperature field for the plate and substrate is fixed as 40 °C and 80 °C respectively. Figure 1 shows the plate on substrate model setup, as used in the simulation. Figure 1 (c) and (d) show two meshing schemes in zoomed view, in which the plate is meshed. Mesh size is the same along all three axes for each case. Fig 1 (c) depicts ten separate powder layers of thickness 0.02 mm each (mesh size=0.02 mm) while Fig 1(d) represents the case where ten combined powder layers (10 x 0.02 mm =0.2 mm) are being added at once, using one (mesh size=0.2 mm) element. The former case is high-fidelity while the latter represent low-fidelity configuration.

Temperature-dependent thermal and mechanical properties of INC-625 [14] are used in this simulation model as material, both for plate and substrate.

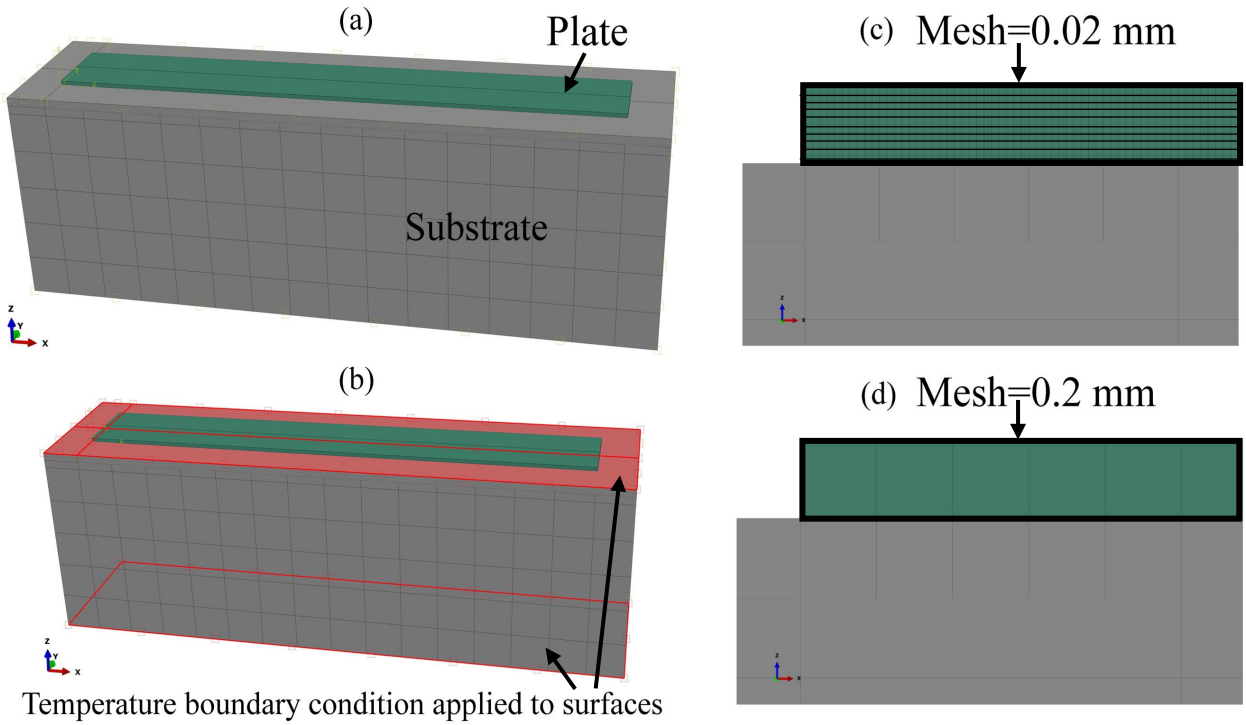

Figure 1: FE model (a) Plate (green) and substrate (grey) (b). Fixed temperature boundary condition applied in FE model (c). Ten separate powder layers with mesh size 0.02 mm per element (d). 10 combined layers lumped into one 0.2 mm element.

AM model setup:

Laser parameters (laser type, speed, power, absorption coefficient) and material spreading/activation needed for the simulation are taken from the literature [14]. A concentrated laser model (type) is used in this study. Printing parameters used in this study are summarized in Table 1.

Table 1: Fixed Printing Parameter used in FE Model.

Laser power	195 W	Laser Speed	800 mm/s
Laser absorption coefficient	0.45	Baseplate Temperature	80 °C
Ambient Temperature	40 °C		

Abaqus uses internal subroutines to activate the material (spread powder layers) according to the time points and roller movement (on/off), as described by the roller-eventseries. Similarly, laser-eventseries must be defined to move laser using start-end timepoints and laser power (in watts or milliwatts). These eventseries are created using 800 mm/s speed for 195 W laser.

Table 2 contains eventseries used for laser and roller according to AM-Modeler template. Roller starts depositing 0.02 mm thick elements at time=0 second (s) from coordinates 0,1,0.02 (X,Y,Z coordinates) to 14,1,0.02 coordinates and finishes at time=0.0039 s. As the second step, the laser starts moving at 0.007 s, from 0,1,0.02 coordinates and finishes at 14,1,0.02 coordinates at 0.0245 s using 195 W power. This cycle then continues if more than one layer is added in the eventseries definition in AM-Modeler, as described in Table 2. Delay time between two laser passes is set to 5 milliseconds. Roller-speed (the speed with which material is deposited) is not considered critical in this simulation and is arbitrarily chosen.

Variable parameters:

Time increment is varied for 0.02 mm mesh scheme and lumping temperature is eventually predicted using the proposed strategy, as summarized in Figure 2. Three different mesh sizes are used in this study, i.e., 0.02 mm, 0.1 mm, and 0.2 mm. Table 3 summarizes mesh sizes and notations used in this research.

Table 2: Laser eventseries and Roller-eventseries used for moving laser and depositing material in Abaqus.

Laser Eventseries					Roller Eventseries				
Time (s)	X (mm)	Y (mm)	Z (mm)	Power (mW)	Time (s)	X (mm)	Y (mm)	Z (mm)	On/Off
0.007	0	1	0.02	195000	0	0	1	0.02	1
0.0245	14	1	0.02	0	0.0039	14	1	0.02	0
0.025	0	1	0.04	195000	0.0246	0	1	0.04	1
0.0425	14	1	0.04	0	0.0247	14	1	0.04	0
0.042989	0	1	0.06	195000	0.0426	0	1	0.06	1
0.060489	14	1	0.06	0	0.0427	14	1	0.06	0
0.060989	0	1	0.08	195000	0.060589	0	1	0.08	1
0.078489	14	1	0.08	0	0.060689	14	1	0.08	0
0.078989	0	1	0.1	195000	0.078589	0	1	0.1	1
0.096489	14	1	0.1	0	0.078689	14	1	0.1	0
0.101489	0	1	0.12	195000	0.096589	0	1	0.12	1
0.118989	14	1	0.12	0	0.096689	14	1	0.12	0
0.123989	0	1	0.14	195000	0.119089	0	1	0.14	1
0.141489	14	1	0.14	0	0.119189	14	1	0.14	0
0.146489	0	1	0.16	195000	0.141589	0	1	0.16	1
0.163989	14	1	0.16	0	0.141689	14	1	0.16	0
0.168989	0	1	0.18	195000	0.164089	0	1	0.18	1
0.186489	14	1	0.18	0	0.164189	14	1	0.18	0
0.191489	0	1	0.2	195000	0.186589	0	1	0.2	1
0.208989	14	1	0.2	0	0.186689	14	1	0.2	0

Table 3: Mesh sizes varied and equivalent number of powder layers per element. Powder layer thickness is fixed, i.e., 0.02 mm.

Mesh size	No. of powder layers per element	Notation
0.02 mm	One layer per element	1 LpE (Fig 1 c)
0.1 mm	Five layers per element	5 LpE
0.2 mm	Ten layers per element or	10 LpE (Fig 1 d)

Proposed methodology:

The objective of this study is to formulate a methodology that bridges the gap between high and low-fidelity simulations. Both configurations are needed to predict residual stresses and deformations at part scale level (considering lumped layers).

In the proposed methodology, as the first step, a minimum mesh size equivalent to actual powder layer thickness must be used in the FE model. In our study, a mesh size of 0.02 mm is considered. From the literature, the melting history of Inconel-625 using 195-watt laser power at 800 mm/s speed is determined and set to as reference temperature, or T_ref (it was found to be approximately 1600 °C [12]). Time increment is then varied to achieve this T_ref temperature. Using 0.02 mm mesh size, time increment was found to be 0.0028 s, with which T_ref can be achieved. This concludes high-fidelity simulation.

In layer lumping, multiple powder layers are added as one element depending upon the choice of user. Mesh size must be integer multiple of layer thickness considered. In this study, 0.1 mm mesh (5 LpE) and 0.2 mm mesh (10 LpE) are considered to represent 5 and 10 layers added into one element (Figure 1). Thermal simulation using time-increment of 0.0028 s is run to determine peak temperature measured using lumped mesh and output nodal temperature (NT) is referred to as T_mesh. T_mesh is specific for mesh size and changes with mesh size.

Next, time-lumping is considered, since it is assumed that multiple layers are deposited at once. For the 5 LpE case, a time-increment of 0.096489 s is used while for the 10 LpE case 0.208989 s is

used (calculated based on Table 2). This time includes a 5 ms delay as well. Resulted NT is designated as T_inc.

As the final step, the difference between T_mesh and T_inc provides combined mesh-time-lumping temperature or T_lump. This lumping temperature can then be used as the initial temperature for setting structural simulation to predict residual stresses in a part-scale model. For all cases, the average peak temperature is measured at unique FE nodes, as shown in Fig 4.

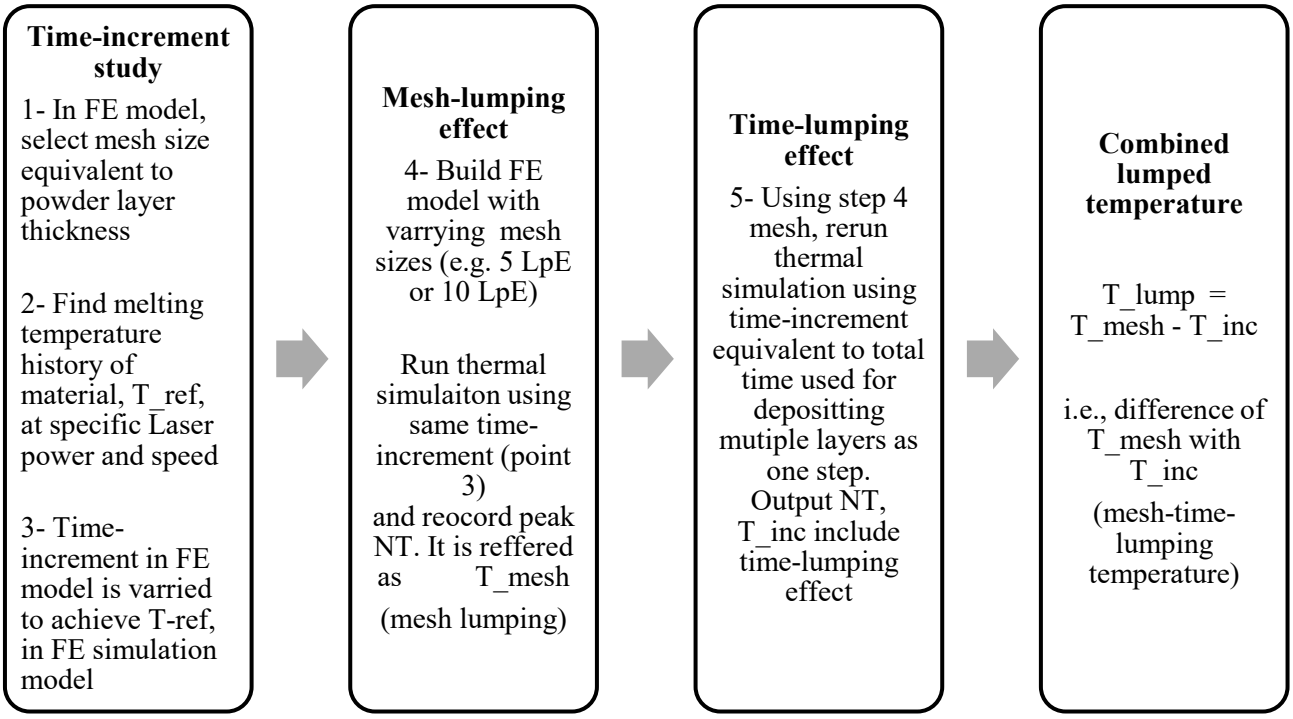

Figure 2: Methodology for predicting lumping temperature due to mesh size and time-increment effect.

Results and Discussion

FE thermal simulation is run following the proposed methodology as described in Figure-2. Time increment is varied to find the peak temperature of 1600 ℃. At 0.0028 s time increment, the output temperature of 1602 ℃ is measured using the mesh size of 0.02 mm (one powder layer). Output NT result is shown in Figure 3, representing high-fidelity simulation.

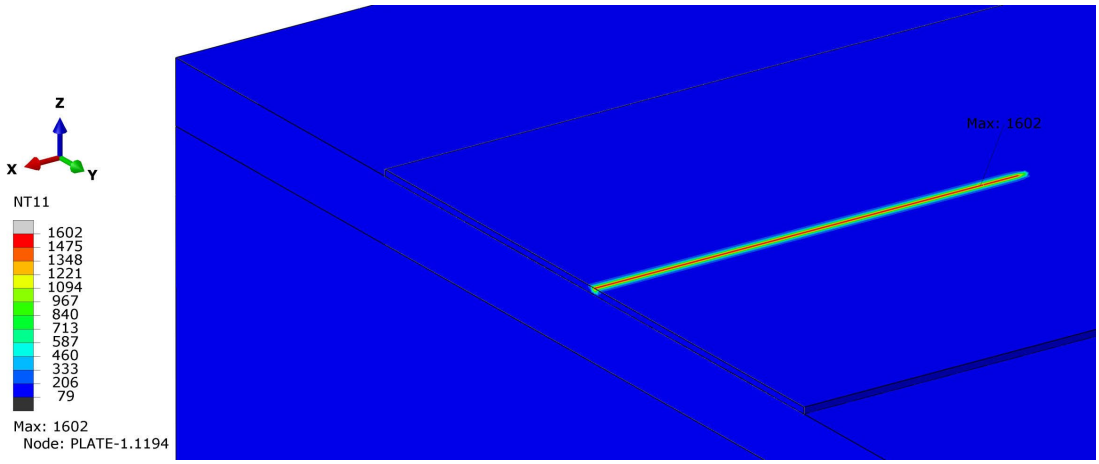

Figure 3: Nodal temperature predicted using time-increment=0.0028 s. Section cut at X=7 mm.

For the low-fidelity configurations, two meshes cases, i.e., 5 LpE and 10 LpE were simulated using 0.0028 s time increment and results are reproduced in Figure 4. A decrease in predicted temperature is due to the larger mesh size. This is referred to as the mesh-lumping effect and denoted as T_mesh (Fig. 2)

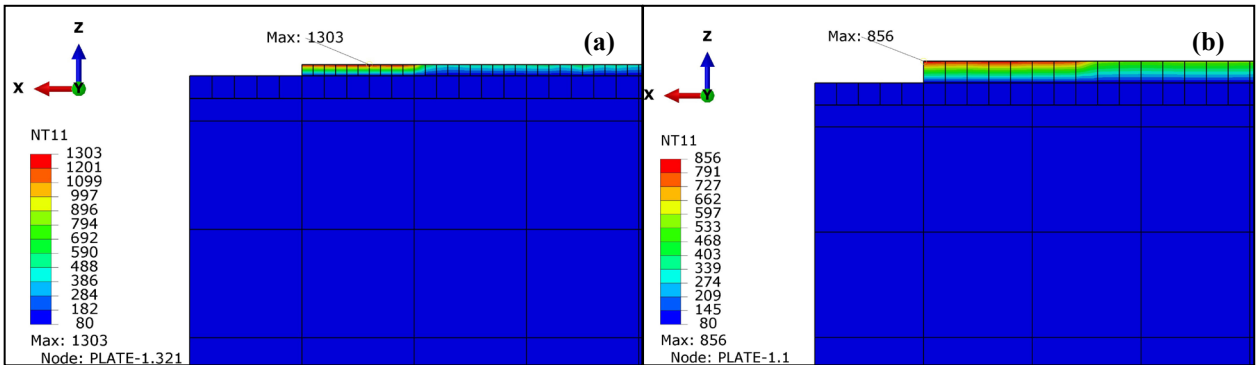

Figure 4: Temperature predicted using time-increment=0.0028 s for both cases: (a) 5LpE (b). 10LpE. Section cut at Y=1 mm.

Time-lumping thermal simulation results are shown in Figure 5. It is observed that the difference of temperature due to meshing and time-increment can provide a combined mesh-time lumping effect on peak nodal temperature predicted. Table 4 enlists the difference in T_mesh and T_inc for two cases. The proposed strategy has predicted lumped temperature which is only 2.53% lower than the previously reported value of 750 °C [14]. T_lump implies that the mesh-time lumping effect can be avoided by considering 750 °C as the initial temperature for structural simulation for 0.2 mm mesh size.

Table 4: Mesh-time lump temperature for 0.1 mm and 0.2 mm meshes.

Mesh	T-lump=T_mesh – T_inc	Comments
5LpE	1303-328=975°C	
10LpE	854-123=731 °C	2.53 % lower than 750 °C

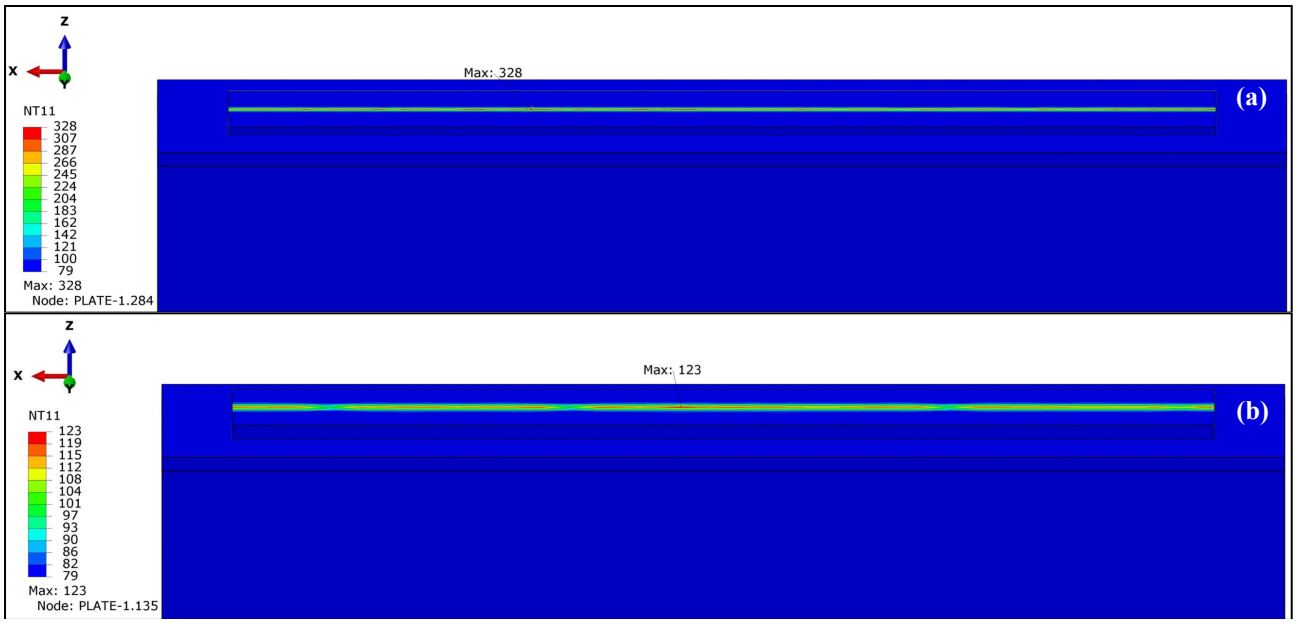

Figure 5: Temperature predicted using (a) lumped time for 5 layers=0.096489 and (b) lumped time for 10 layers= 0.208989.

Summary of output NT measured for 1 LpE and 10 LpE is presented in Figure 6. NT is measured at each of 10 layers in 1 LpE case (measured at Y=1mm and X=7 mm) while for 10 LpE case, NT is measured at 0.2 mm height only (at Y=1mm and X=7 mm). For better readability, only the first peak

of NT is plotted for ten layers in 1 LpE case and other lower temperature peaks are omitted. Results suggest a non-uniform rise in NT as more layers are deposited for 1 LpE case while NT stays approximately constant for 10 LpE. This suggests 10 LpE model might not be useful for predicting the actual temperature history of Inconel-625.

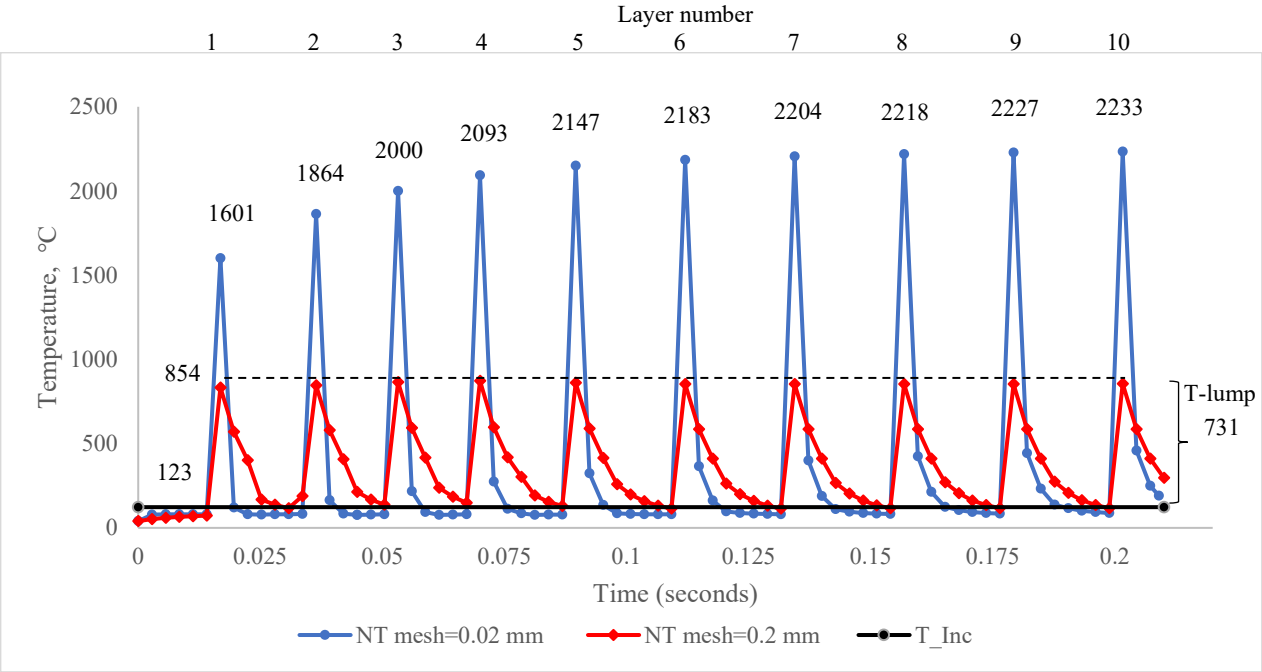

Figure 6: Summary of temperature prediction using one layer per element with 0.02 mm mesh and 10-layers lumped per element with 0.2 mm mesh.

Summary

This study outlines the effect of space and time lumping on peak nodal temperature prediction in finite element analysis for powder bed fusion process simulation. The main outcome of this research is that a significant difference is found in thermal simulation using high and low-fidelity configurations. The space and time lumping in the low-fidelity thermal simulation results in lower peak temperature prediction. Therefore, a methodology is proposed to consider the effect of space and time lumping, providing temperature compensation for part-scale level structural simulation to reach the level of accuracy as the high-fidelity simulation.

References

[1]. Mukherjee T, Zhang W, DebRoy T (2017) An improved prediction of residual stresses and distortion in additive manufacturing. Comput Mater Sci 126:360–372. https://doi.org/10.1016/j.commatsci.2016.10.003

[2]. ISO/ASTM 52900:2015(en), Additive manufacturing — General principles — Terminology. https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en. Accessed 30 Nov 2021

[3].Ullah R, Akmal JS, Laakso SVA, Niemi E (2020) Anisotropy of additively manufactured AlSi10Mg: threads and surface integrity. Int J Adv Manuf Technol 107:3645–3662. https://doi.org/10.1007/s00170-020-05243-8

[4]. Dunbar AJ, Denlinger ER, Gouge MF, Michaleris P (2016) Experimental validation of finite element modeling for laser powder bed fusion deformation. Addit Manuf 12:108–120. https://doi.org/10.1016/j.addma.2016.08.003

[5]. Huang Y, Yang LJ, Du XZ, Yang YP (2016) Finite element analysis of thermal behavior of metal powder during selective laser melting. Int J Therm Sci 104:146–157. https://doi.org/10.1016/j.ijthermalsci.2016.01.007

[6]. Williams RJ, Davies CM, Hooper PA (2018) A pragmatic part scale model for residual stress and distortion prediction in powder bed fusion. Addit Manuf 22:416–425. https://doi.org/10.1016/j.addma.2018.05.038

[7]. Zhang Y, Zhang J (2017) Finite element simulation and experimental validation of distortion and cracking failure phenomena in direct metal laser sintering fabricated component. Addit Manuf 16:49–57. https://doi.org/10.1016/j.addma.2017.05.002

[8]. An N, Yang G, Yang K, et al (2021) Implementation of Abaqus user subroutines and plugin for thermal analysis of powder-bed electron-beam-melting additive manufacturing process. Mater Today Commun 27:102307. https://doi.org/10.1016/j.mtcomm.2021.102307

[9]. Bonifaz EA, Mena A (2021) Directed Energy Deposition Additive Manufacturing Process Simulated with ABAQUS AM Modeler. Int J Robot Eng 6:034

[10]. Bhandari S, Lopez-Anido RA (2020) Discrete-Event Simulation Thermal Model for Extrusion-Based Additive Manufacturing of PLA and ABS. Materials 13:4985. https://doi.org/10.3390/ma13214985

[11]. Calignano F, Manfredi D, Ambrosio EP, et al (2013) Influence of process parameters on surface roughness of aluminum parts produced by DMLS. Int J Adv Manuf Technol 67:2743–2751. https://doi.org/10.1007/s00170-012-4688-9

[12]. Gan Z, Lian Y, Lin SE, et al (2019) Benchmark Study of Thermal Behavior, Surface Topography, and Dendritic Microstructure in Selective Laser Melting of Inconel 625. Integrating Mater Manuf Innov 8:178–193. https://doi.org/10.1007/s40192-019-00130-x

[13]. Ganeriwala RK, Strantza M, King WE, et al (2019) Evaluation of a thermomechanical model for prediction of residual stress during laser powder bed fusion of Ti-6Al-4V. Addit Manuf 27:489–502. https://doi.org/10.1016/j.addma.2019.03.034

[14]. Yang Y, Allen M, London T, Oancea V (2019) Residual Strain Predictions for a Powder Bed Fusion Inconel 625 Single Cantilever Part. Integrating Mater Manuf Innov 8:294–304. https://doi.org/10.1007/s40192-019-00144-5

[15]. AMB2018-01 Description. In: NIST. https://www.nist.gov/ambench/amb2018-01-description. Accessed 10 Nov 2021

[16]. Yang Y, Allen M, London T, Oancea V (2019) Residual Strain Predictions for a Powder Bed Fusion Inconel 625 Single Cantilever Part. Integrating Mater Manuf Innov 8:294–304. https://doi.org/10.1007/s40192-019-00144-5