COMSOL CONFERENCE 2020 NORTH AMERICA

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Numerical Modeling of Wire Directed Energy Deposition Additive Manufacturing (Wire-DED) Process

North America, 7-8 Oct 2020

Directed Energy Deposition (DED)

Wire-DED: Process Principle

- DED System
  - Co-axial nozzle with focused laser and a wire-feeder, both intersecting at a common focal point generally in an inert environment
- Process Physics
  - The energy density generated at a particular point leads to the melt pool formation and incoming wire is fed in the melt-pool leading to the formation of a bead
- Wire-DED Advantages
  - Fabrication of larger parts as compared to Powder-DED
  - Almost no material wastage as compared to Powder-DED

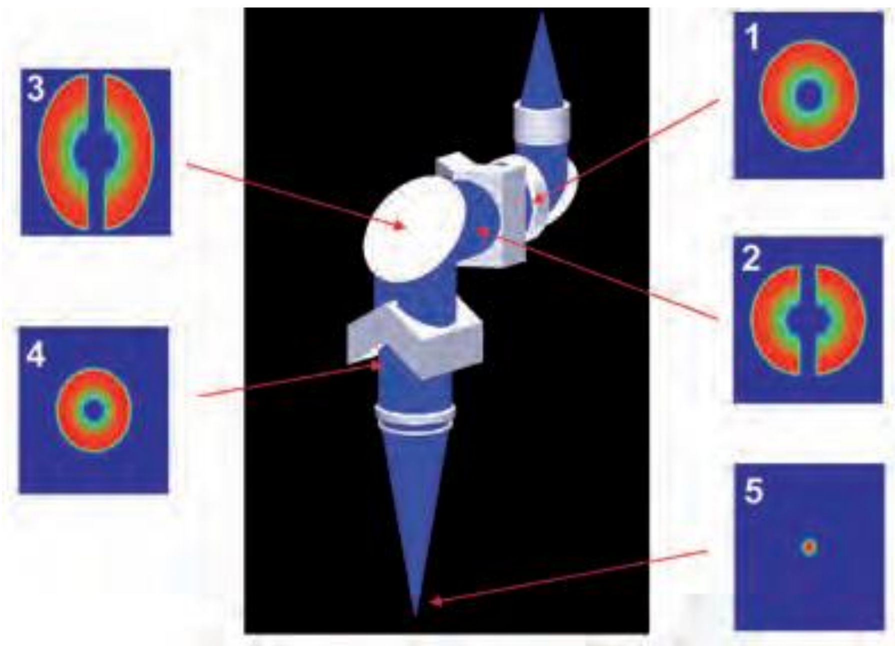

Figure 1: Beam Shaping Principle
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BEAM SHAPING PRINCIPLE
1 ring-shaped laser beam profile
2 Opening of the beam profile
3 Coaxial feeding of the filler wire
4 Closing the beam profile
5 Focussing to a closer laser spot

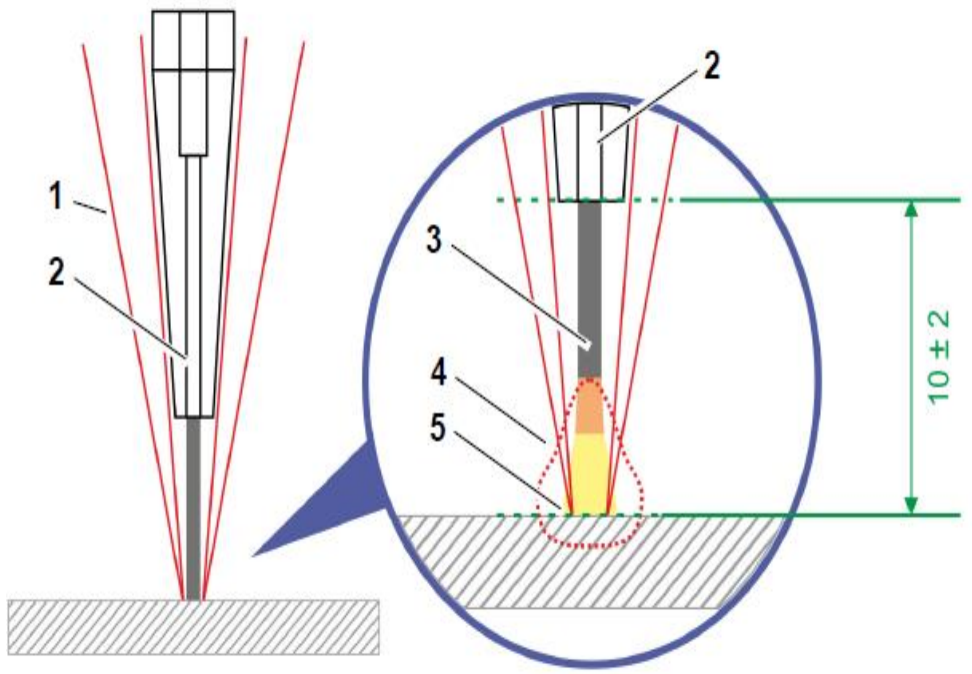

Figure 2: Wire-DED Process Principle

Wire nozzle distance-Process Principle
1 Annular beam
2 Wire nozzle
3 Wire Stick-out
4 Melt-Pool
5 Workpiece Surface

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Why model Wire-DED process ?

Distortion & Residual Stresses

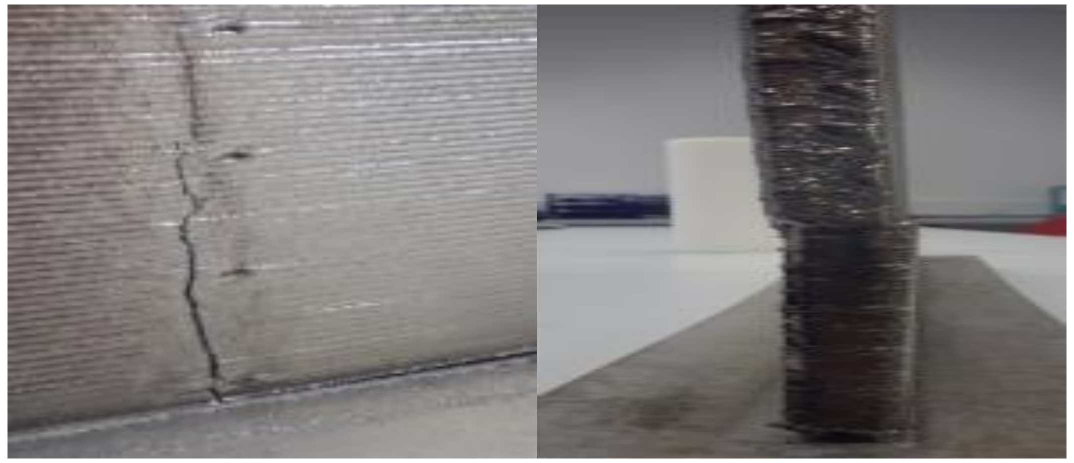
- DED Process
  - Due to the complex thermal cycles in Wire-DED process, it leads to the generation & accumulation of unwanted levels of ***distortion & residual stresses***

- DED Disadvantages
  - Unwanted levels of distortion & residual stresses
  - Leads to crack formations, misalignment & failure of parts

- DED Process still not understood due to
  - It involves complex multiple heat cycles
  - Lack of understanding of accumulation of distortion & residual stress
  - Complicated evolution of microstructure of build materials

- *Modeling can help to*
  - *Develop the better understanding of process physics*
  - *Predict & minimize deformation & residual stresses*
  - *Achieve the objective FABRICATE PART FIRST TIME RIGHT*

Figure 3: Wire-DED fabricated part & Distortion accumulation can lead to rejection of part



(a) Crack (b) Mismatch

Figure 4: DED fabricated part failure due to crack generation & misalignment during & after deposition

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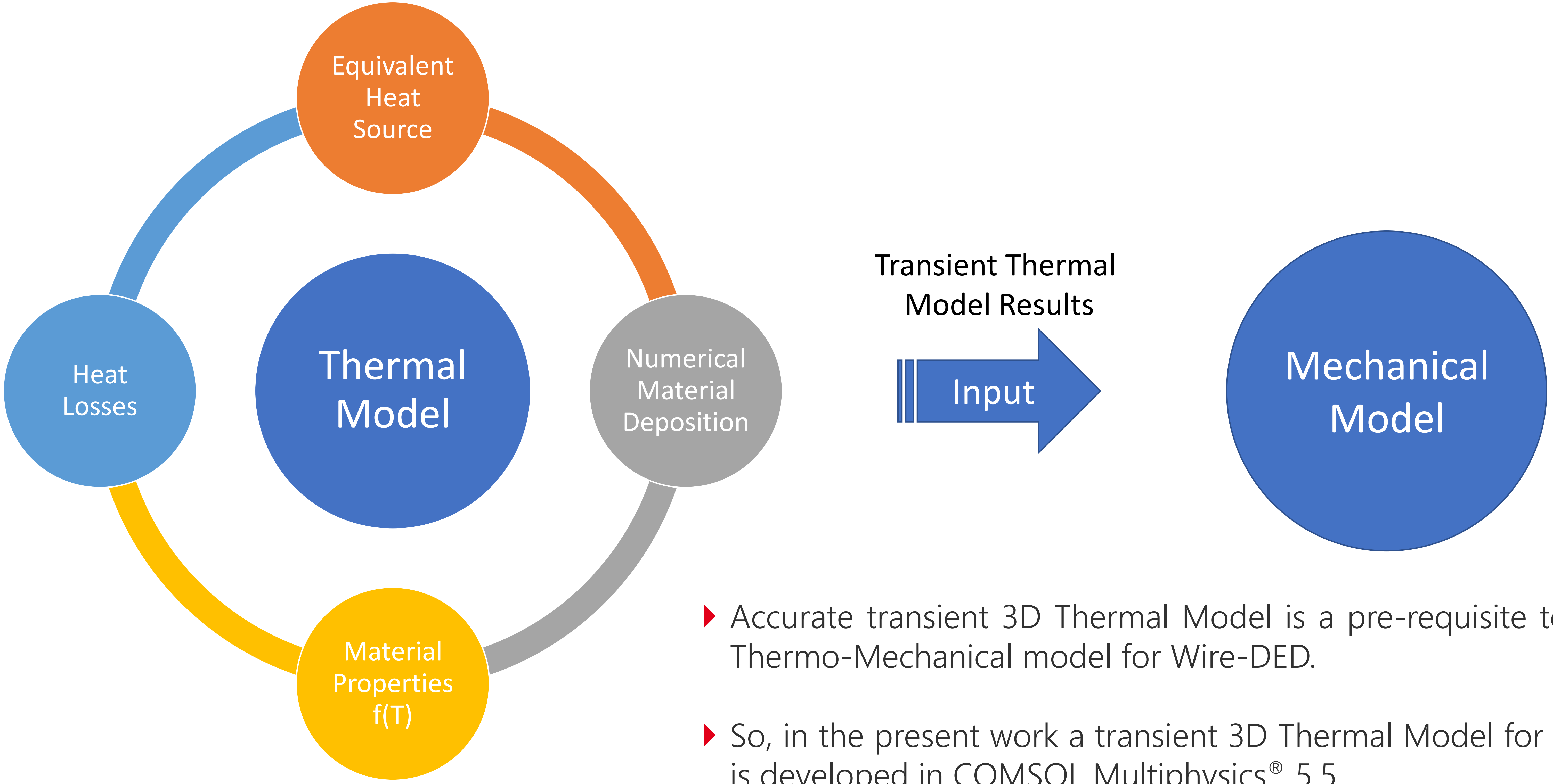
Numerical Model

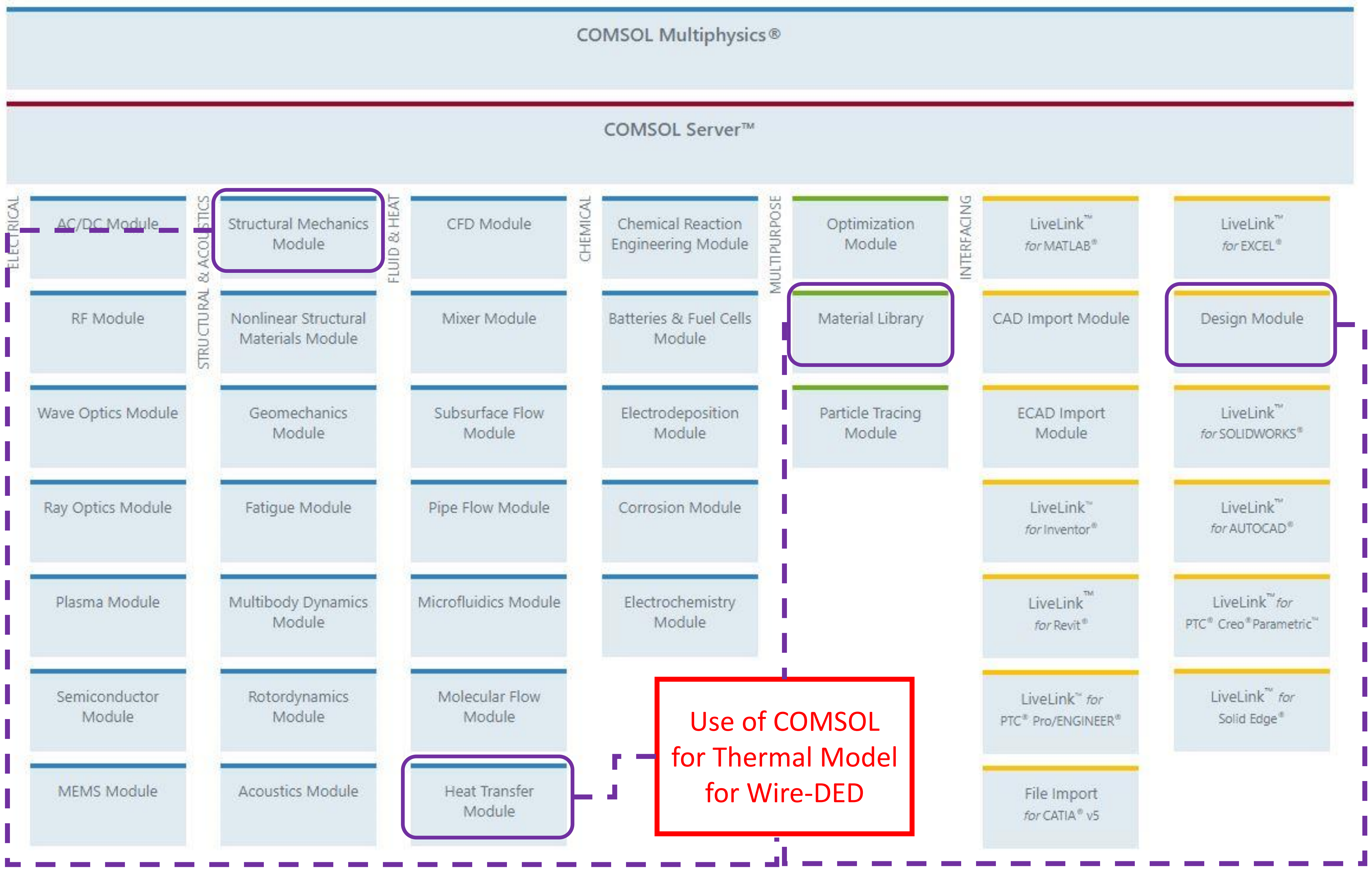
Development of the model for Wire-DED



- Accurate transient 3D Thermal Model is a pre-requisite to develop Thermo-Mechanical model for Wire-DED.
- So, in the present work a transient 3D Thermal Model for Wire-DED is developed in COMSOL Multiphysics® 5.5.

Thermal Model for Wire-DED

Use of COMSOL Multiphysics® 5.5



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Thermal Model for Wire-DED

Numerical Model Development

PROCESS PHYSICS

LASER + ***WIRE FEEDING***

↓

MELTING

↓

MELT POOL & SOLIDIFICATION
Dynamics
Heat transfer

↓

CONDUCTION

↓

BUILD PART AND SUBSTRATE HEAT LOSS

NUMERICAL MODEL

Equivalent Numerical Heat Source

$$Q(x,y,z) = \frac{6\sqrt{3}AP}{abc\pi\sqrt{\pi}} exp\left(-\left(\frac{3(x - V*t)^2}{a^2} + \frac{3(y)^2}{b^2} + \frac{3(z)^2}{c^2}\right)\right)$$

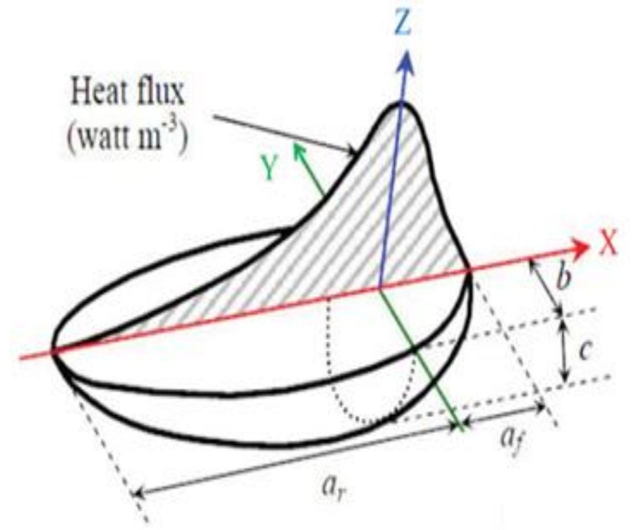

Figure 5: Intensity Distribution Goldak Double Ellipsoid Source

Numerical Material Addition/Deposition

- Quiet/Active Element Activation
- Quiet Elements: Weak Thermal Properties
- Active Elements: Temperature dependent Thermal properties (Metal)
- Activation Criterion:

$$exp\left(-\left(\frac{3(x)^2}{a^2} + \frac{3(y)^2}{b^2} + \frac{3(z)^2}{c^2}\right)\right) \geq 5\%$$

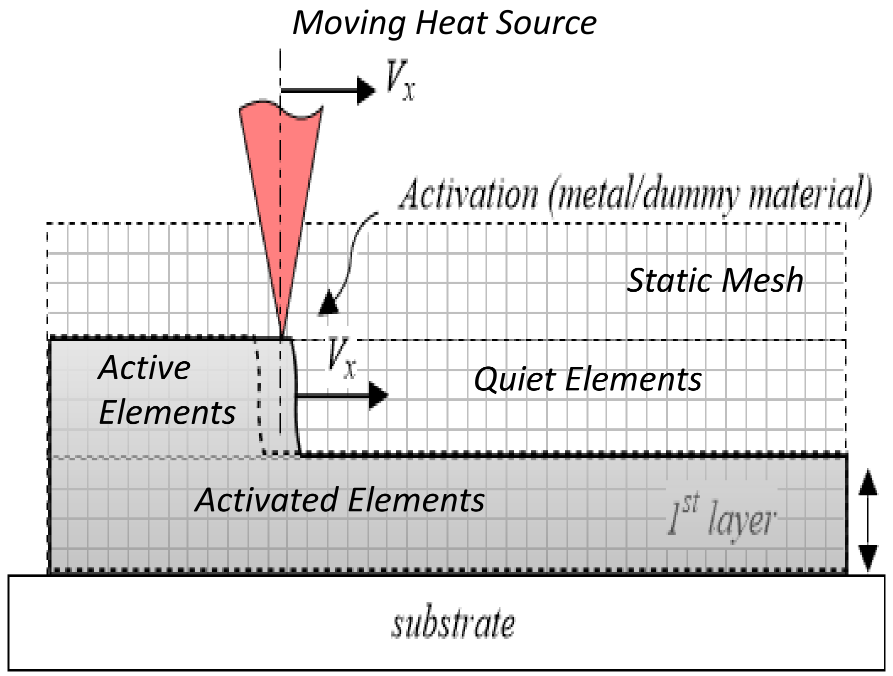

Figure 6: Schematic of Quiet/Active Element Activation method

Heat Equation

$$\rho(T)C_p^*(T)\frac{\partial T}{\partial t} + \nabla . q = 0, where\ q = -k^*(T)\nabla T$$

Heat Losses

$$Q_{loss} = -h_{FC}(T_s - T_a) - \varepsilon\sigma(T_s^4 - T_a^4)$$

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Thermal Model for Wire-DED

Experiment (at IREPA LASER)

Experiment Set-Up

- Process Parameters
- Deposition Pattern
- Temperature Location & Measurement
- Melt-Pool Analysis

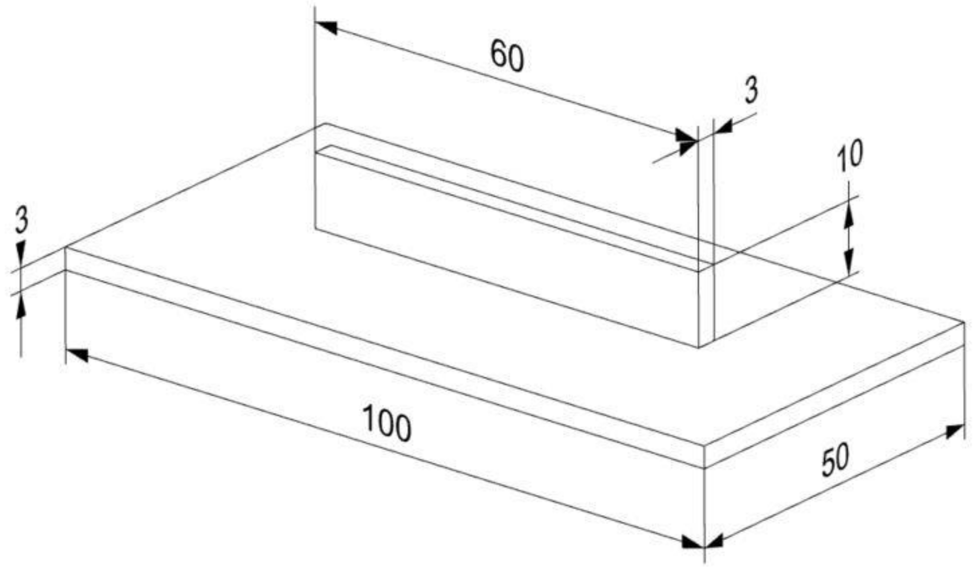

Figure 7: Substrate & Build Part Schematic

Process Parameter	Value
Feedstock Type	
Substrate & Feedstock Material	Stainless Steel 316L
Mass feed rate	1.5 m/min
Dimensions	
Substrate	100×50×3 mm^3
Deposited Layer	60×3×1 mm^3
Number of Layers	10
Laser Parameters	
Laser Power	2300 Watt
Laser Scan Speed	1000 mm/min
Laser Spot Radius	2.2 mm

Table 1: Process parameters

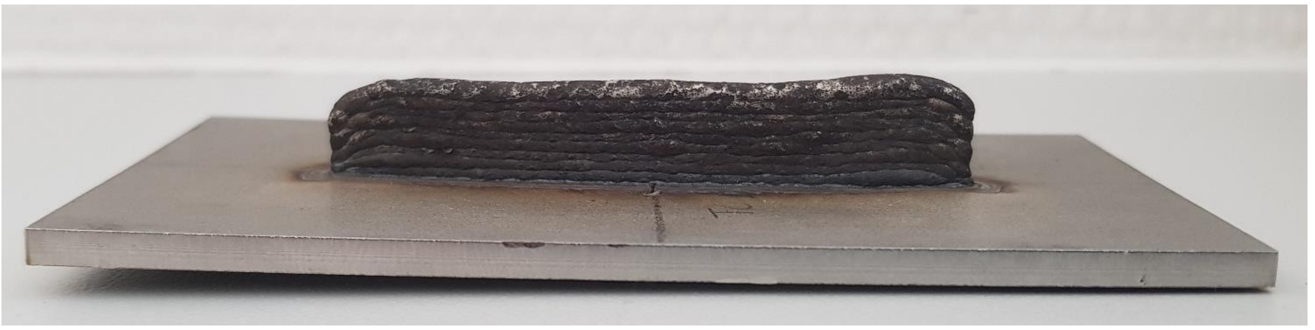

Figure 9: Fabricated part after the deposition process

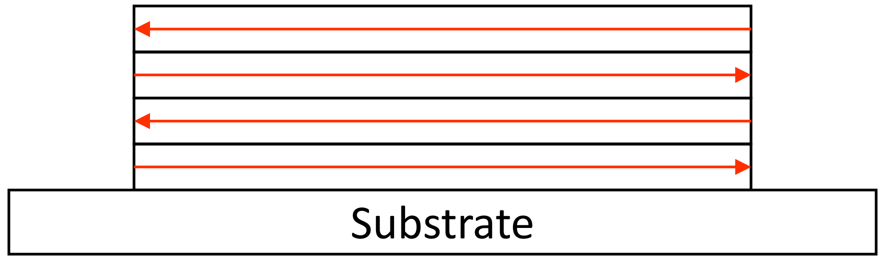

Figure 8: Zig-Zag Deposition Pattern

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Thermal Model for Wire-DED

Experiment (at IREPA LASER)

Experiment Set-Up

- Process Parameters
- Deposition Pattern
- Thermocouple Location & Measurement
- Melt-pool analysis

Figure 11: Infra-Red Camera (NIT)

- NIT Tachyon 16K Infra-Red Camera
- 2000 frames per second
- 128 ✕ 128 acquisition mode

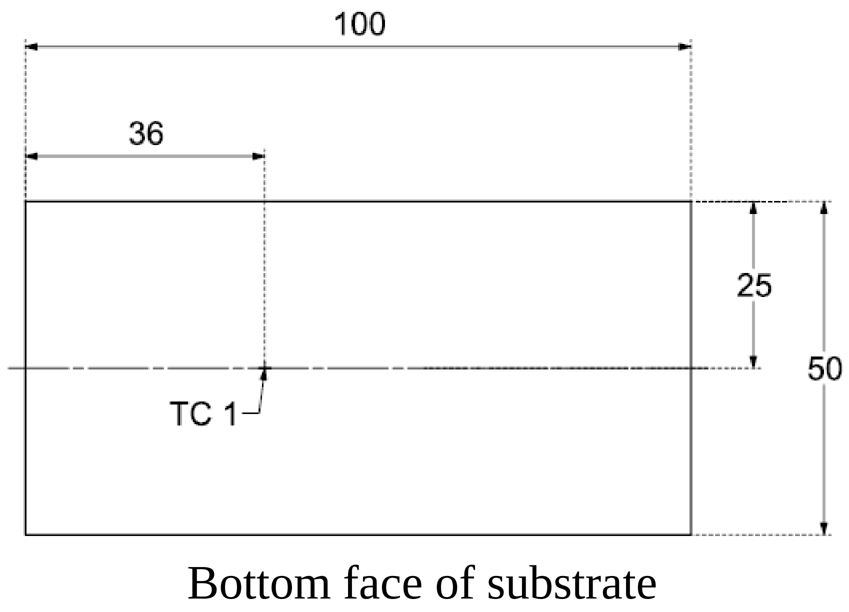

Figure 10: Thermocouple Location

- Type K thermocouple Omega GG-Ki-SLE-15M (250µm)
- Data Acquisition Controller: National Instruments 9184
- Data Acquisition Module : National Instruments 9213
- Data Acquisition Frequency:200 Hz

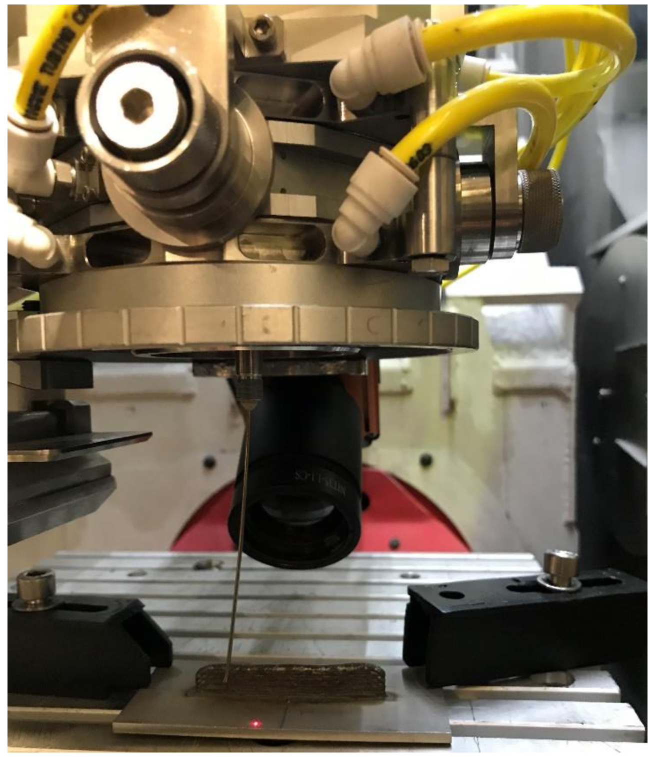

Figure 12: NIT camera installed co-axially with deposition nozzle from the side

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Melt-pool analysis is done during the process continuously as infra-red camera is installed co-axially with the deposition nozzle

Thermal Model for Wire-DED

Numerical Model Set-Up

Model Definition

- CAD Design
- Material Properties
- Mesh Strategy

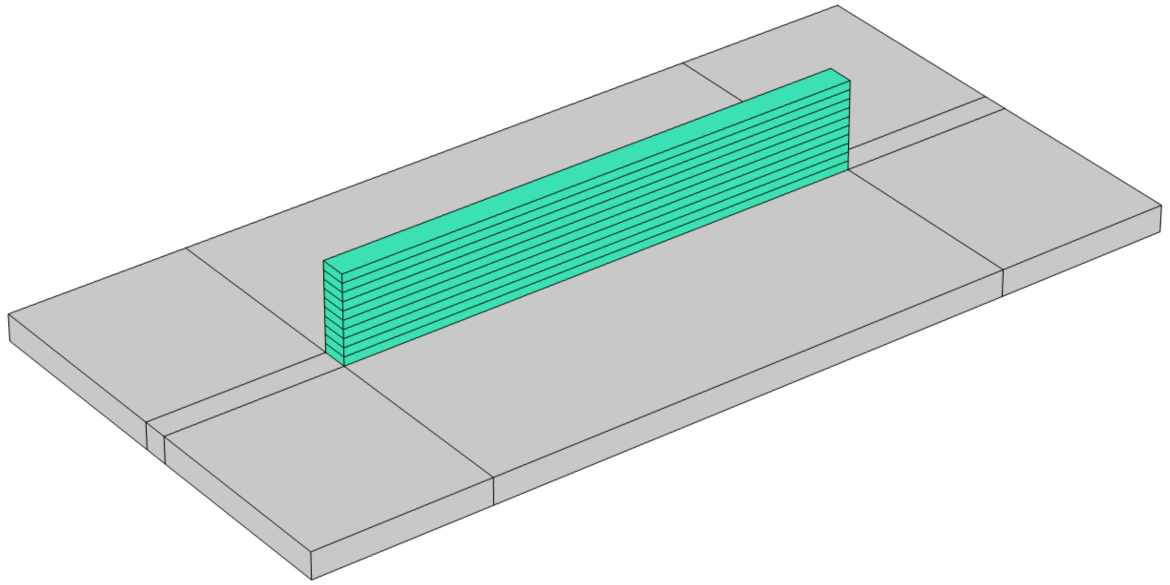
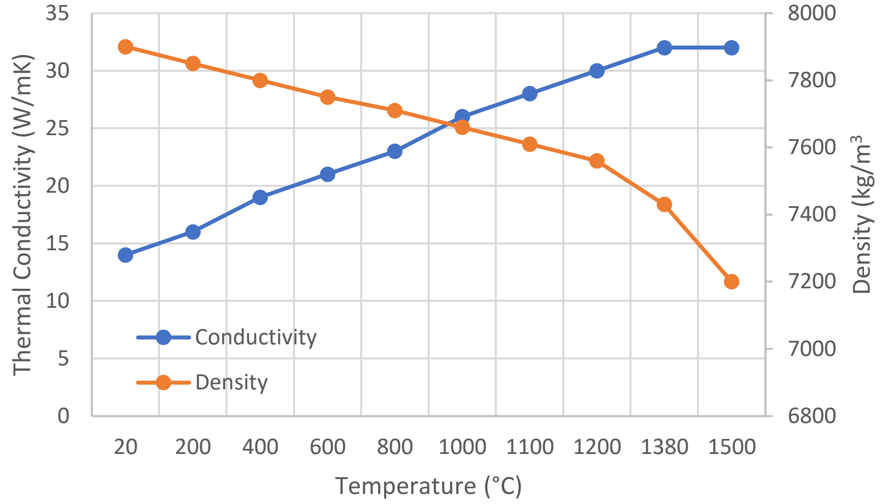
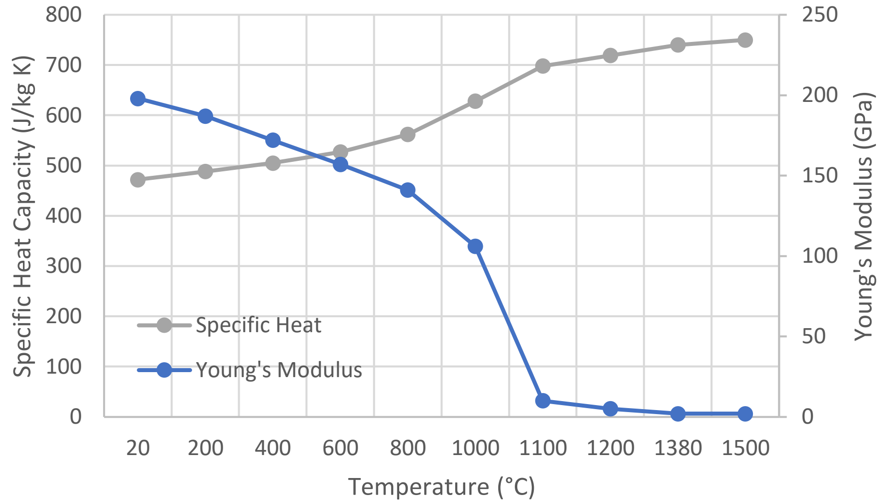


Figure 13: CAD design done in Comsol Design Module

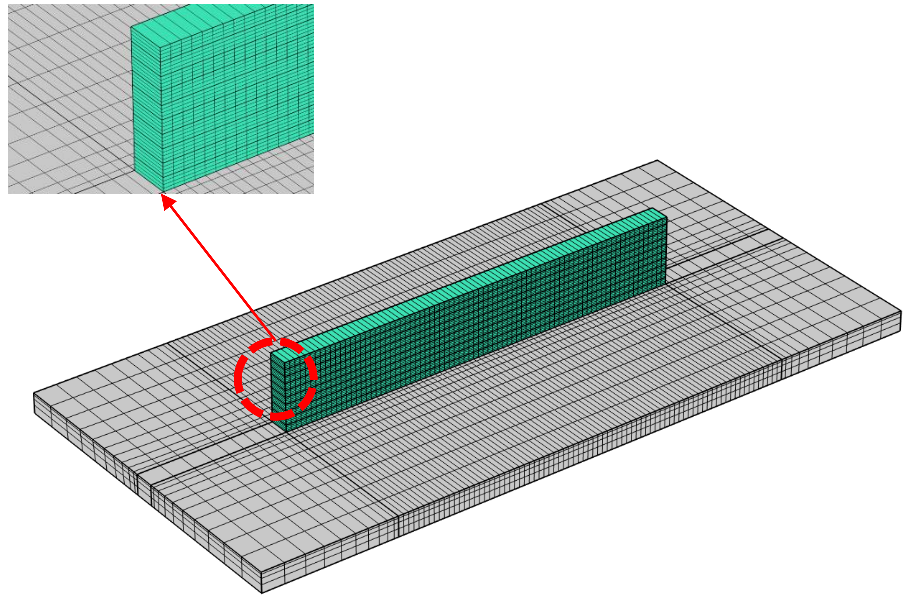


(a) Thermal Properties [1]

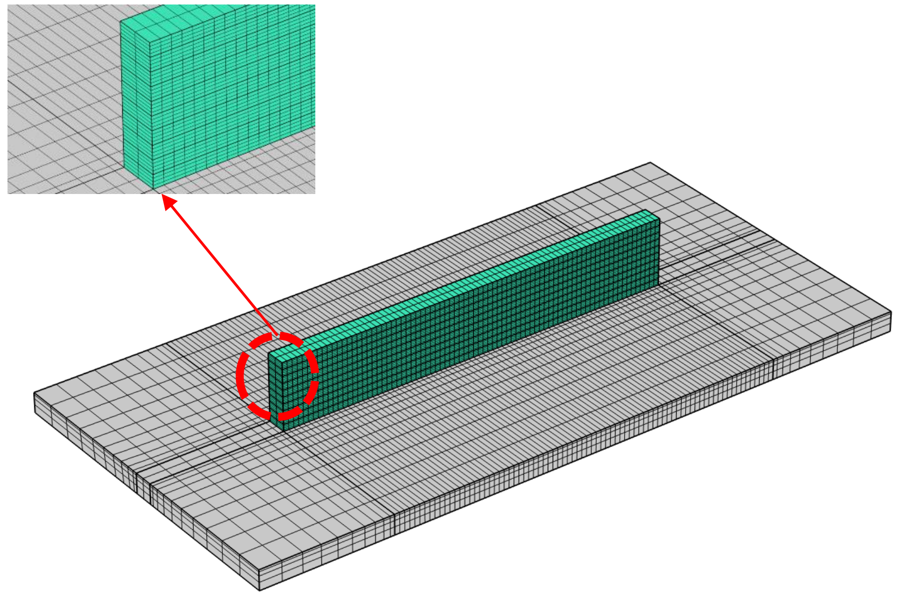


(a) Mechanical Properties [1]

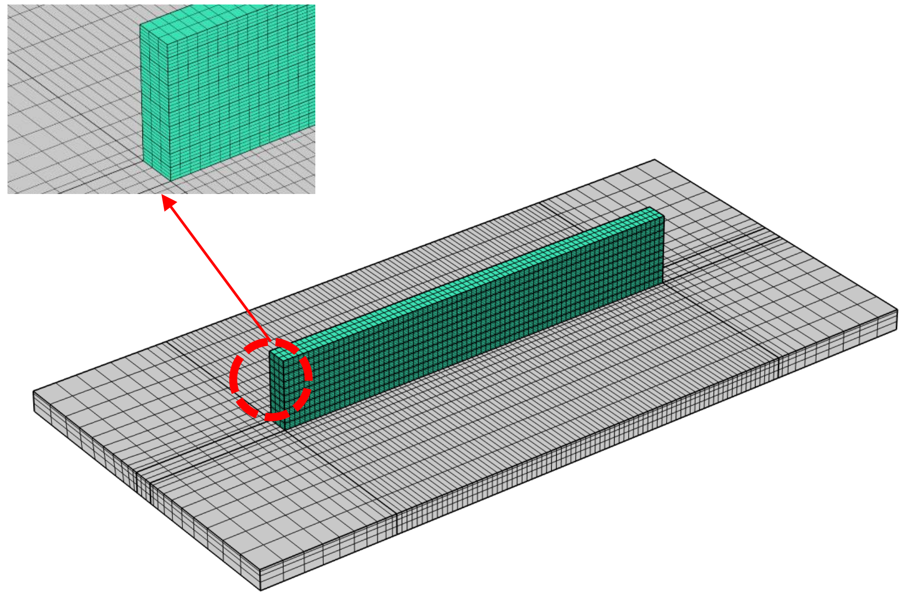
Figure 14: Temperature dependent Material Properties [1]



(a) Original Mesh



(b) Single Refinement



(c) Double Refinement

Figure 15: Original Mesh & Mesh Refinement along the width of track

[1] M. Biegler, B. Graf, and M. Rethmeier, "In-situ distortions in LMD additive manufacturing walls can be measured with digital image correlation and predicted using numerical simulations," *Additive Manufacturing*, vol. 20, pp. 101–110, Mar. 2018, doi: 10.1016/j.addma.2017.12.007.

Thermal Model for Wire-DED

Numerical Model Set-Up

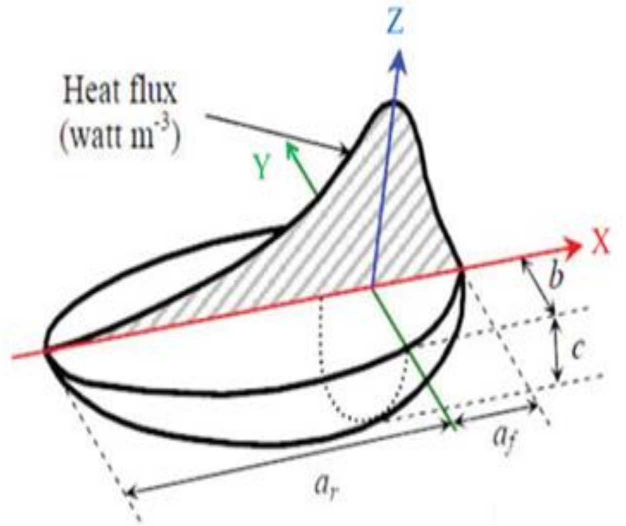


Figure 5: Intensity Distribution Goldak Double Ellipsoid Source

Numerical Model Calibration

- Heat Source Parameters
- Convection coefficient
- Emissivity

Process Parameter	Symbol	Value
Heat Source Parameters		
Energy Efficiency	A	0.45
Front Ellipsoid length	a_f	1.5 mm
Rear Ellipsoid Length	a_r	4.5 mm
Ellipsoid Width	b	1.5 mm
Ellipsoid Depth	c	1.7mm
Weighing fraction for front ellipsoid	f_f	0.5
Weighing fraction for rear ellipsoid	f_r	1.5
Forced Convection Heat Loss		
Heat transfer coefficient	h_{FC}	35 W/m^2 K
Natural Convection Heat Loss		
Heat transfer coefficient	h_N	5 W/m^2 K
Radiation Heat Loss		
Emissivity coefficient	ε	0.6

Table 2: Final parameters after calibration

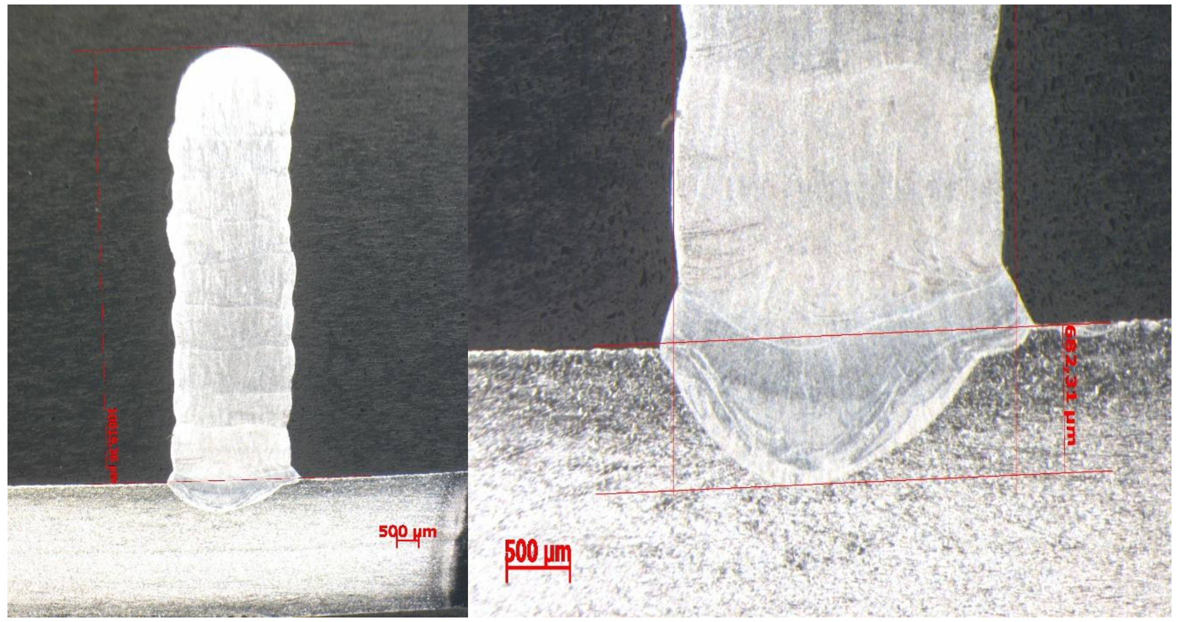


Figure 17: Build part & Melt-pool dimensions visualisation with Macrography analysis on cross-section

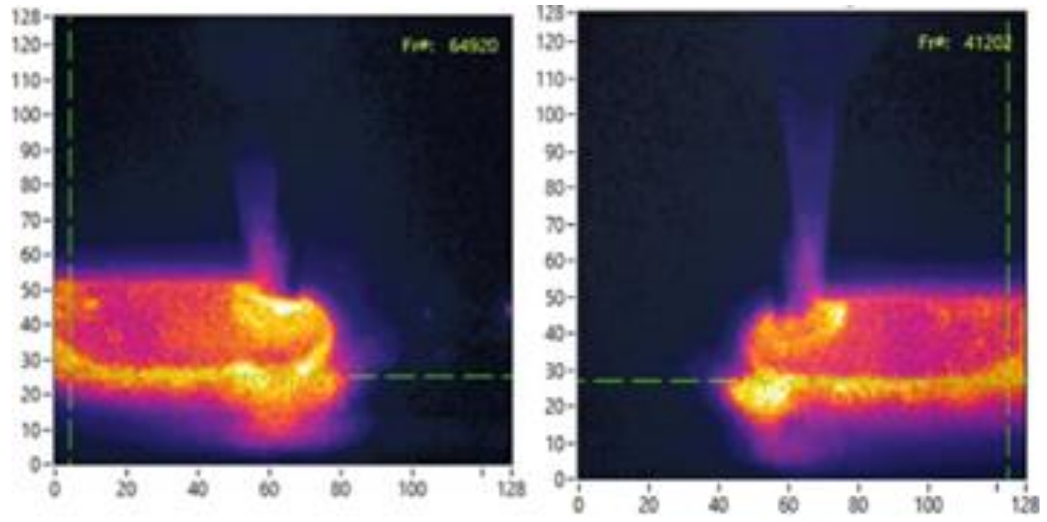


Figure 16: Melt-pool length & depth analysis

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Thermal Model for Wire-DED

Numerical Model Implementation

Model features

- Material Addition
- Heat Transfer Analysis
- Mesh Analysis

<u>COMSOL modules used</u>

- Design Module
- Heat Transfer in solids
  - Heat Source
  - Heat flux (convective heat flux)
  - Surface-to-ambient radiation
- Structural Mechanics
  - Linear Elastic Material
    - Activation

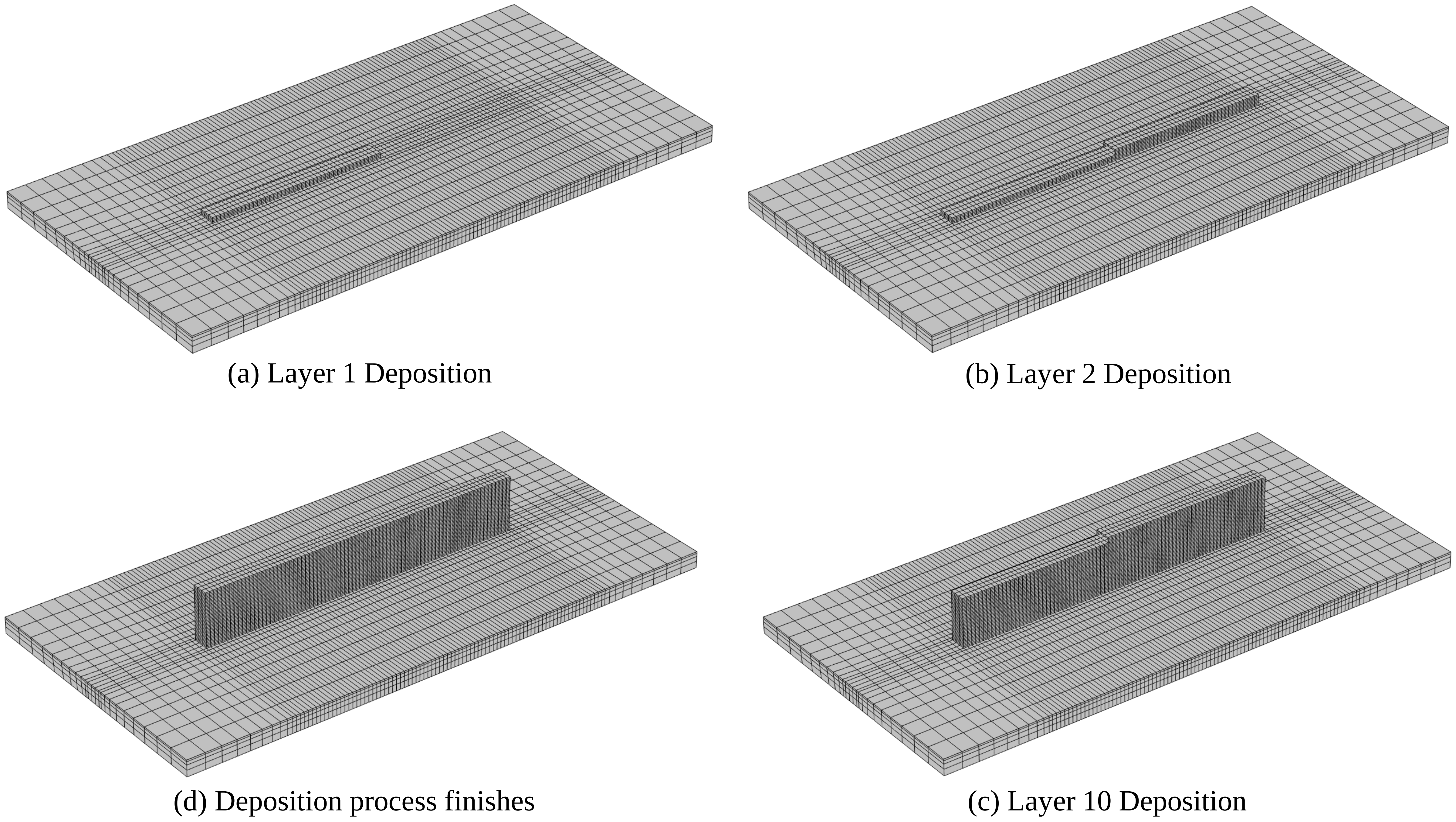

Figure 18: Quiet/Active method material activation

Activation Criteria COMSOL:

$$exp\left(-\left(\frac{3(x-traj\_x(t))^2}{a^2}+\frac{3(y-traj\_y(t))^2}{b^2}+\frac{3(z-traj\_z(t))^2}{c^2}\right)\right) \geq 5\%$$

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Thermal Model for Wire-DED

Numerical Model Implementation

Model features

- Material Addition
- Heat Transfer Analysis
- Mesh Analysis

COMSOL modules used

- Design Module
- Heat Transfer in solids
    - Heat Source
    - Heat flux (convective heat flux)
    - Surface-to-ambient radiation
- Structural Mechanics
    - Linear Elastic Material
        - Activation

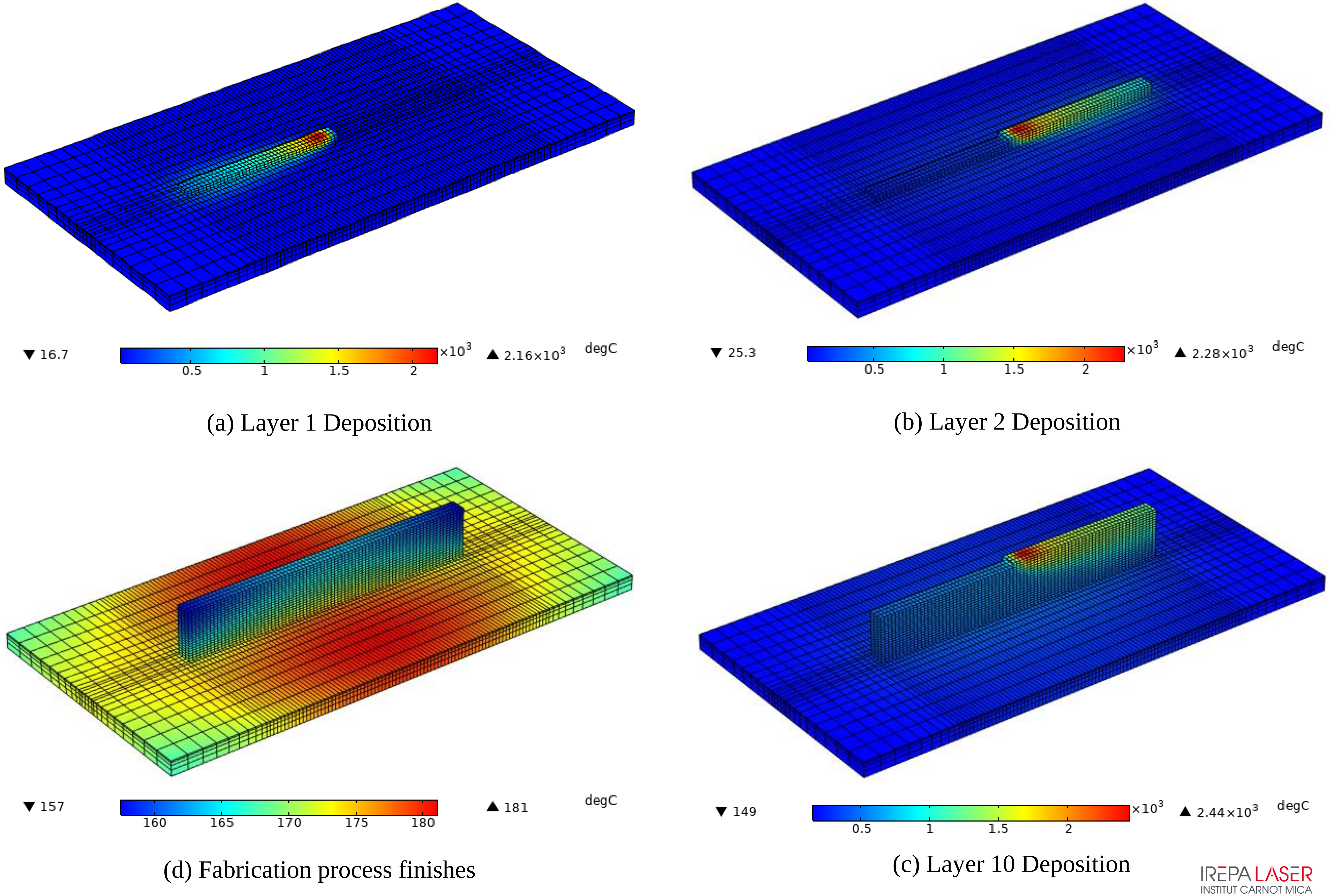


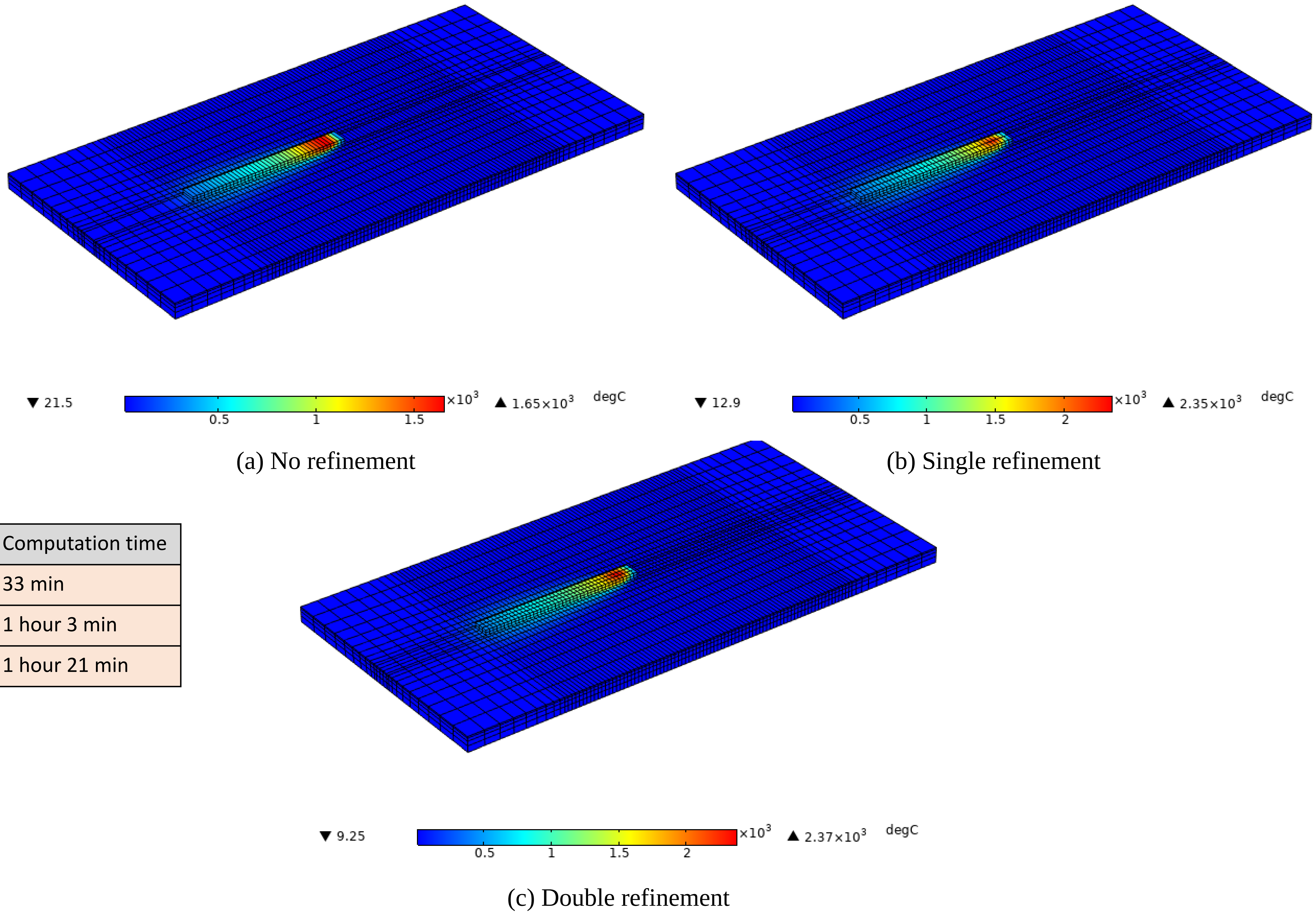
Figure 19: Heat Transfer Analysis during Wire-DED process

Thermal Model for Wire-DED

Numerical Model Implementati

Model features

- Material Addition
- Heat Transfer Analysis
- Mesh Analysis



Mesh Type	No. of elements	Dof (solved for)	Computation time
Original Mesh	9896	63200	33 min
Single Refinement	11872	74800	1 hour 3 min
Double Refinement	13848	86400	1 hour 21 min

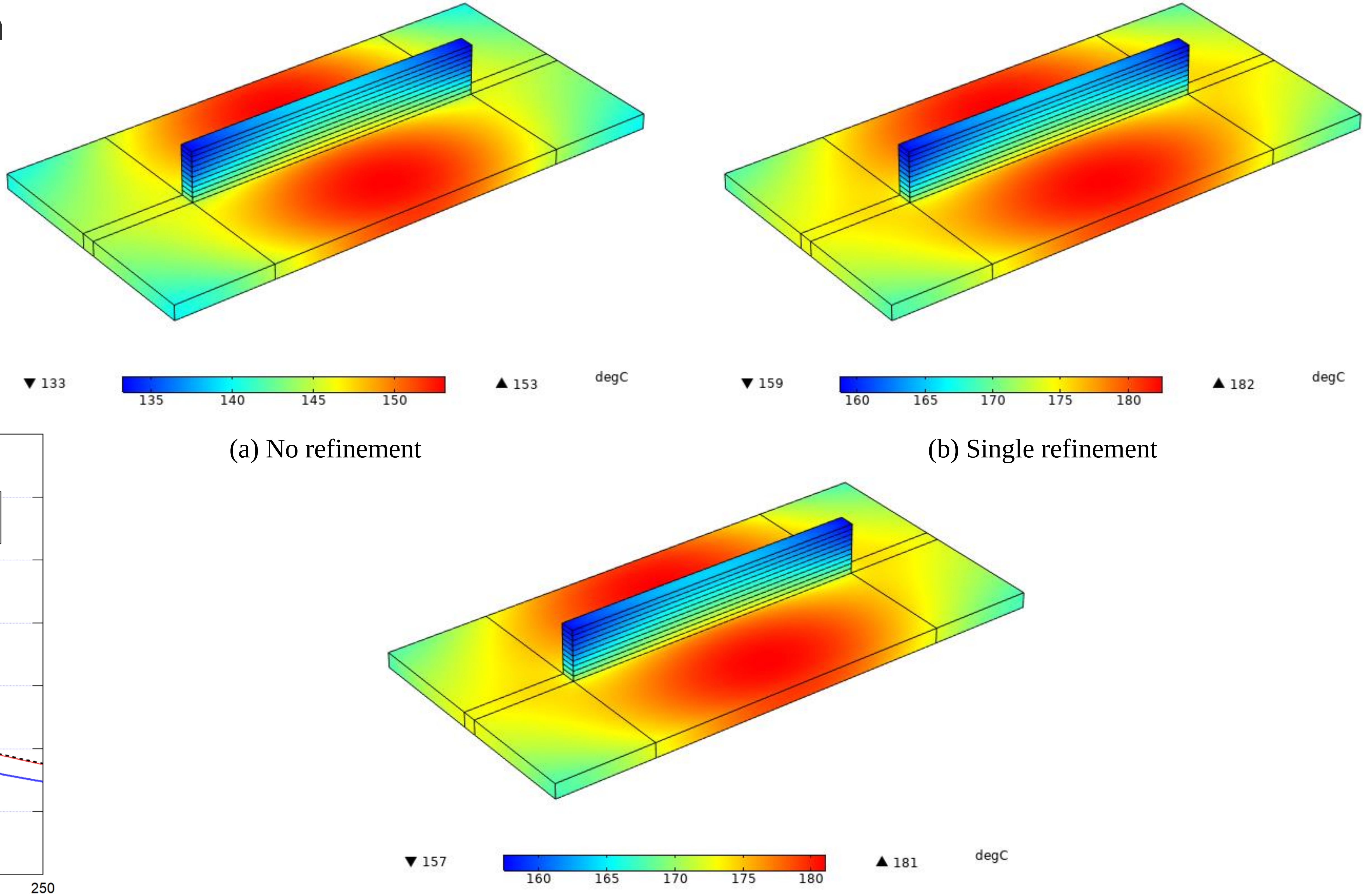
Figure 20: Effect of Mesh Refinement on Accuracy of Heat Transfer phenomenon (Layer 1 deposition)

Thermal Model for Wire-DED

Numerical Model Implementation

Model features

- Material Addition
- Heat Transfer Analysis
- Mesh Analysis



(a) No refinement

(b) Single refinement

(c) Double refinement

Figure 21: Effect of Mesh Refinement on Accuracy of Heat Transfer phenomenon (deposition process is finished and build part is cooling down)

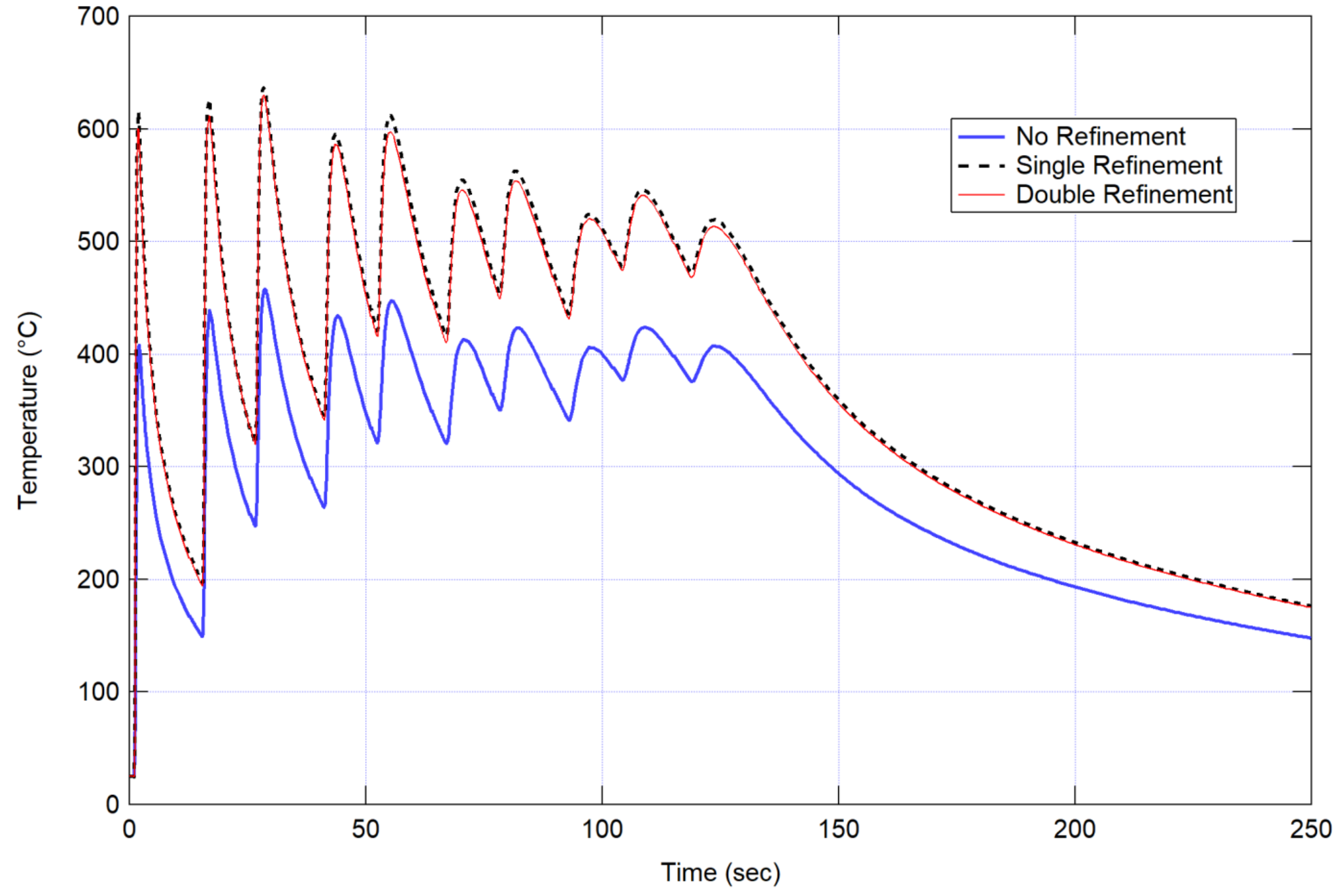


Figure 22: Temperature evolution at TC 1 with different mesh refinement

Thermal Model for Wire-DED

Numerical Model Validation

Temperature Results

- Process Simulation
- Comparison b/w experimental & numerical results

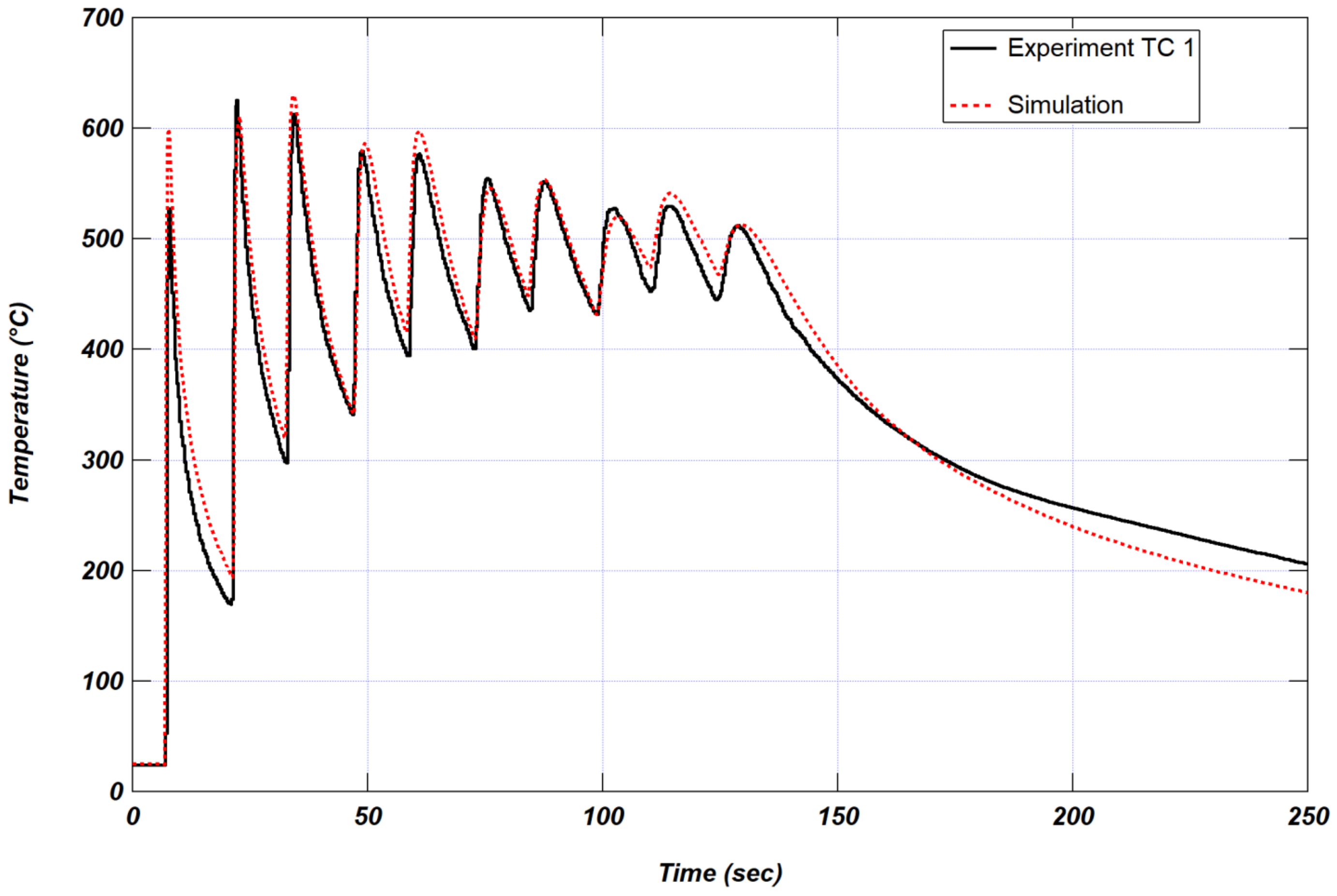
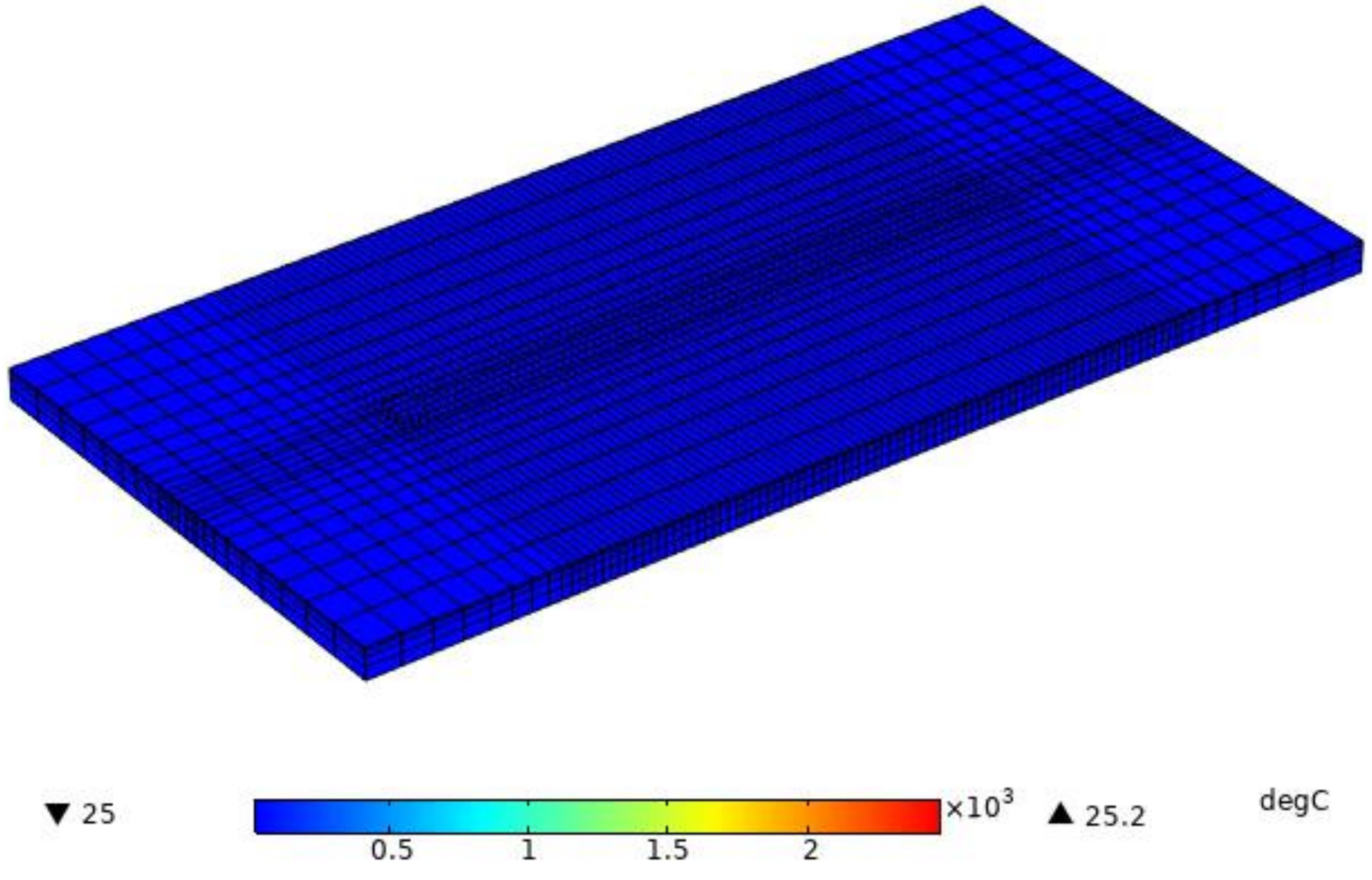


Figure 23: Comparison b/w Experimental & Numerical results



Animation 1: Wire-DED Thermal Model process simulation

Numerical model shows good agreement with experimentally measured trends of temperature evolution during the process

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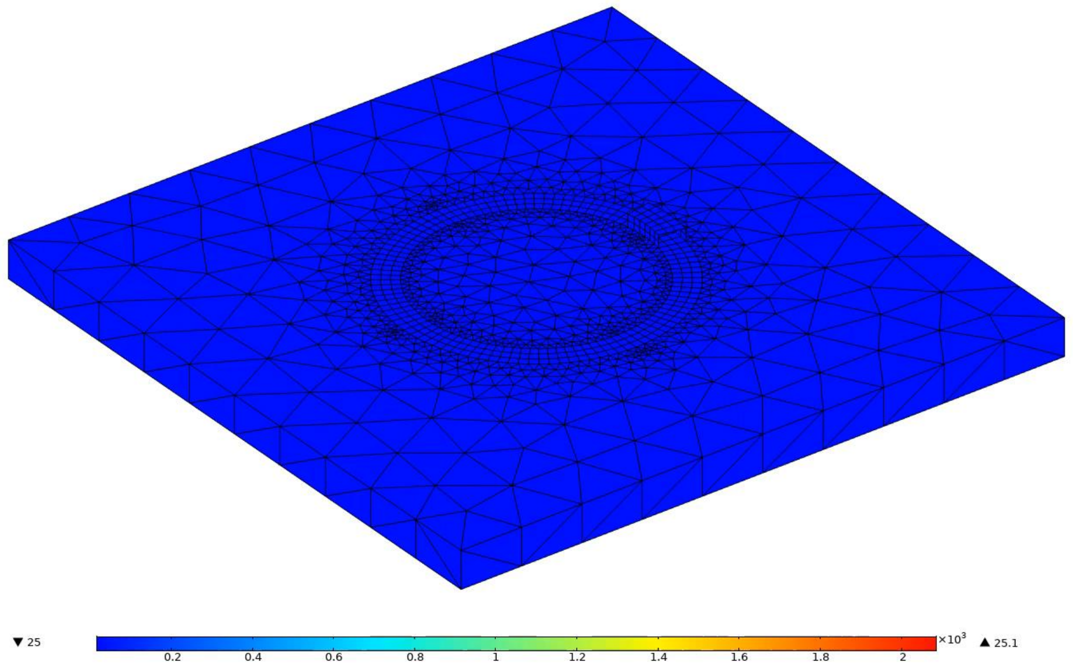
Future Work

Thermal Model

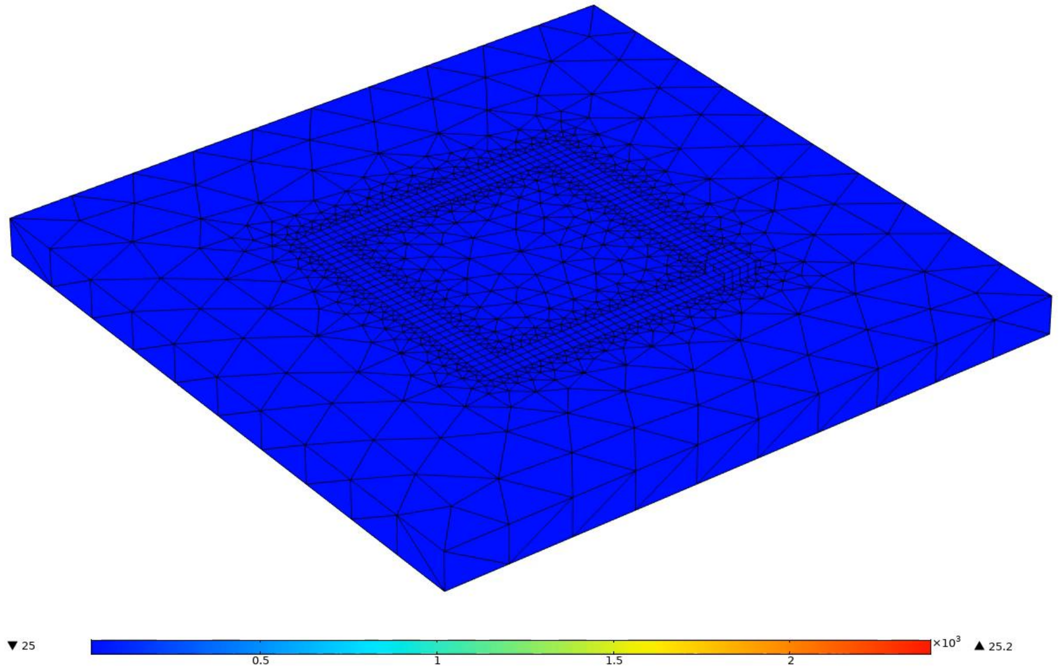
- Validation of Thermal Model for other material
  - Ti-6Al-4V
  - Inconel 718
  - Inconel 625

Mechanical Model

- Development of Mechanical Model
  - Identification of Material properties
  - Identification of Material Hardening Law
  - Validation of Mechanical Model with experiment results



Thankyou



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