High-fidelity Modelling of Thermal Stress for Additive Manufacturing by Linking Thermal-fluid and Mechanical Models

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Faculty of Engineering

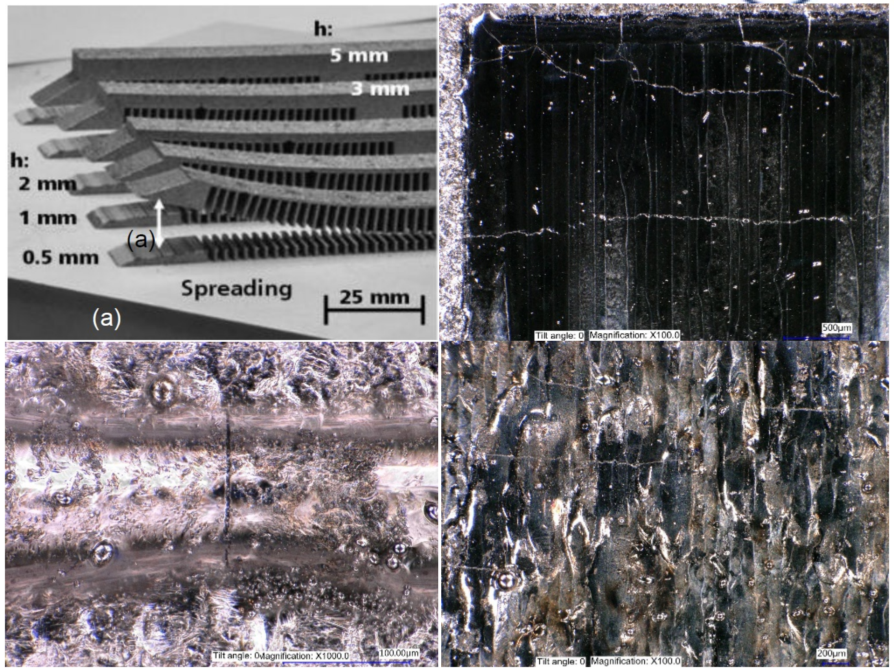
Contents

- Background
- High-fidelity multi-physics modelling
- Results and discussion

Background

Thermal Stress

- The part distortion;
- Loss of geometric tolerance;
- Delamination of layers during depositing;
- Deterioration of the fatigue performance;
- Fracture resistance.



Prediction

- Trial-and-error;
- Assumptions & Analytical calculations;
- Over-simplified Thermal-mechanical simulations.

$$\sigma_{maxCorr} = \frac{100\sigma_{maxASTM}}{m\left(\frac{\sigma_{maxASTM}}{\sigma_y} - 0.5^2\right) + 100}$$ (Schajer, g. S.)

$$\sigma_a = c * (\mathrm{HV} + 120)x(\sqrt{area})^{-\frac{1}{6}}$$ (Y. Murakami)

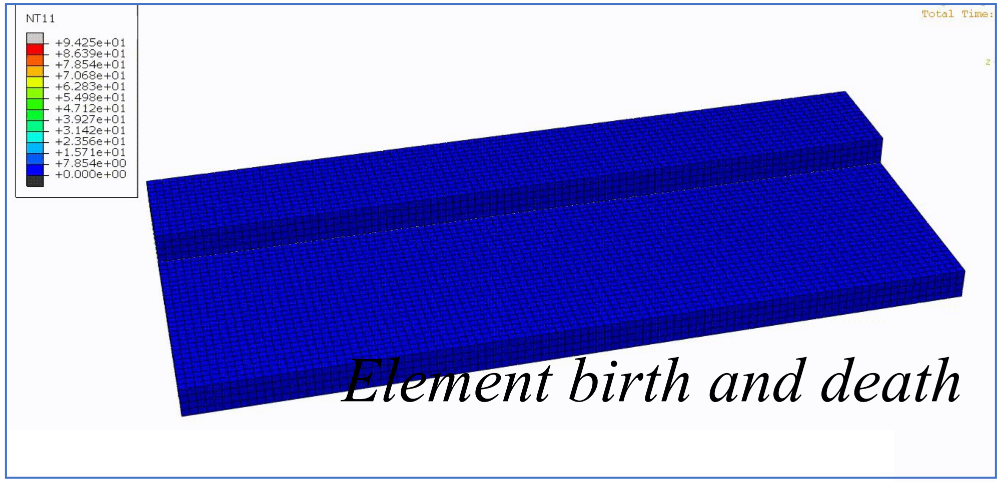
$$\sigma_a = \frac{\Delta K_{\mathrm{th}}}{F} * (\pi a)^{-\frac{1}{2}}.$$ (A. Spagnoli)

• Li, C., et al. "Residual stress in metal additive manufacturing." *Procedia Cirp* 71 (2018): 348-353.

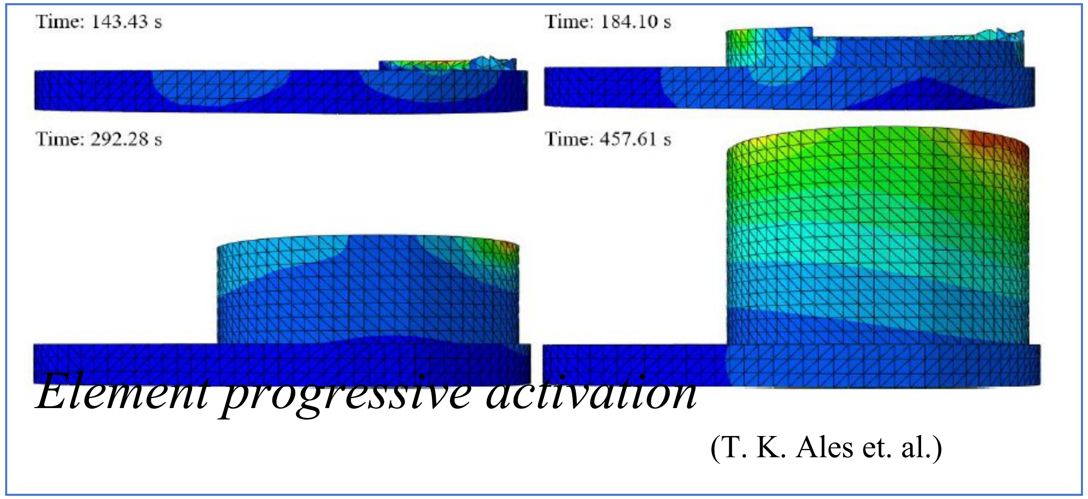
Background

Macro-scale (Part scale) modelling

Part distortion prediction & stress concentration



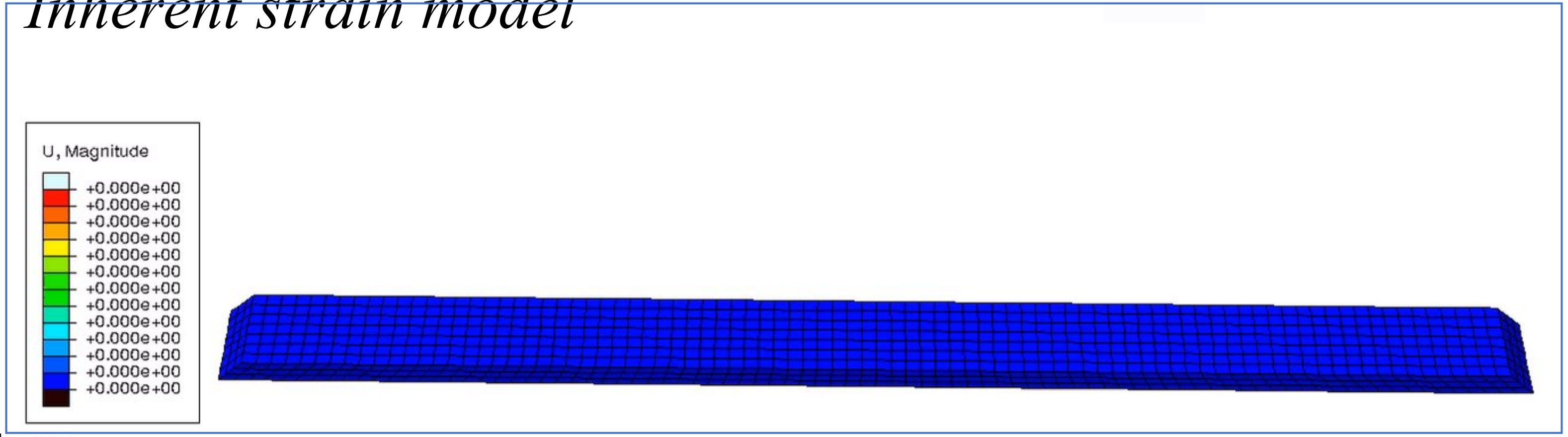
Element birth and death

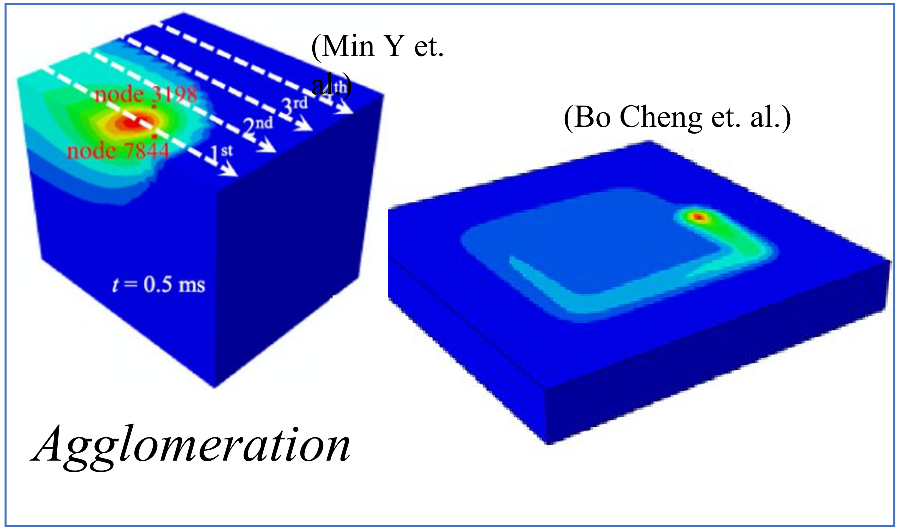


Element progressive activation

(T. K. Ales et. al.)

Inherent strain model





(Min Y et. al.)

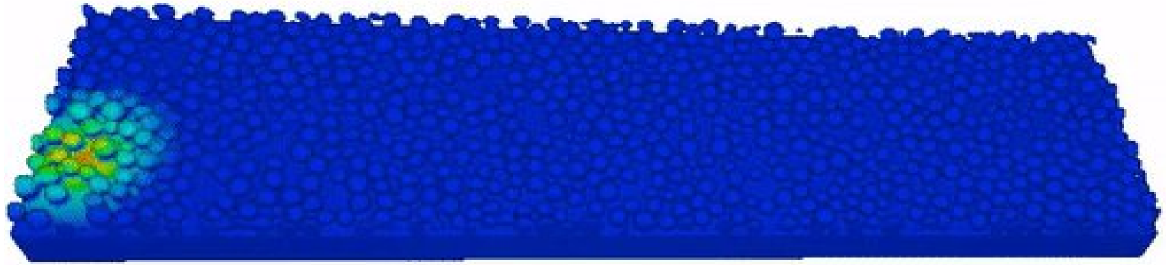
(Bo Cheng et. al.)

Agglomeration approaches

Background

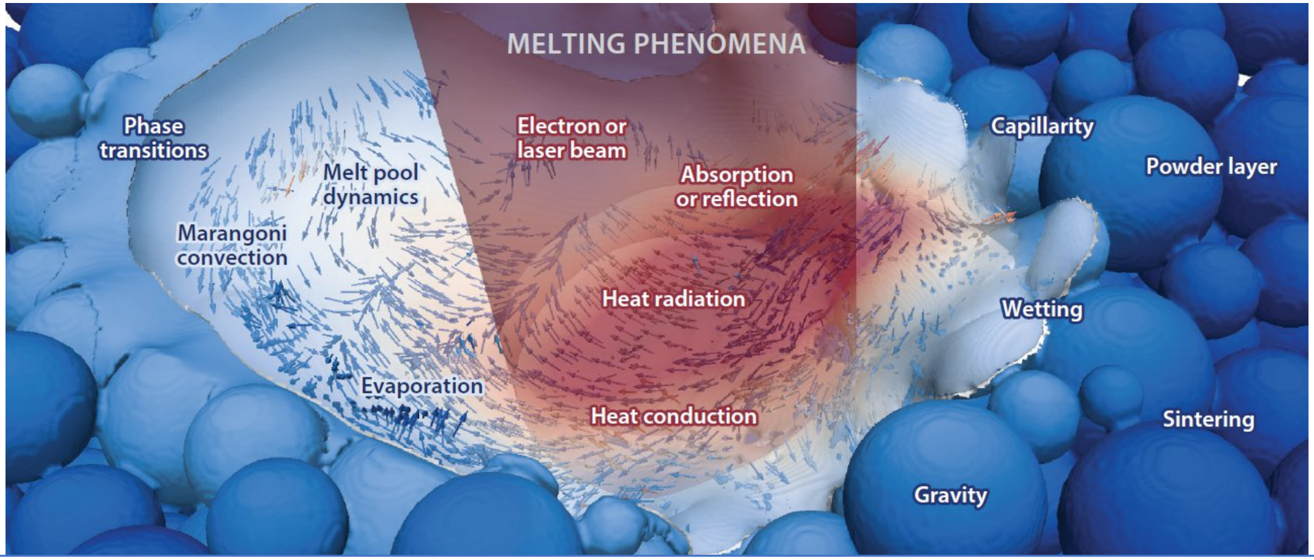
Meso-scale (Powder scale) modelling

Thermal-fluid flow simulation

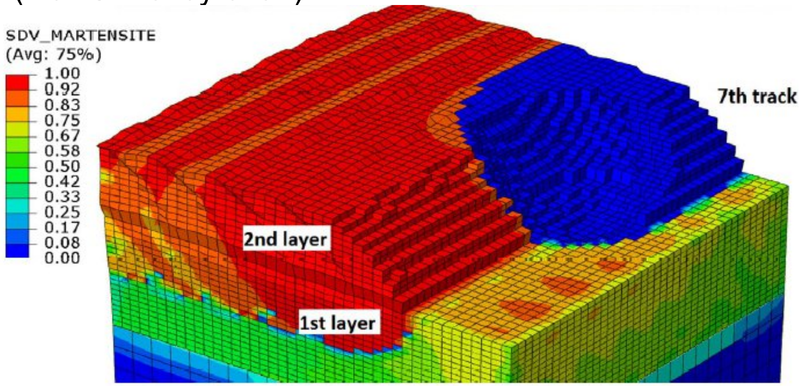


- ❖ Voids
- ❖ Surface roughness
- ❖ Cracks
- ❖ Grain growth
- ❖ Dislocation

Thermal-fluid flow effects (Markl M et. al.)



(Neil S. Bailey et al.)

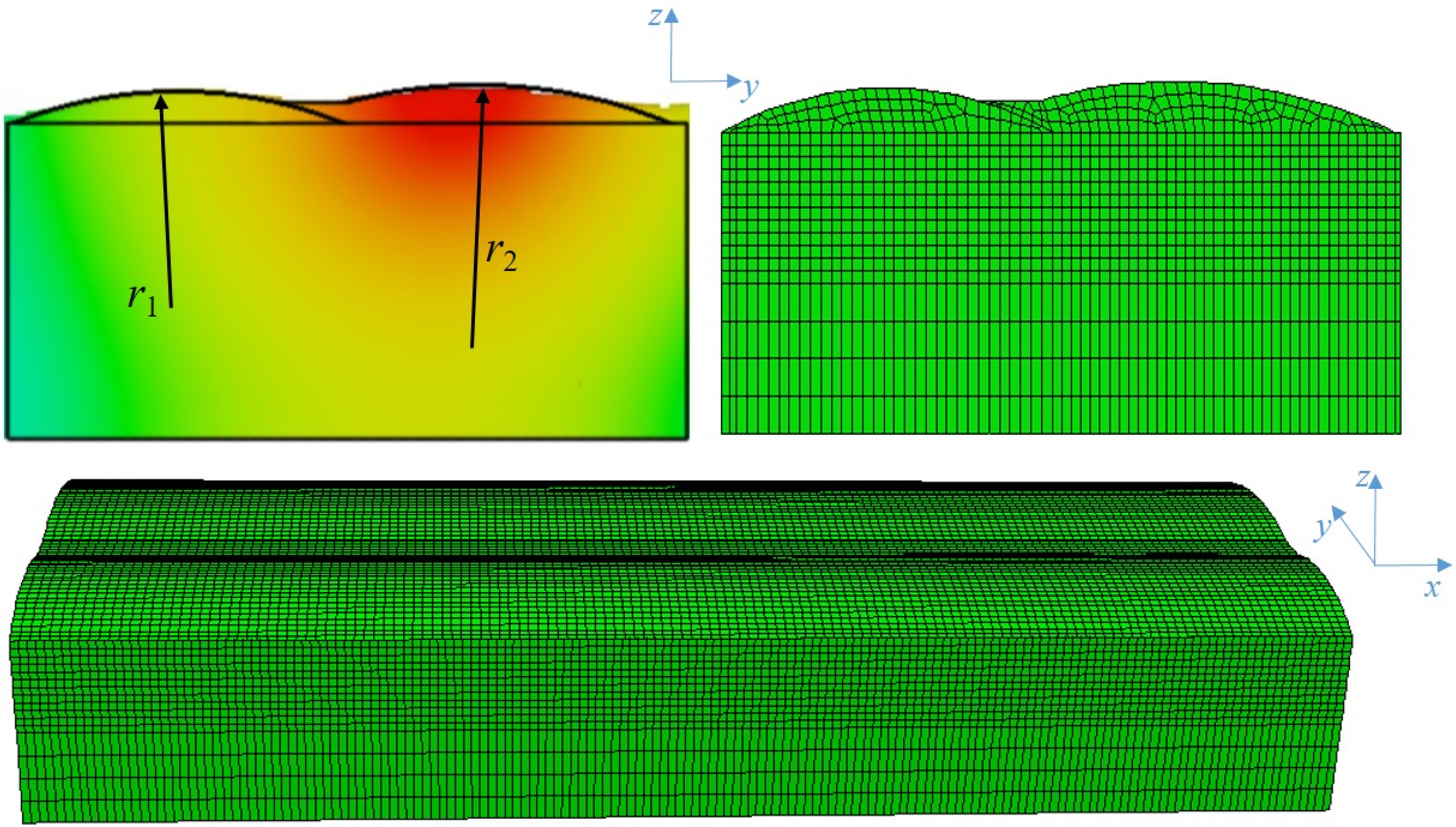


- Markl M, Körner C. Multiscale modeling of powder bed–based additive manufacturing[J]. Annual Review of Materials Research, 2016, 46: 93-123.

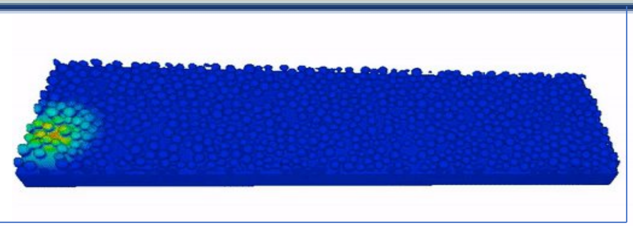
Thermo-mechanical analysis

Simplifications & Assumptions

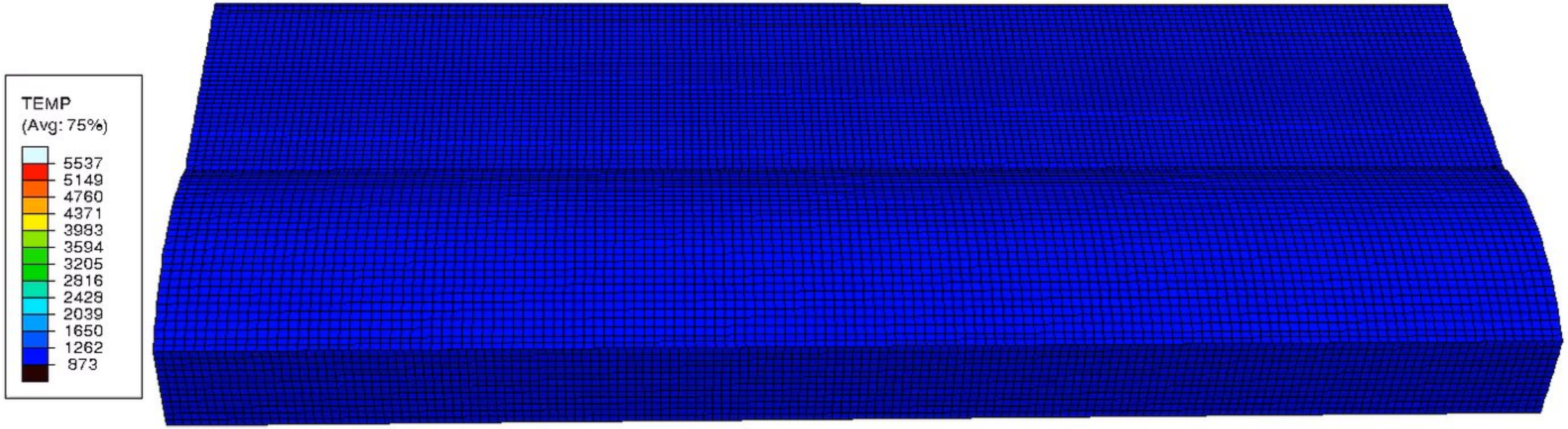
track morphology & fluid flow



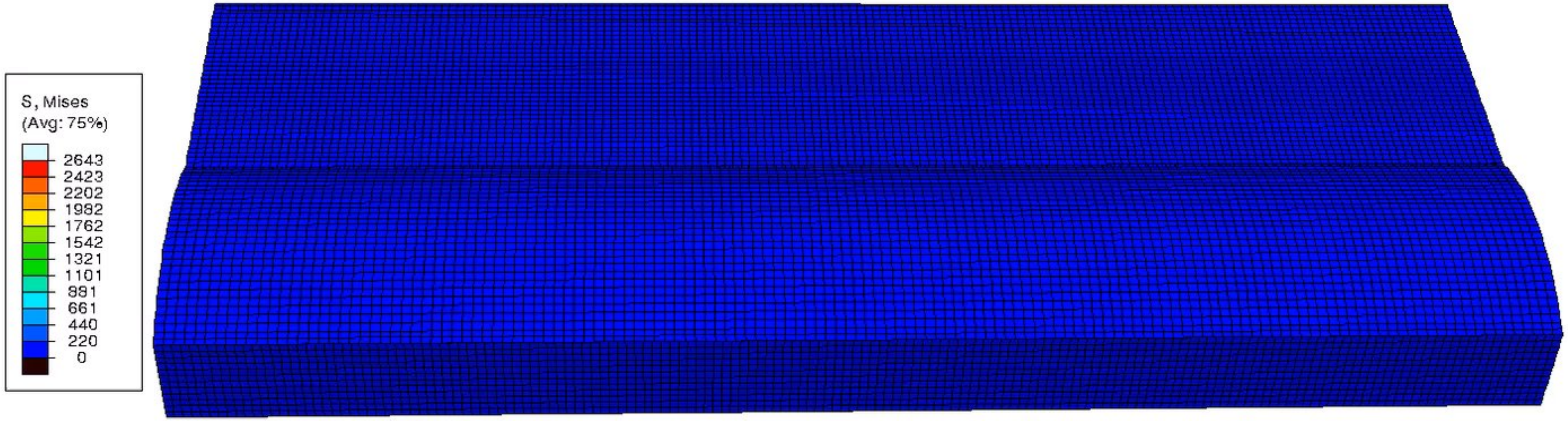
Thermo-mechanical analysis



Temperature distribution

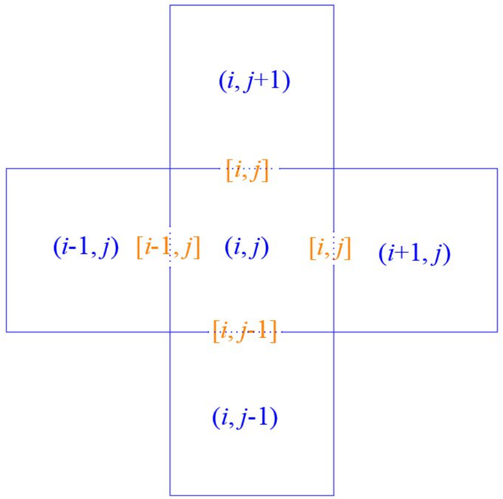


Von-Mises stress



Framework

Governing equations



CFD

$$\frac{\partial f}{\partial x} = \frac{1}{Vol}\oint f\bar{n_x}\cdot d\bar{A} = \sum_{i,j}^{CV} f_{[i,j]}\bar{n}_{[i,j],x}$$

$$\frac{\partial f}{\partial y} = \frac{1}{Vol}\oint f\bar{n_y}\cdot d\bar{A} = \sum_{i,j}^{CV} f_{[i,j]}\bar{n}_{[i,j],y}$$

$$f_{[i,j],x} = \frac{1}{2}(f_{(i,j)} + f_{(i+1,j)})$$

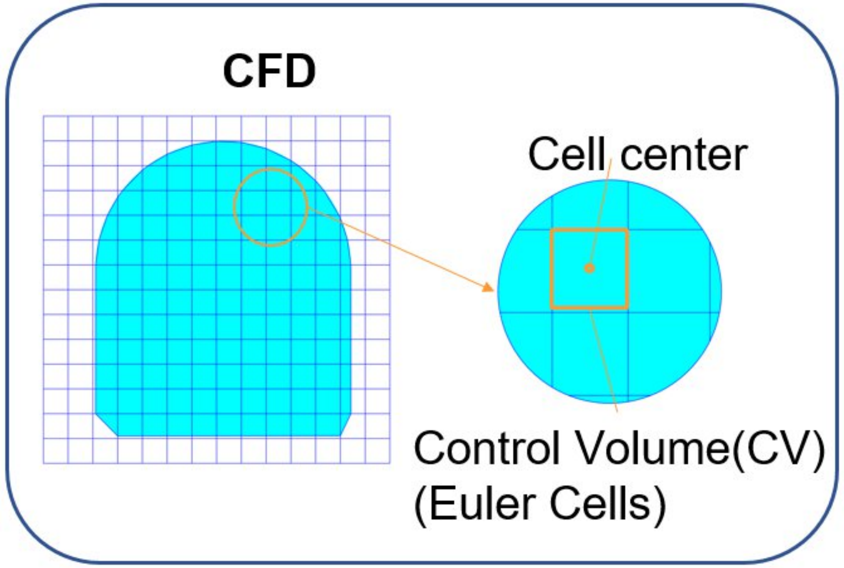
$$f_{[i,j],y} = \frac{1}{2}(f_{(i,j)} + f_{(i,j+1)})$$

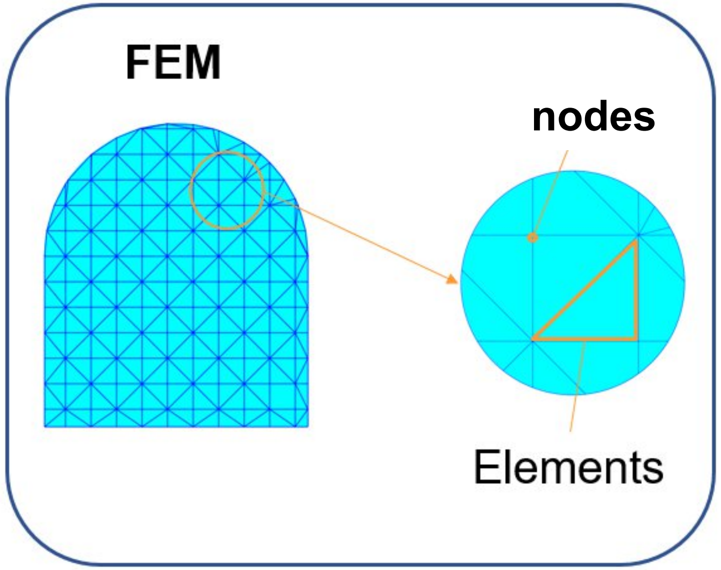
FEM

$$f_{[i,j],x} = Function(f_{(m,n)})$$

$$f_{[i,j],y} = Function(f_{(m,n)})$$

Meshing difference





High-fidelity multi-physics modelling

ANNUAL INTERNATIONAL VIRTUAL Solid Freeform Fabrication SYMPOSIUM

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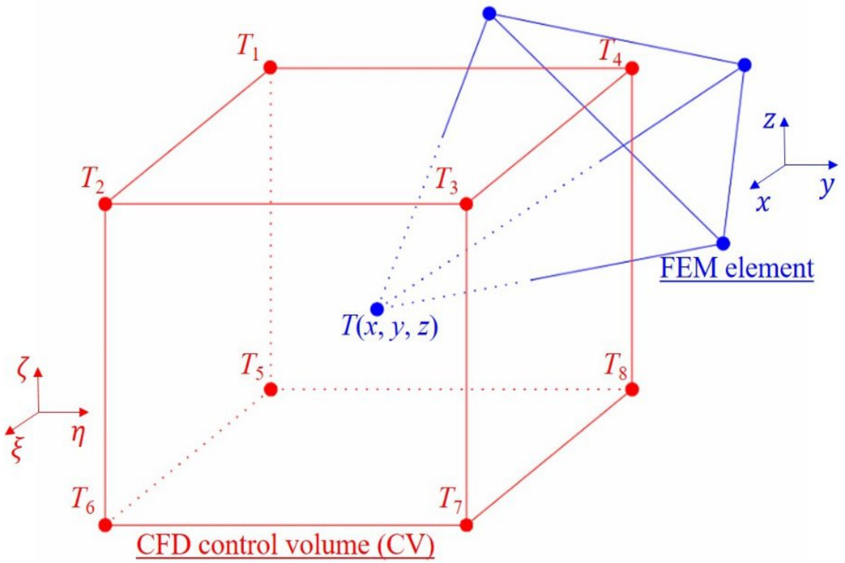
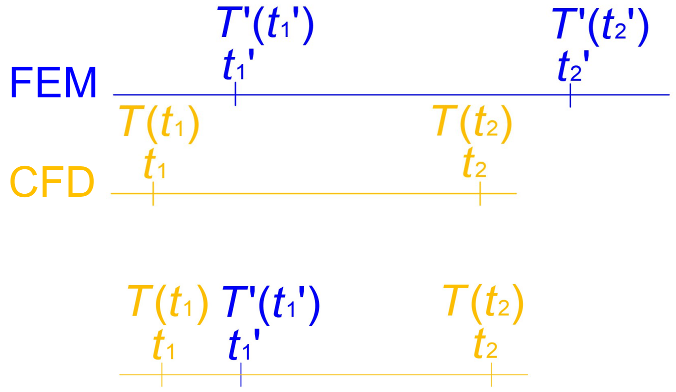
Spatial interpolation:



$$T(x,y,z) = \sum_{i=1}^{8} N_i(\xi, \eta, \varsigma) T_i$$

Temporal interpolation:

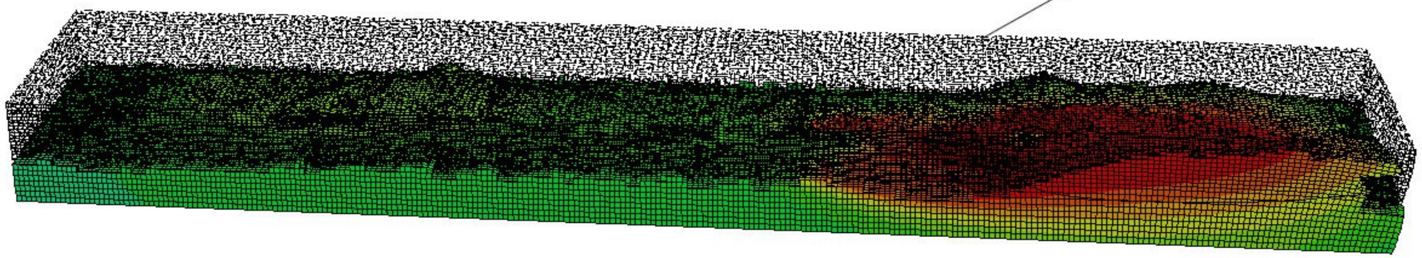


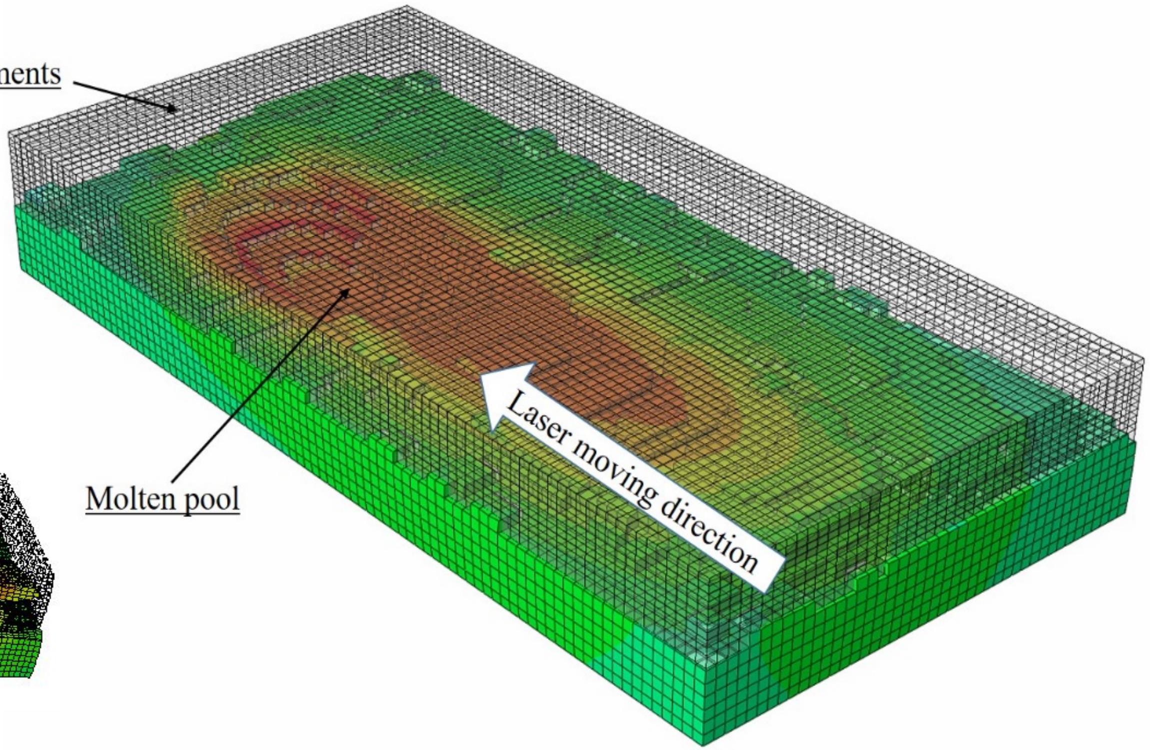
$$T'(t_1') = T(t_1) + \frac{T(t_2) - T(t_1)}{t_2 - t_1}(t_1' - t_1)$$

High-fidelity multi-physics modelling

Quiet element method

- No activation or deactivation;
- Field variables for different state;
- High flexibility;
- Easy implementation.



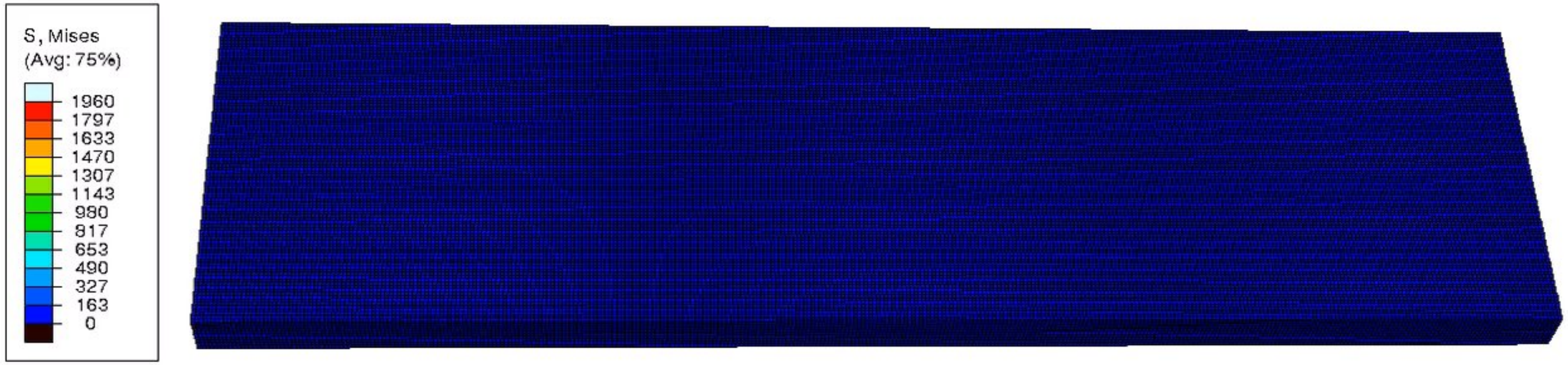


Material states	Young's modulus(Pa)	Poisson ratio	Thermal expansion coefficient(1/K)
Solid	1.32×10^{11}	0.31	9.2×10^{-6}
Liquid	1×10^{4}	0.001	9.2×10^{-6}
Air	1×10^{4}	0.001	0

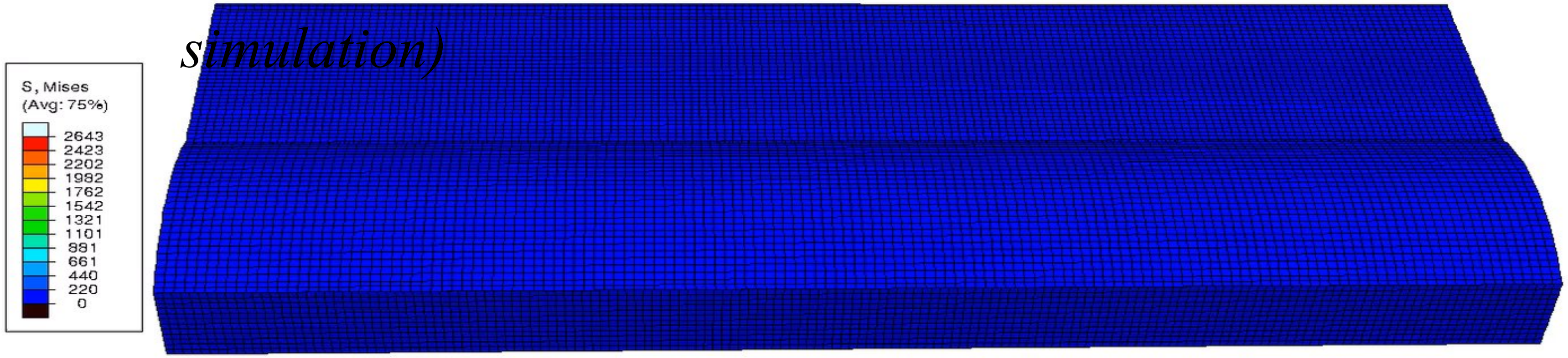
Results and discussion

Temperature mapping result

Von-Mises stress evolution (CFD-FEM simulation)

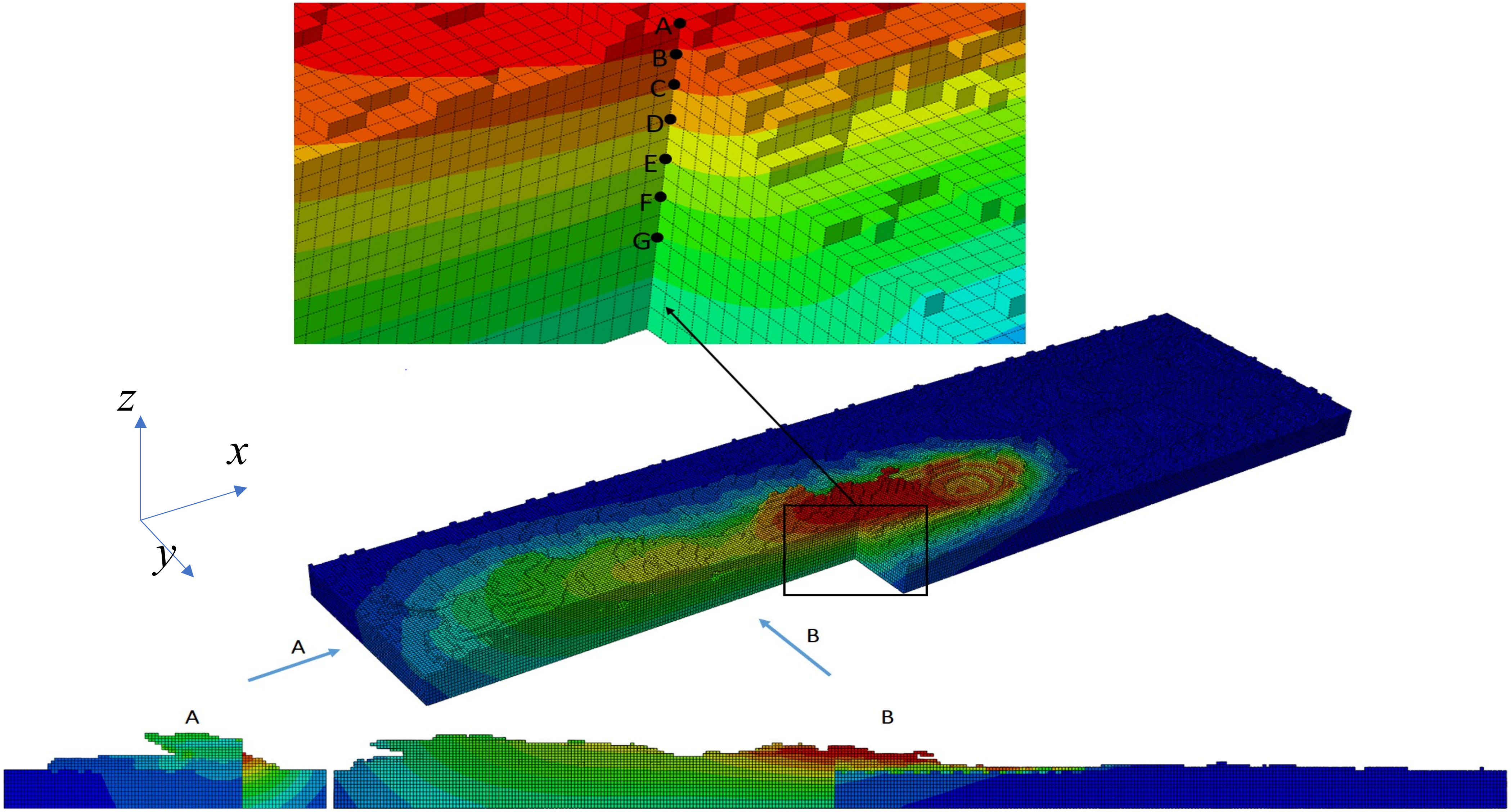


Mises-stress evolution (thermo-mechanical simulation)



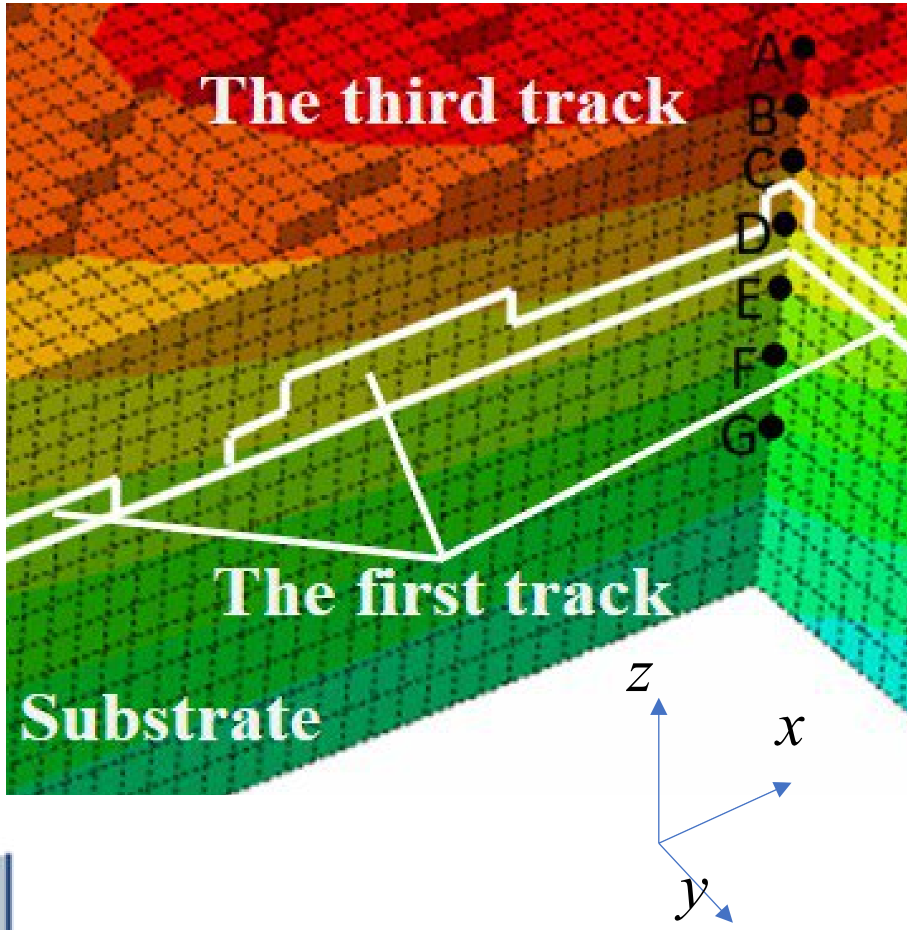
Results and discussion

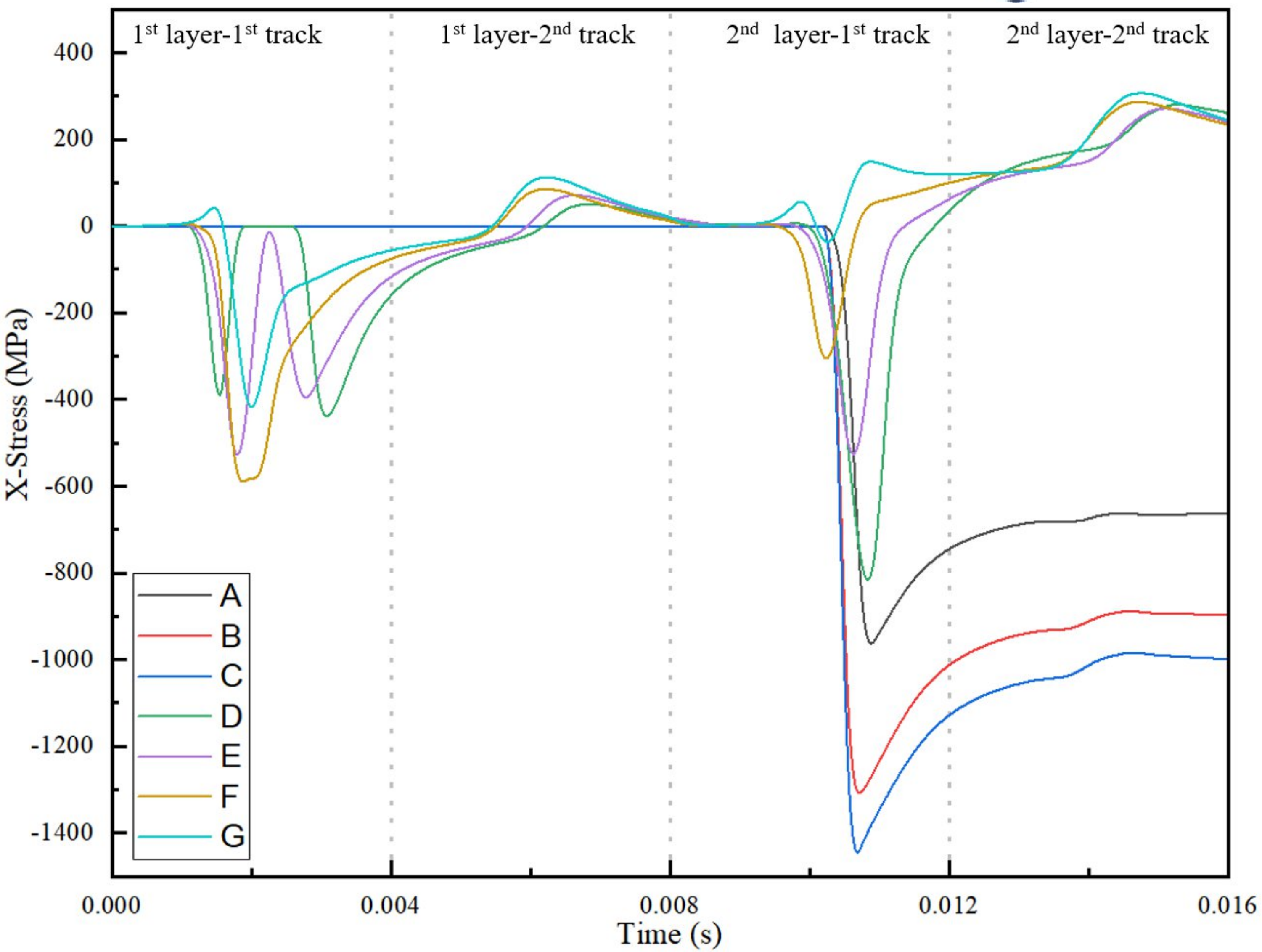
Temperature distribution & Track morphology



Results and discussion

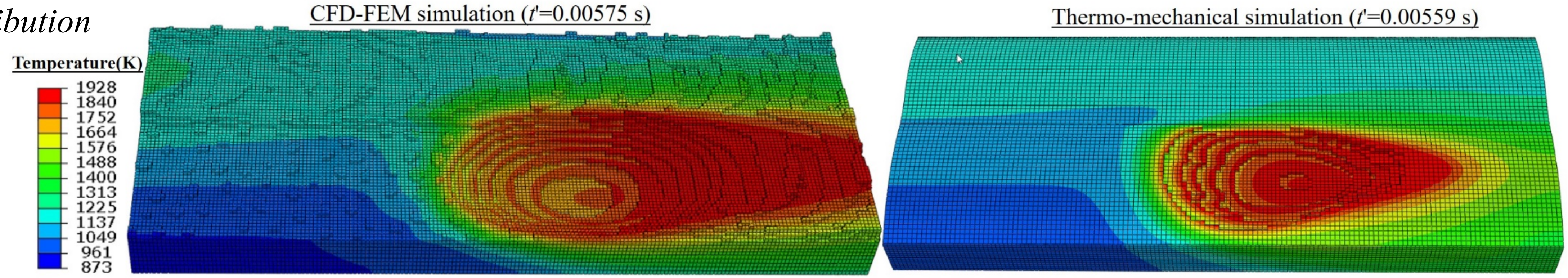
X-X stress component



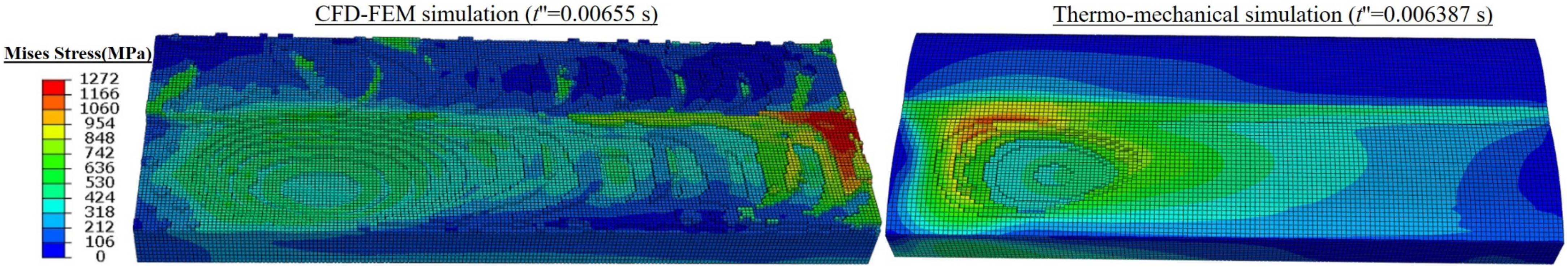


Results and discussion
Comparison

Temperature distribution



Von-Mises stress

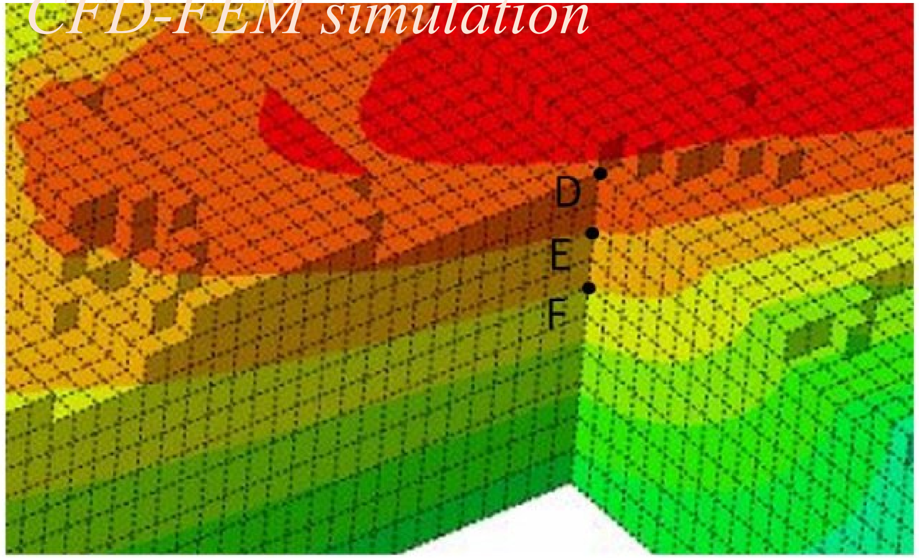


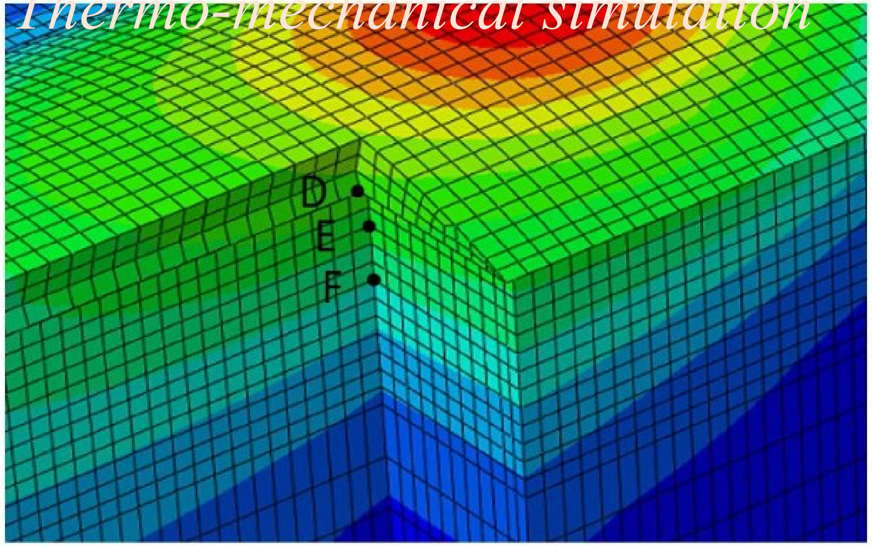
Conclusion ***Geometrical features *Peak temperature *Molten pool size *Stress distribution**

Results and discussion

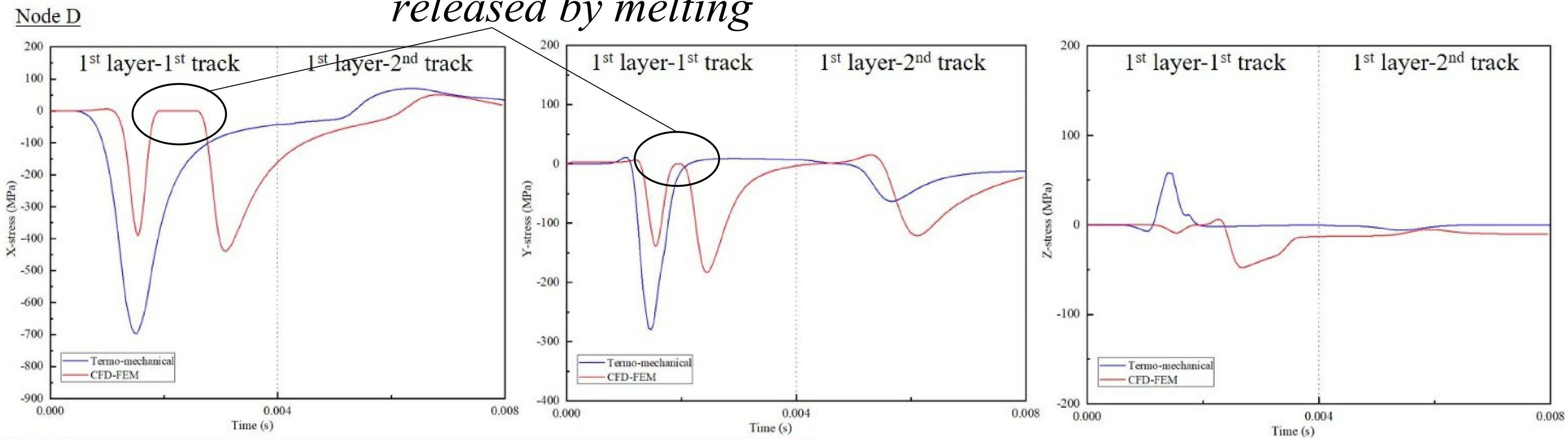
Comparison

- *Magnitude*
- *Trend*





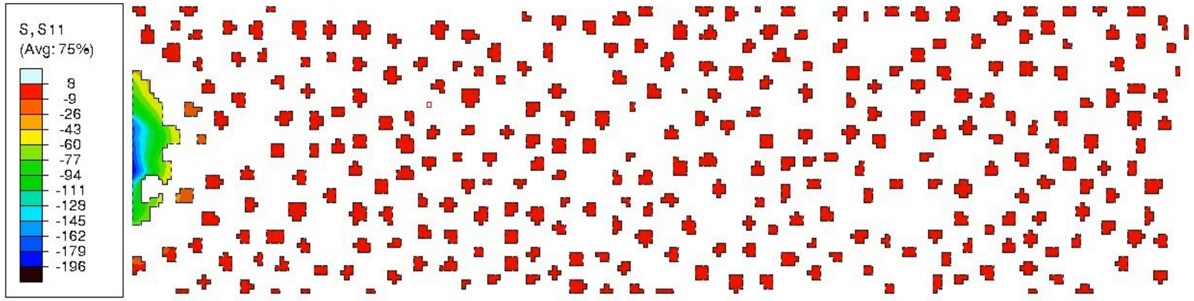
released by melting

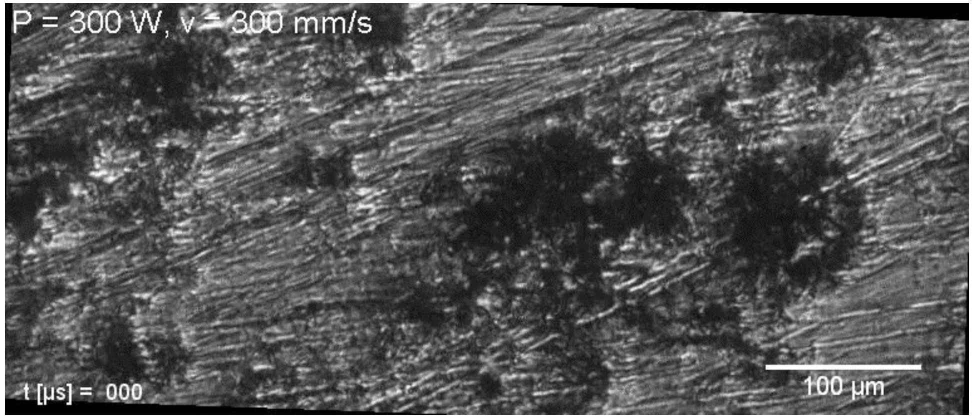


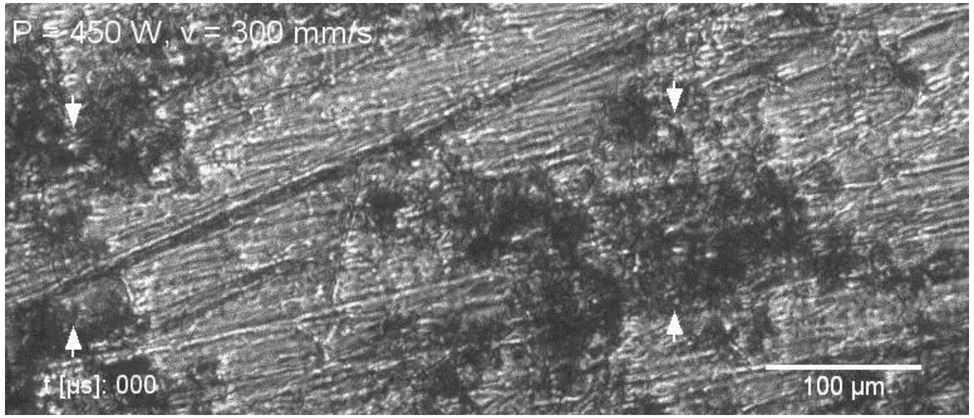
Single track experiments

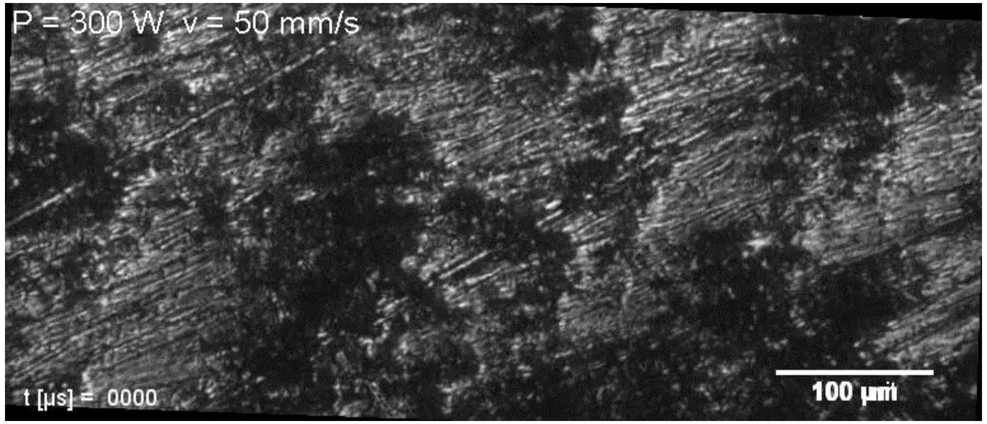
The experiments are conducted by Vrancken et al.[1] *(reuse under CC-BY 4.0 license)*

X-stress (MPa) (by CFD-FEM simulation, P=60 W, v=500 mm/s)









B. Vrancken, R. K. Ganeriwala, M. J. Matthews, Analysis of laser-induced microcracking in tungsten under additive manufacturing conditions: experiment and simulation, Acta Materialia (2020).

Single track experiments

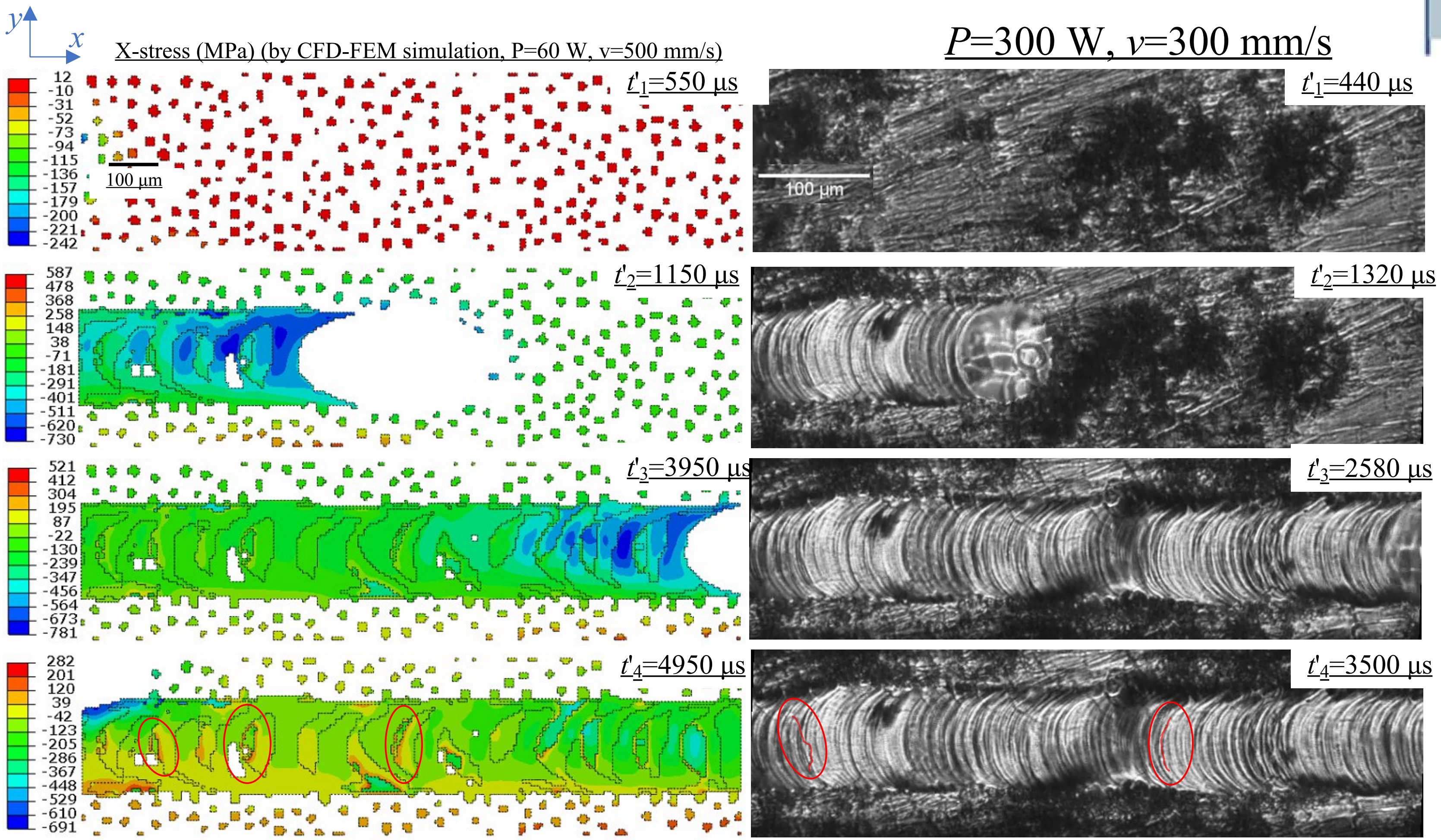
Snapshots in 4 stages

t_1' -- the heat is ready on the left side;

t_2' -- the track is being fabricated;

t_3' -- the track has been formed but the observed region has not cooled down;

t_4' -- the material has almost cooled down.



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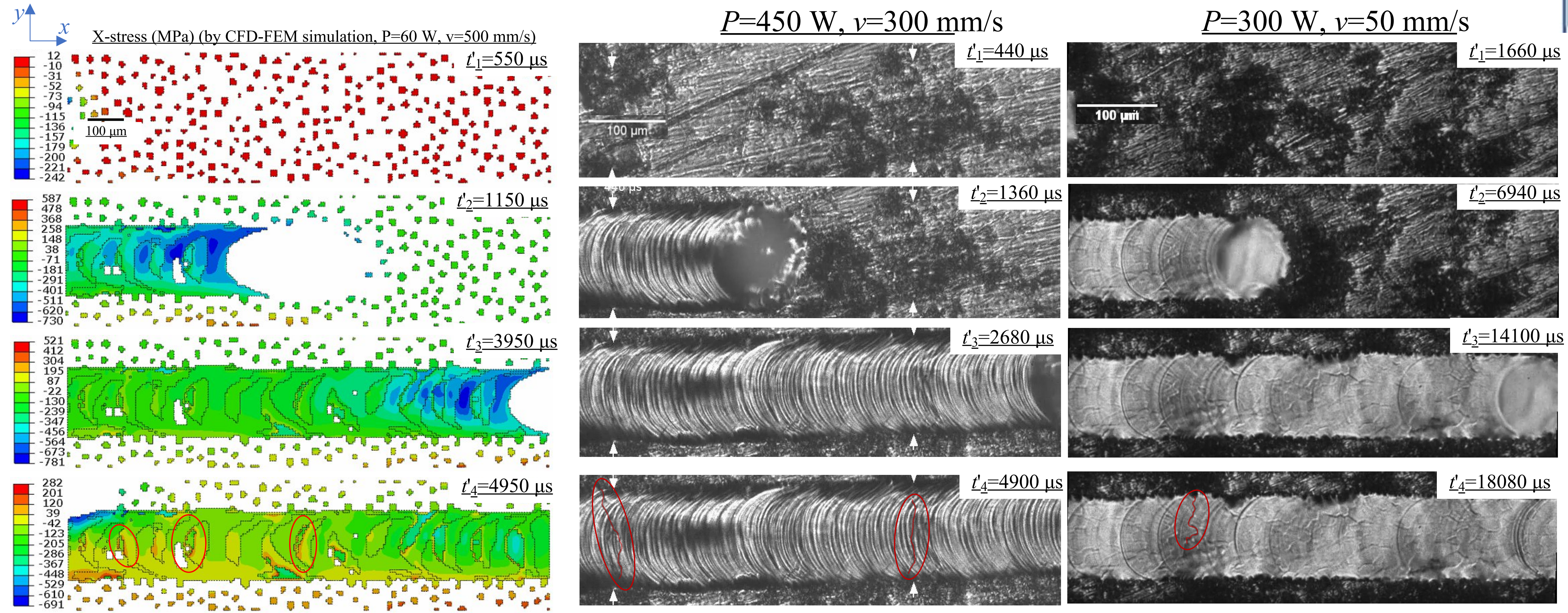
Single track experiments

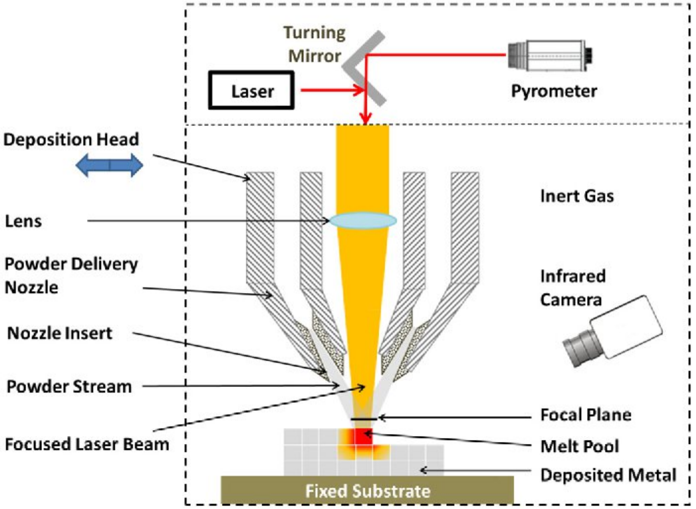
Snapshots in 4 stages



B. Vrancken, R. K. Ganeriwala, M. J. Matthews, Analysis of laser-induced microcracking in tungsten under additive manufacturing conditions: experiment and simulation, Acta Materialia (2020).

Other applications

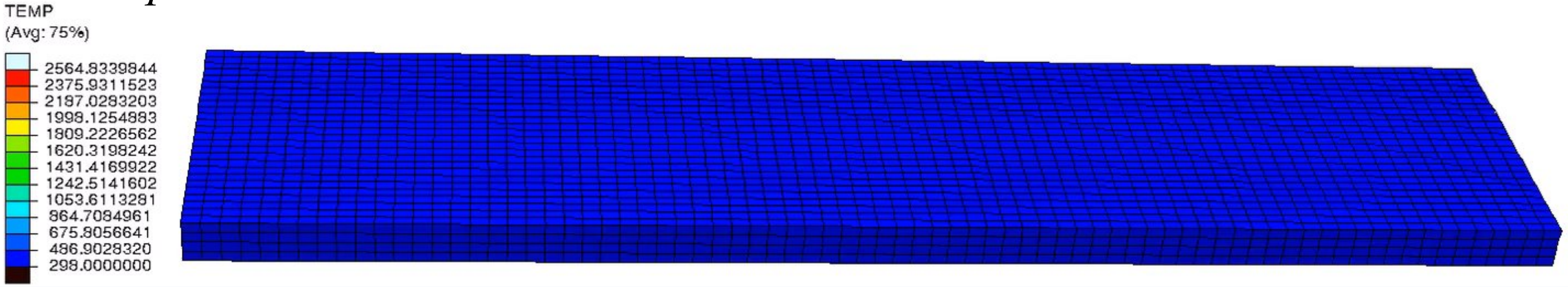
Direct energy deposition



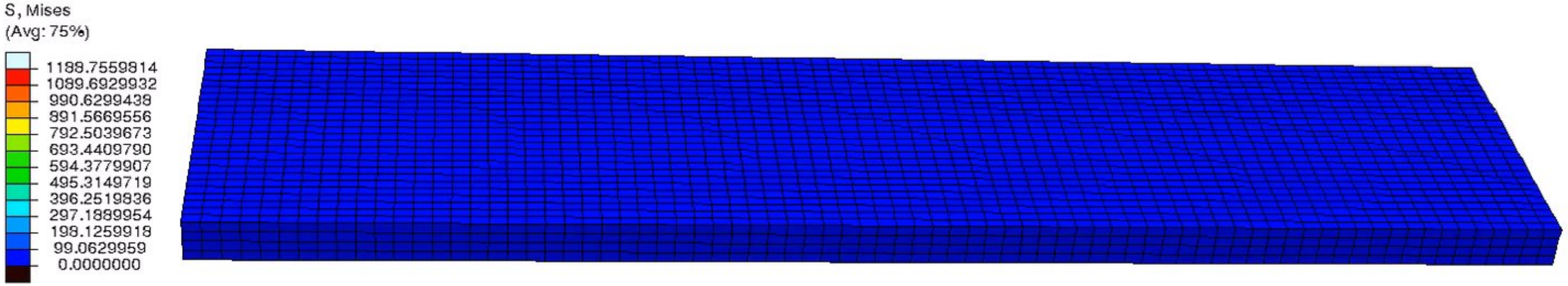
Thompson S M, Bian L, Shamsaei N, et al. An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics[J]. Additive Manufacturing, 2015, 8: 36-62.

CFD temperature field:

Coupled CFD-FEM model:



Mises-stress evolution:



Other applications

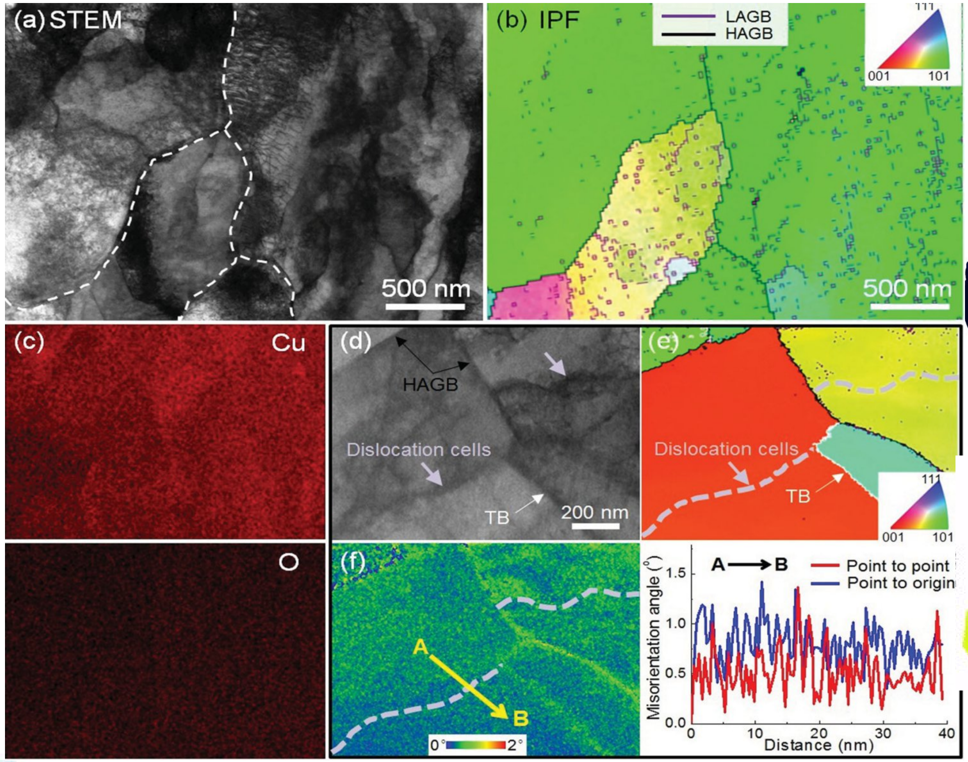
Origin of high-density dislocations in additively manufactured metals

Major finding on the origin:

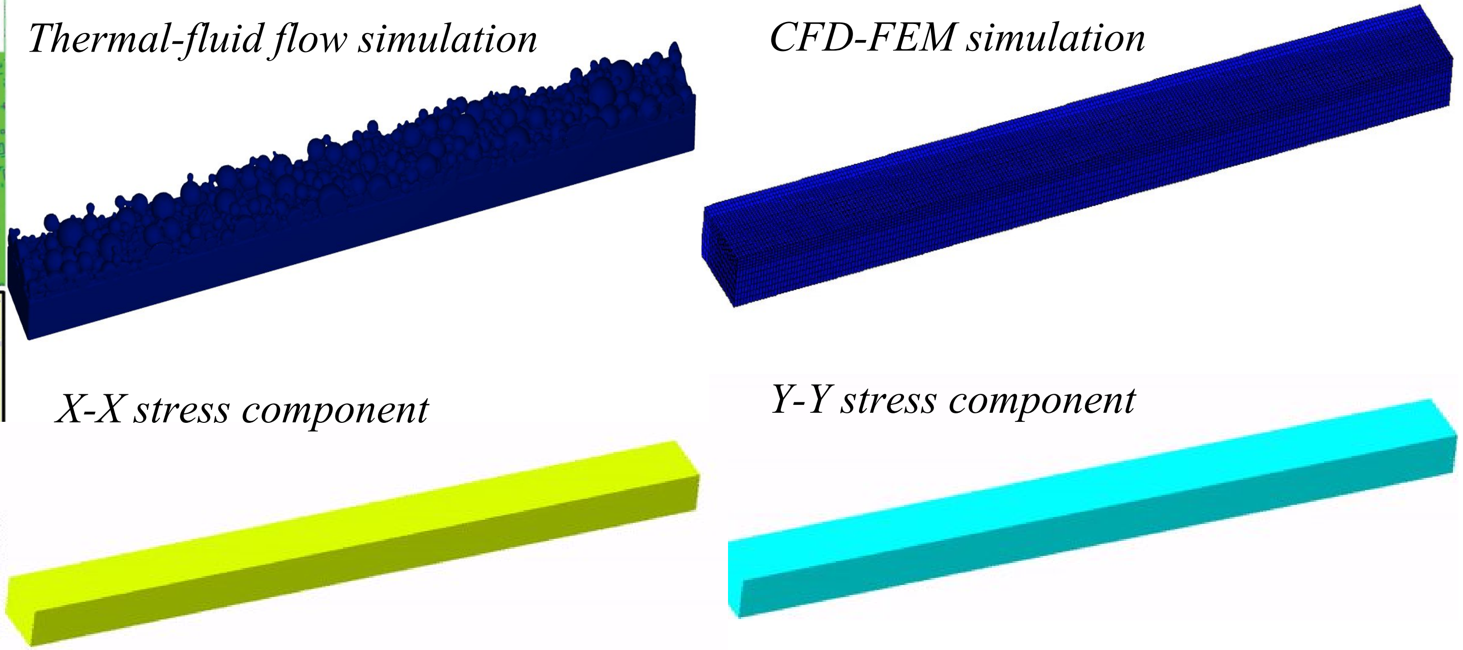
× Previously proposed mechanisms (cell solidification or nanoparticle blockage).

√ Repeated compression-tension cycles of thermal stress

Experiments: high-density dislocations in AMed copper



Simulation of temperature and thermal stress



Wang, Ge, Heng Ouyang, Chen Fan, Qiang Guo, Zhiqiang Li, **Wentao Yan***, and Zan Li. "The origin of high-density dislocations in additively manufactured metals." *Materials Research Letters* 8, no. 8 (2020): 283-290.

Thank you for listening!

Q&A

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Faculty of Engineering