University of Liège

Predicted microstructure in repair technology of Ti-6Al-4V

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(master thesis)

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Microstructure in Ti6Al4V parts built or repaired by Additive Manufacturing

What are still the scientific challenges?

Understanding all the out of balance phenomena due to high thermal and cyclic gradients

Developing accurate models to predict microstructures

This presentation:

- Two different experiments enhancing different microstructures
- A validated thermal model able to give reliable temperature history → qualitative prediction and analysis to progress toward quantitative prediction

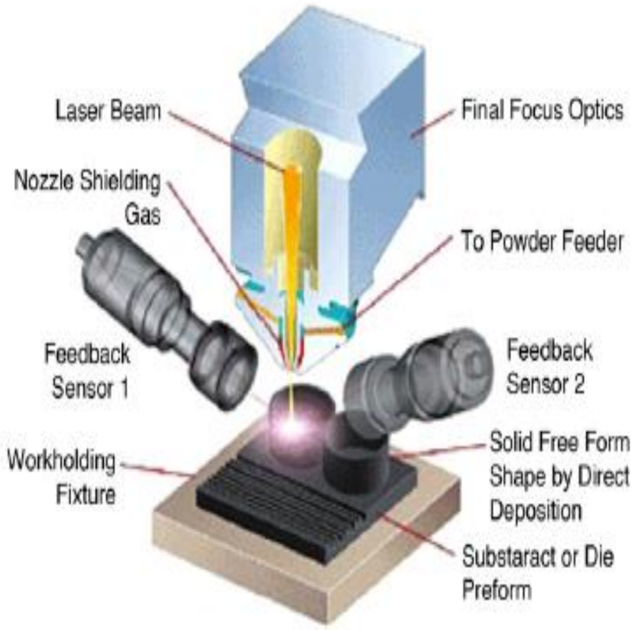
Laser cladding, DMD, LMD, LENS, DED, LAM...

Innovative technology

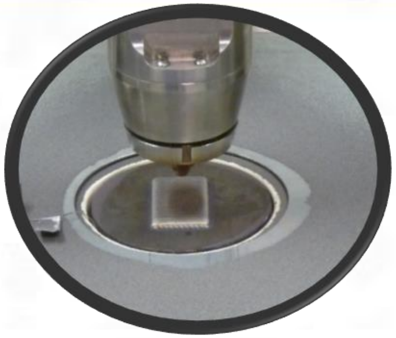
Production of dense parts

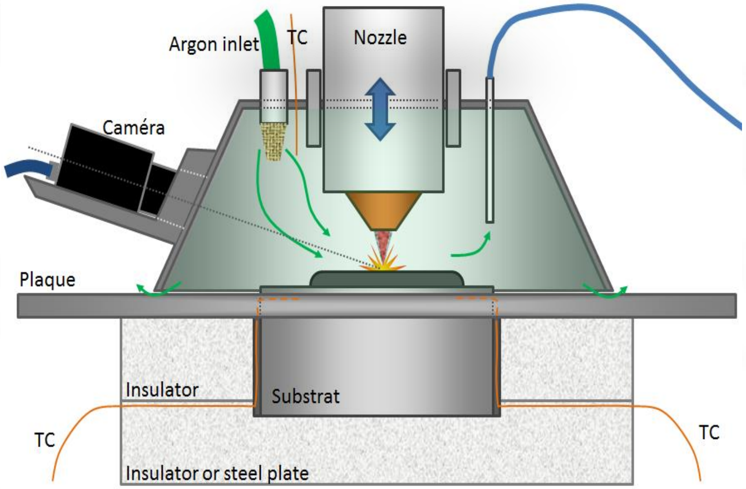
Multilayer metal deposit

Very high cooling rates (ultrafine grain microstructure)



Bhattacharya & al. (2011)





Sirris

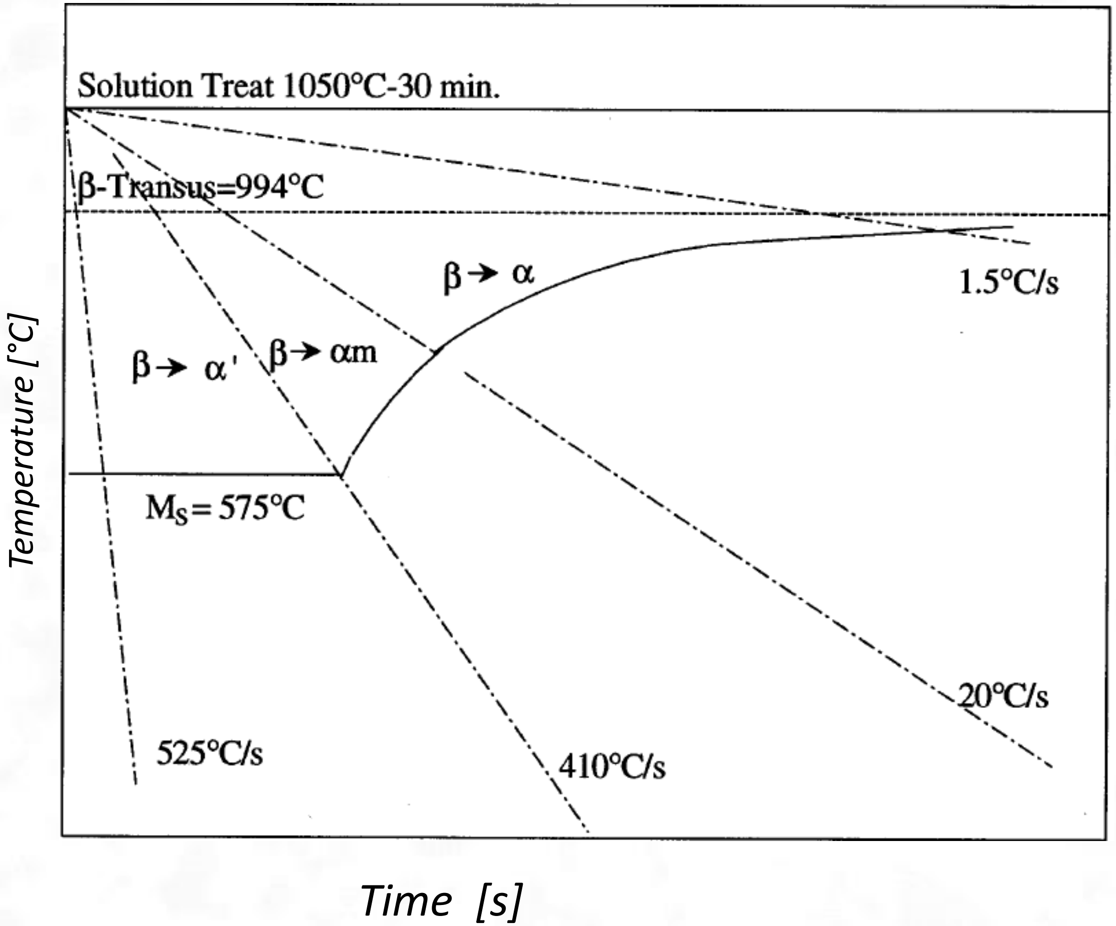
Need of a thermal model:

Study of processing parameters:

- laser power
- powder flow
- preheating temperature (T°)
- laser beam velocity

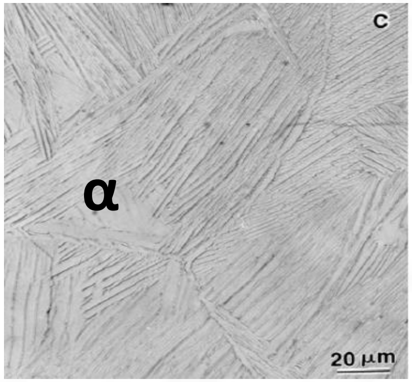
Material: Ti-6Al-4V

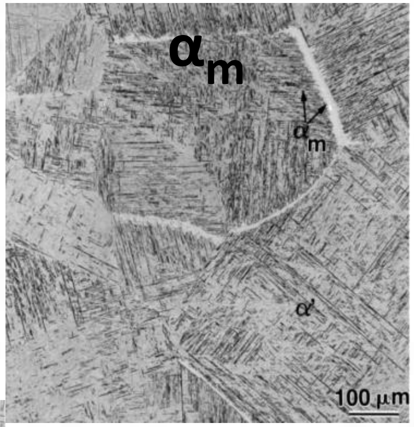
Éléments	Al	V	Fe max.	C max.	O max.	N max.	H max.	Ti
Composition %mass.	5.5 – 6.5	3.5 – 4.5	0.25	0.08	0.13	0.05	0.012	Bal.

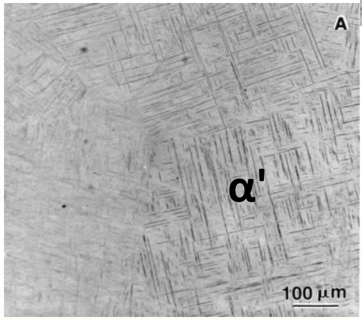


Continuous Cooling diagram– *Ahmed et al.1998*

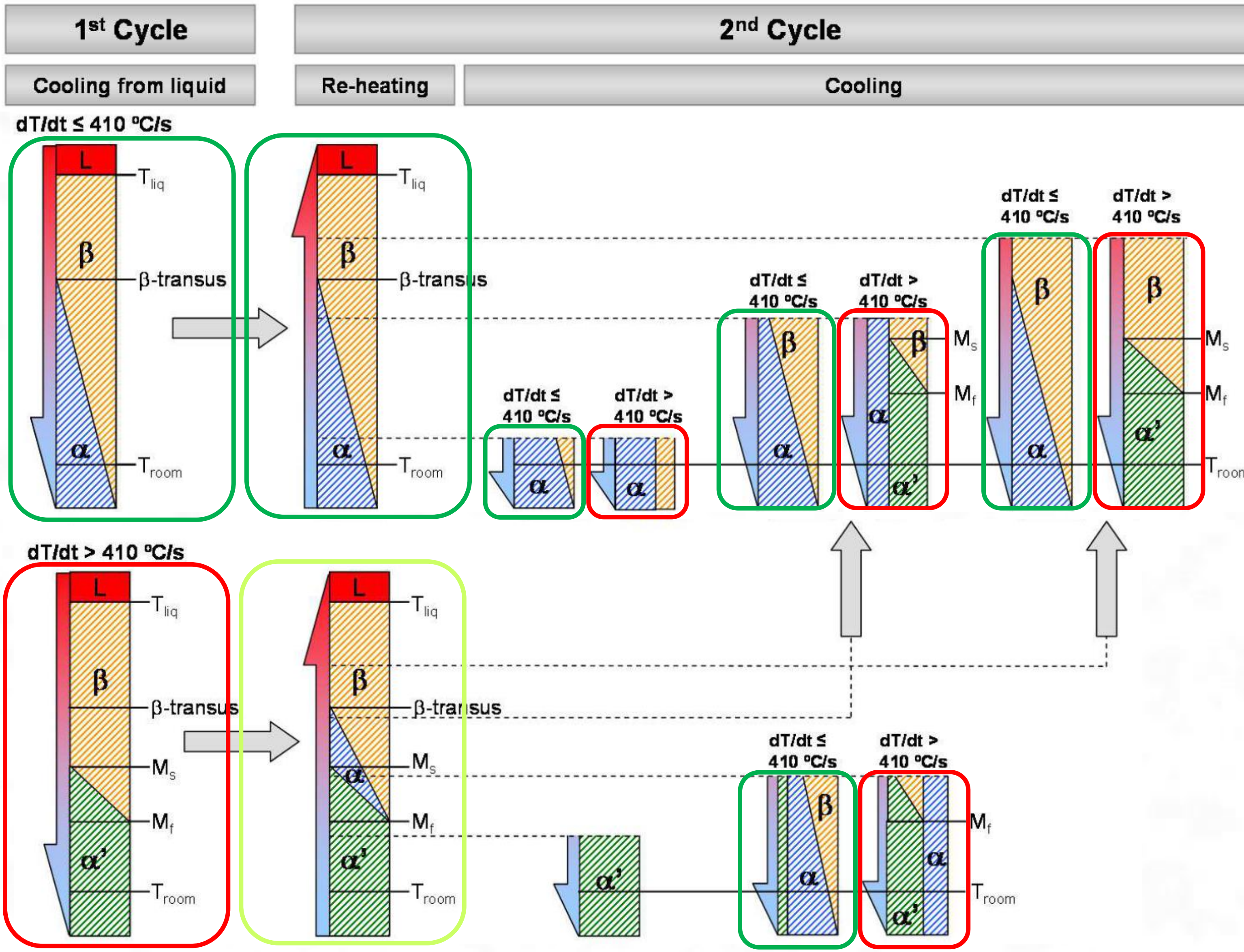
Microstructure evolution







Phenomenological Models of Solid-phase Transformations



Transformation #1

Martensitic transformations at fast cooling rates ($dT/dt > 410$ °C/s)

$$\beta \rightarrow \alpha'$$

Transformation #2

Diffusional transformations during heating

$$\alpha' \rightarrow \alpha + \beta$$

Transformation #3

Diffusional transformations at slow cooling rates ($dT/dt \leq 410$ °C/s)

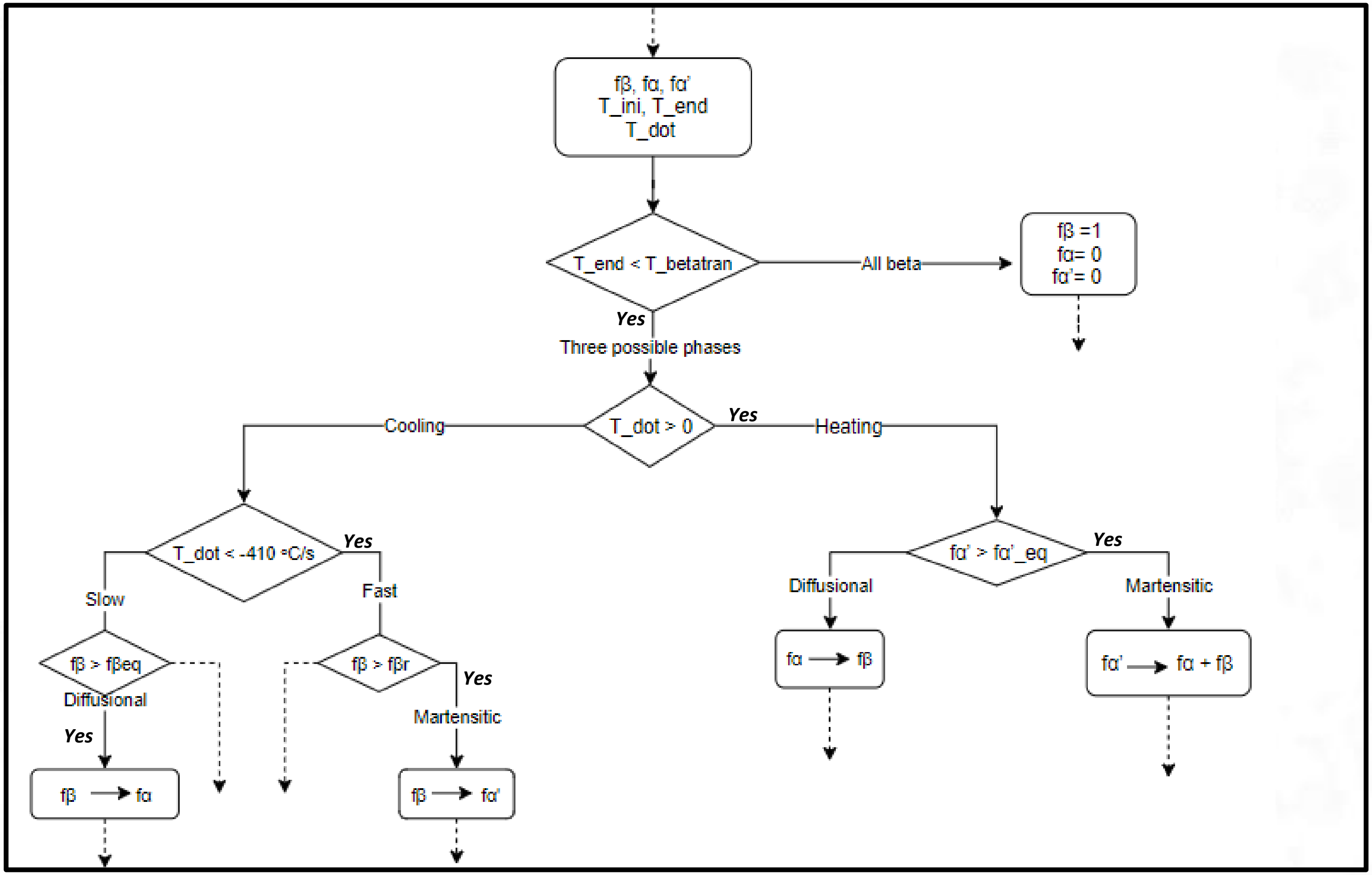
$$\beta \leftrightarrow \alpha$$

Crespo, A.,*2010 Modelling of Heat Transfer and Phase Transformations in the Rapid Manufacturing of Titanium Components*

Phenomenological Models of Solid-phase Transformations

Master thesis
2018
Elena Esteva

Flowchart for microstructure model implementation



Martensitic transformation (β→α'): temperature dependent only

- Koisitinen – Marburger Model : $f_{\alpha'}(T) = f_{\alpha'}(T_0) + (f_{\beta}(T_0) - f_{\beta r})[1\text{-exp}[-\gamma(Ms - T)]]$

Diffusional transformation (α'→α+ β, β↔ α): temperature and time dependent

- Johnson-Mehl-Avarami-Kolmogorov Model + additivity rule $f_{\alpha'}(T + dT) = 1 - [1\text{-exp}[-k(t^f + \Delta t)^n]](1 - f_{\alpha'}{}^{eq})$
  where t^f is fictious time which would resulted in fraction $f_{\alpha'(T)}$ at $T + dT$

Phenomenological Models of Solid-phase Transformations

Martensitic transformation ($\beta \rightarrow \alpha'$): temperature dependent only

- Koisitinen – Marburger Model : $f_{\alpha'}(T) = f_{\alpha'}(T_0) + (f_{\beta}(T_0) - f_{\beta_r})[1\text{-}\exp[-\gamma(Ms - T)]]$

M_s is a great variety in the literature

- (Tan *et al.* 2015) consider an M_s =1073 K
- (Kelly SM 2004) Use lower values such as M_s = 848 K
- (Charles Murgau C et al. 2012) M_s = 898 K
- (Crespo A, et al. 2010) M_s = 923 K

M_s point depend on the chemical composition of titanium alloys and **cooling rate**

The completion of the martensitic reaction is almost achieved when the temperature reaches the end point of the transformation temperature (M_f).

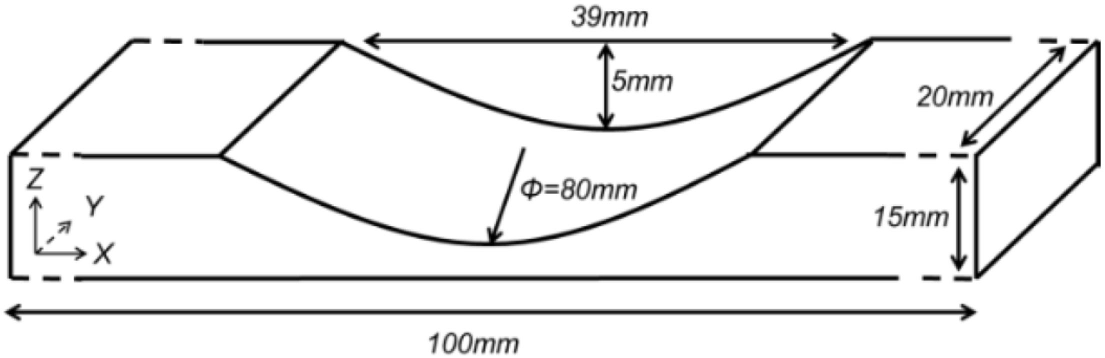
- Very **few** values are mentioned in the literature , very **disparate**
- (Crespo A, et al. 2010) M_f = 673 K
- (Jovanovic *et al.* 2006) M_f = 298 K

M_s and M_f $\rightarrow$ need further investigation

Experiments

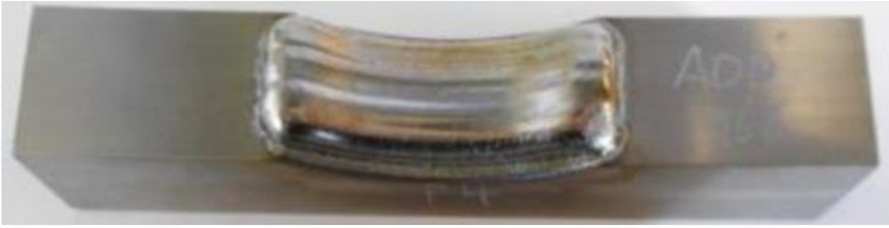
Laser cladding as a repair technology for Ti6Al4V alloy: influence of incident energy and building strategy on microstructure and hardness.

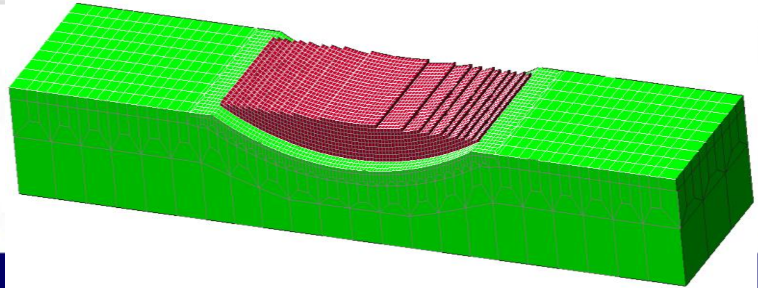
Paydas,et al. **Materials and Design 2015.**

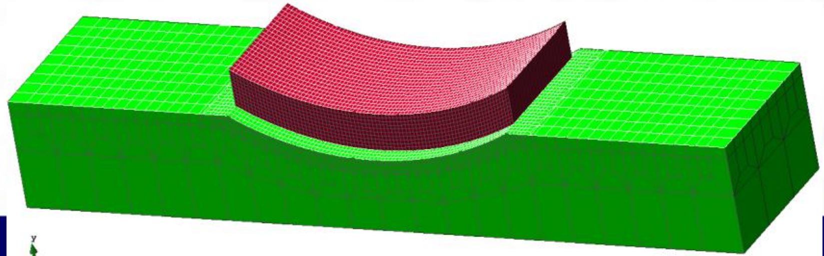


«MacroClad» et «Decrease Track Length (DTL)» strategy

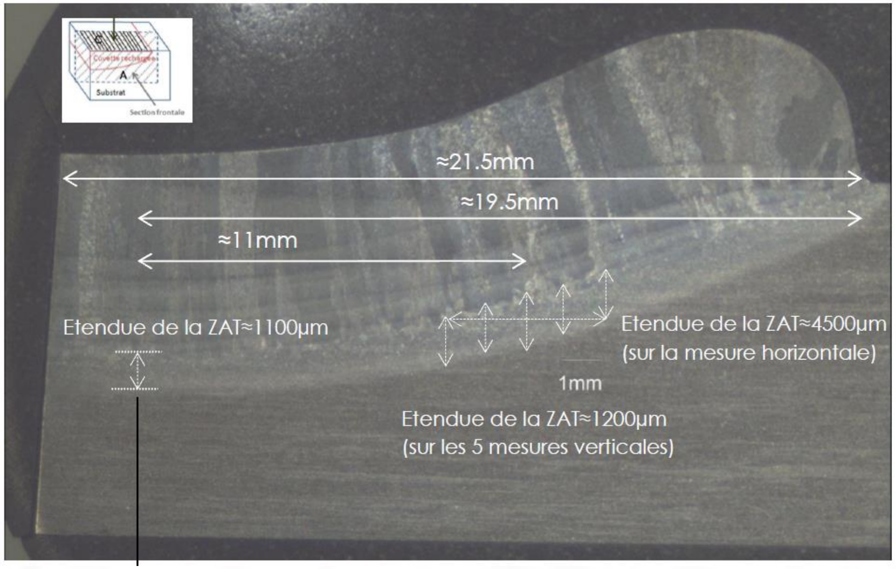
«MacroClad» et «Constant Track Length (CTL)» strategy

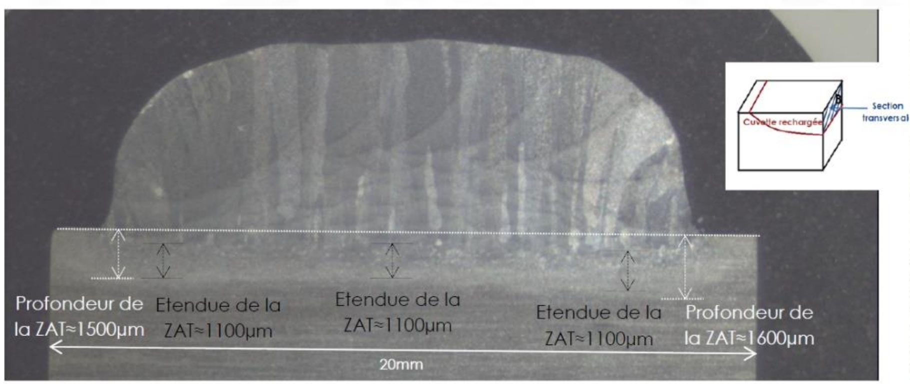


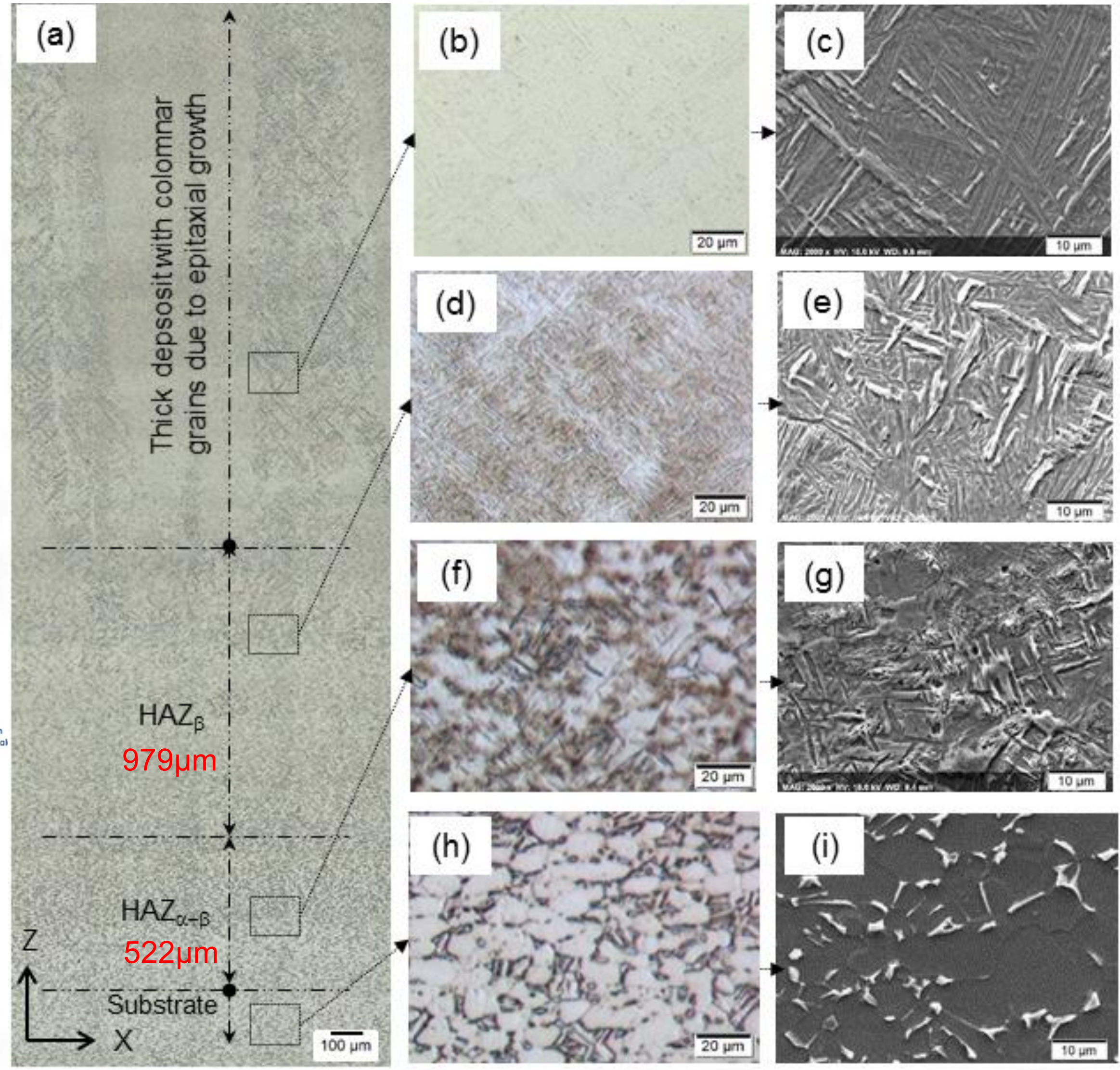




Experimental data







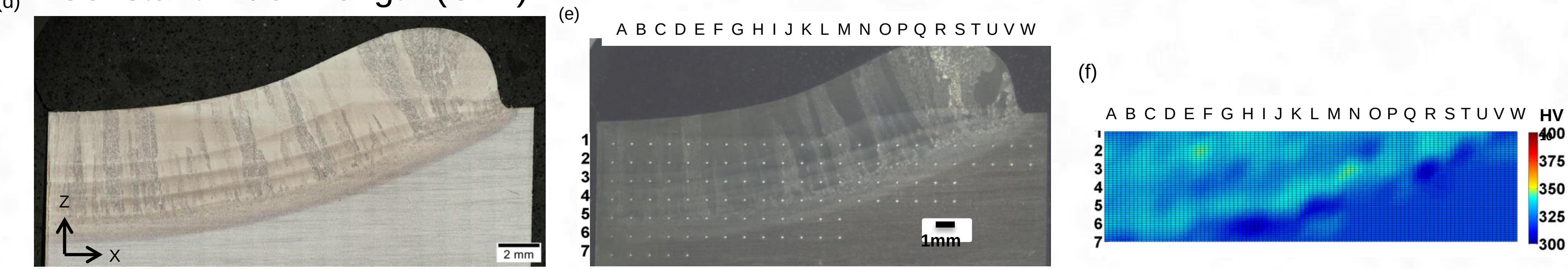
Paydas,et al. **Materials and Design 2015**
\+ Tran et al. **Materials & Design 128 2017**

Microstructure of Constant Track Length (CTL)

Results of indentation campaign

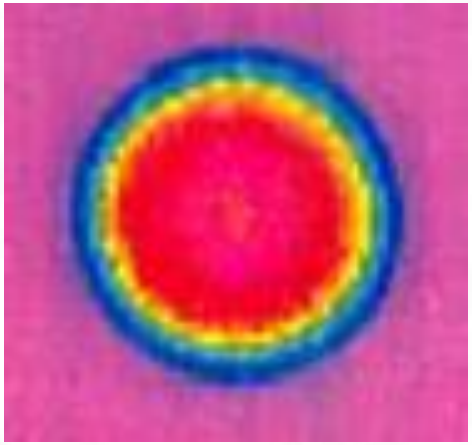
Decrease Track Length (DTL)

Constant Track Length (CTL)

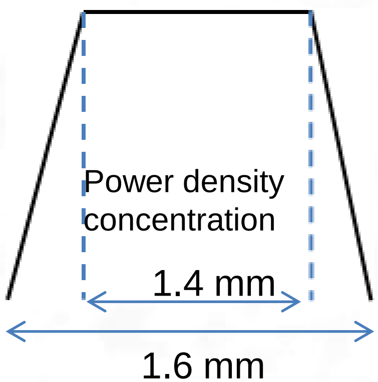


Hardness maps and corresponding hardness indentation grids (*Paydas et al.2015)*

Numerical model

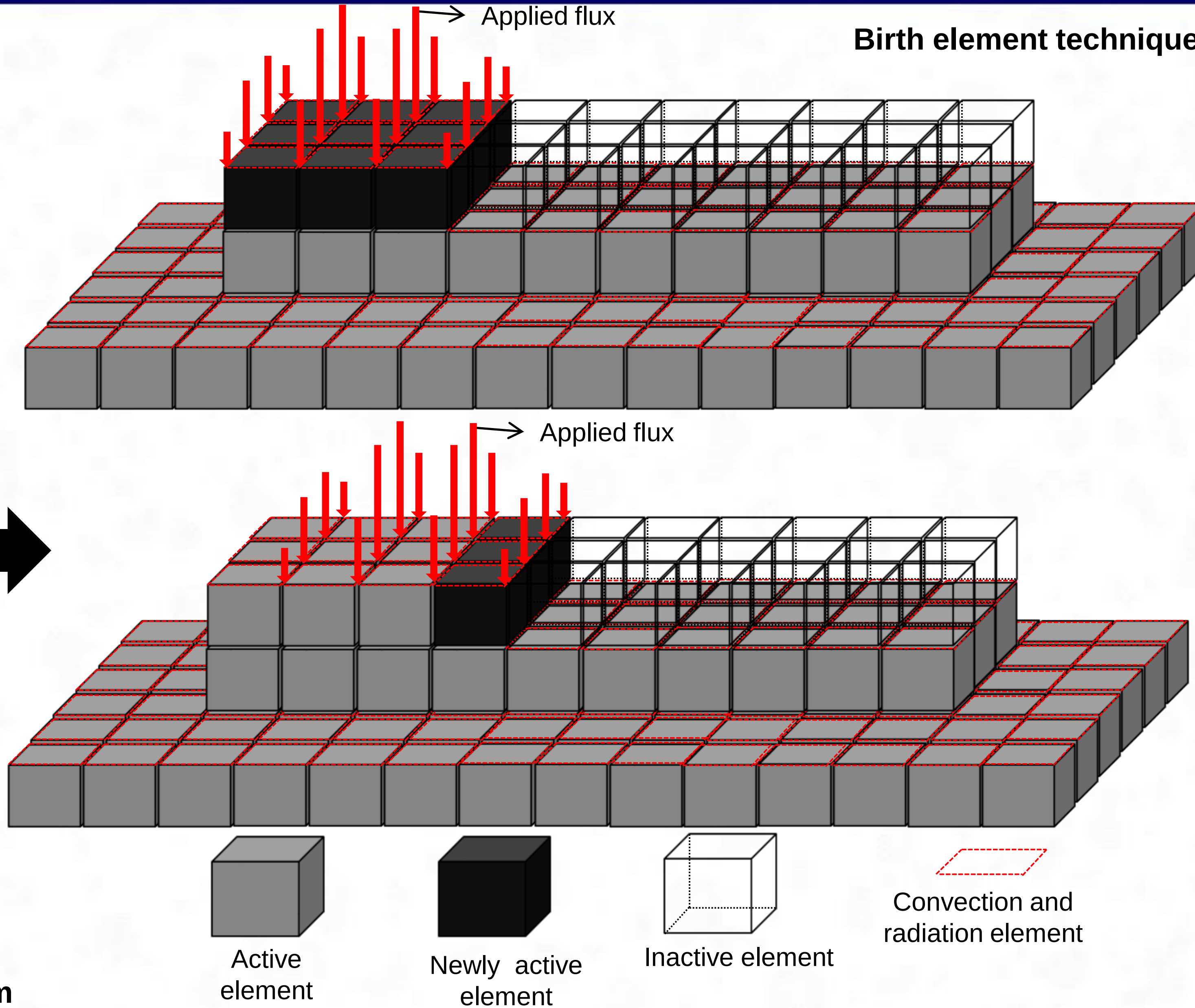


Laser used by Sirris



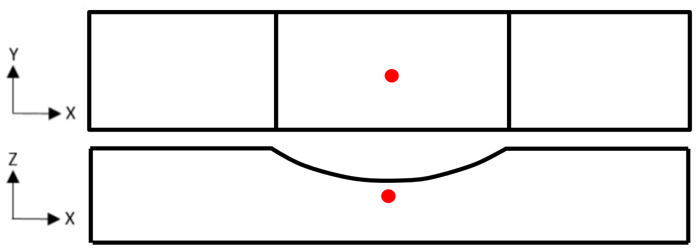
Top-hat profile of the laser beam energy

Birth element technique

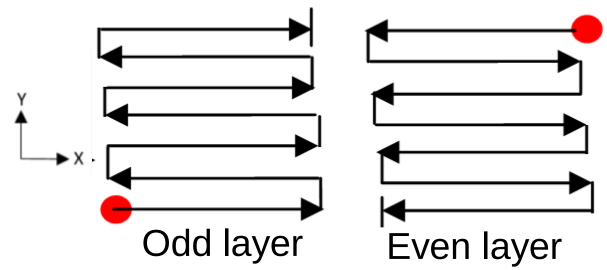


At each time step → Updated boundary conditions

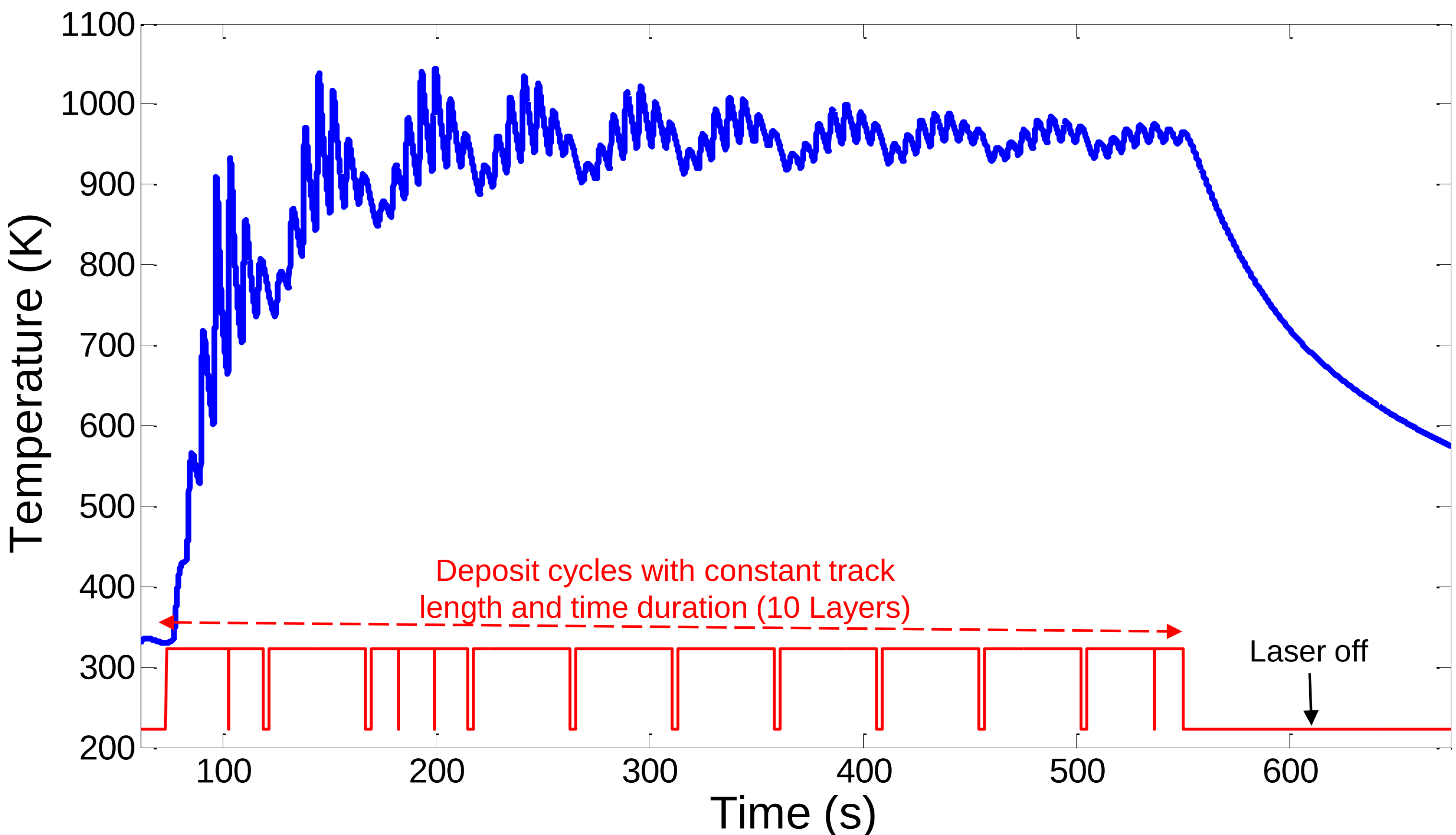
Temperature measurement



Geometry of the machined substrate



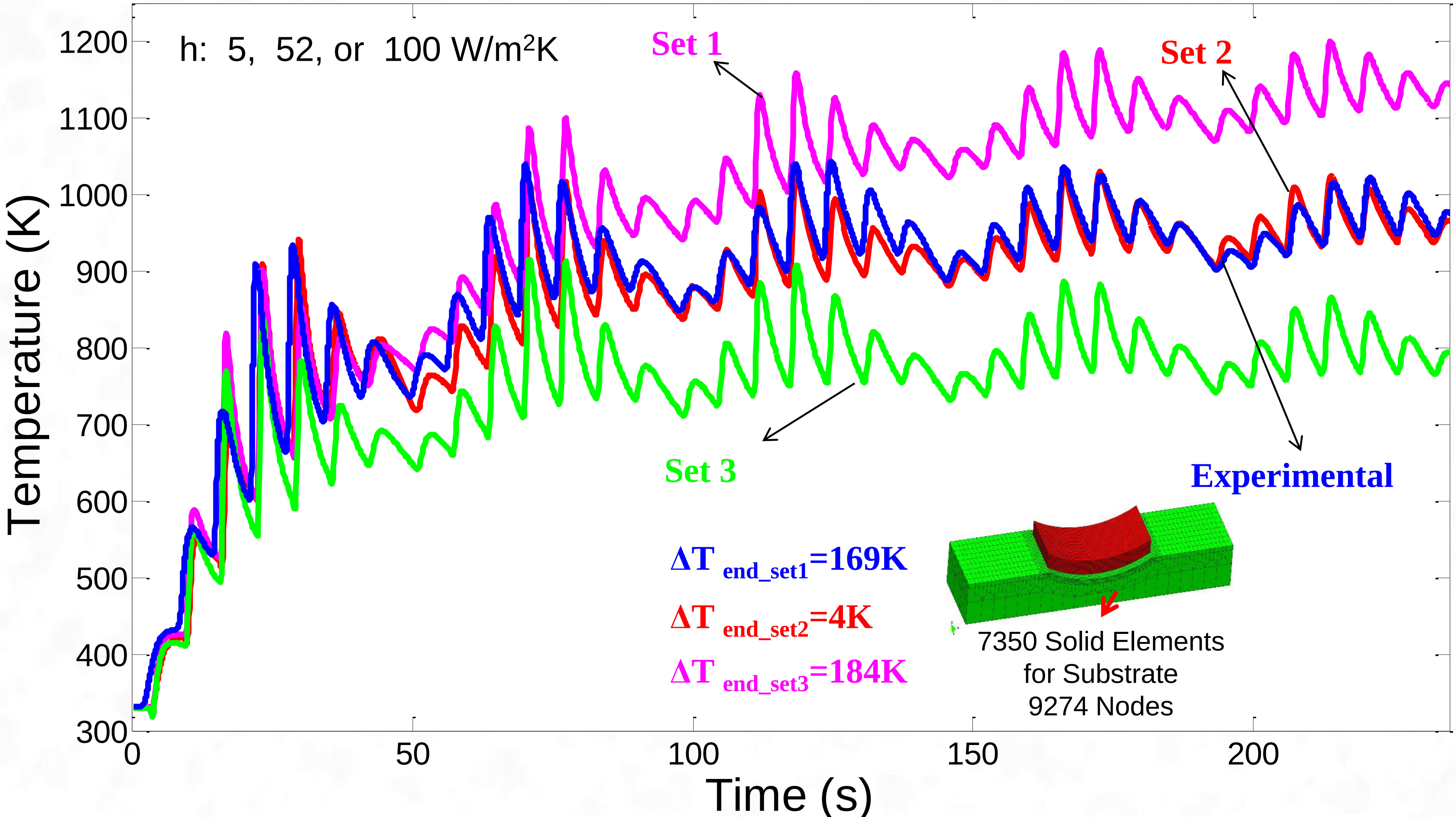
Path of laser beam (7 tracks/layer)



Temperature measured at the thermocouple

Constant Track Lenght strategy

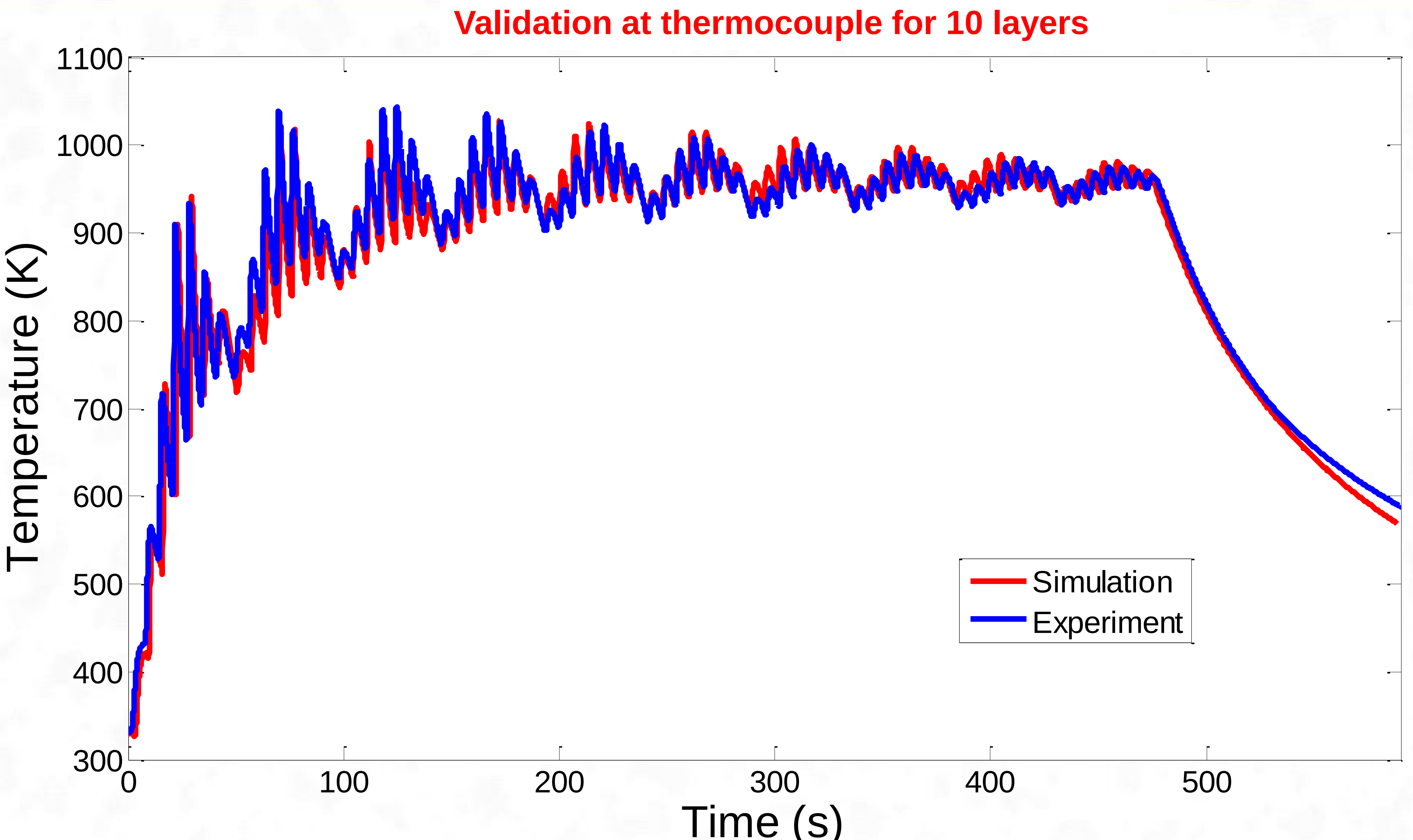
Sensitivity analysis: T° at thermocouple



Thermal history at the thermocouple due to the first five layers

Tran et al.
Materials and Design 2017

Constant Track Lenght strategy

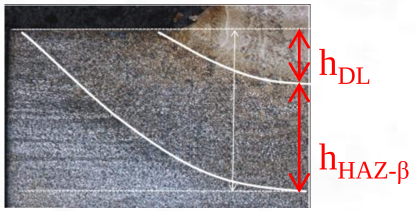


Comparison between the simulated and the experimental thermal history from the thermocouple

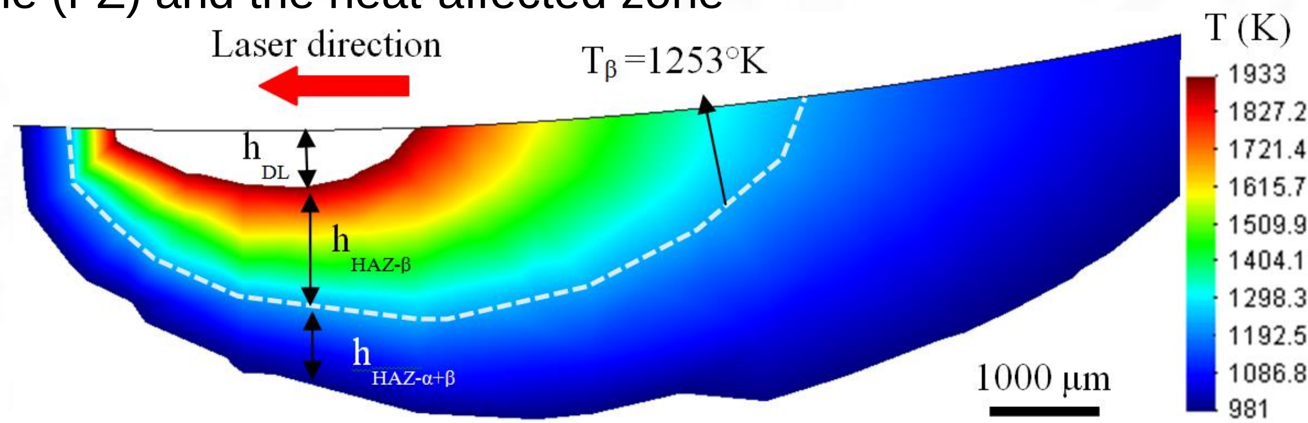
Tran et al.
Materials and Design 2017

Constant Track Lenght strategy

Fusion zone (FZ) and the heat-affected zone (HAZ)



Depth of Fusion zone

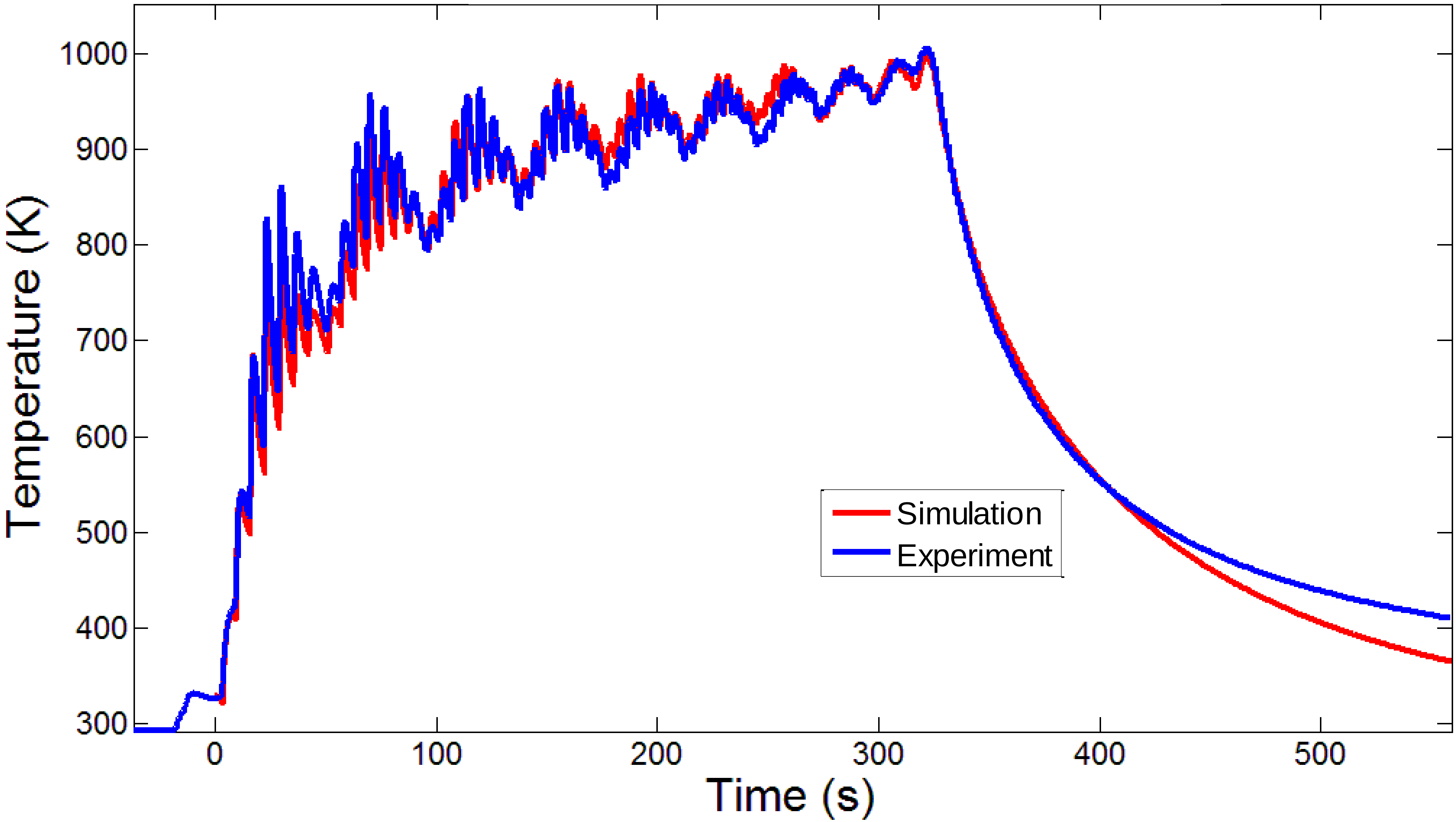


2D view of thermal field within HAZ

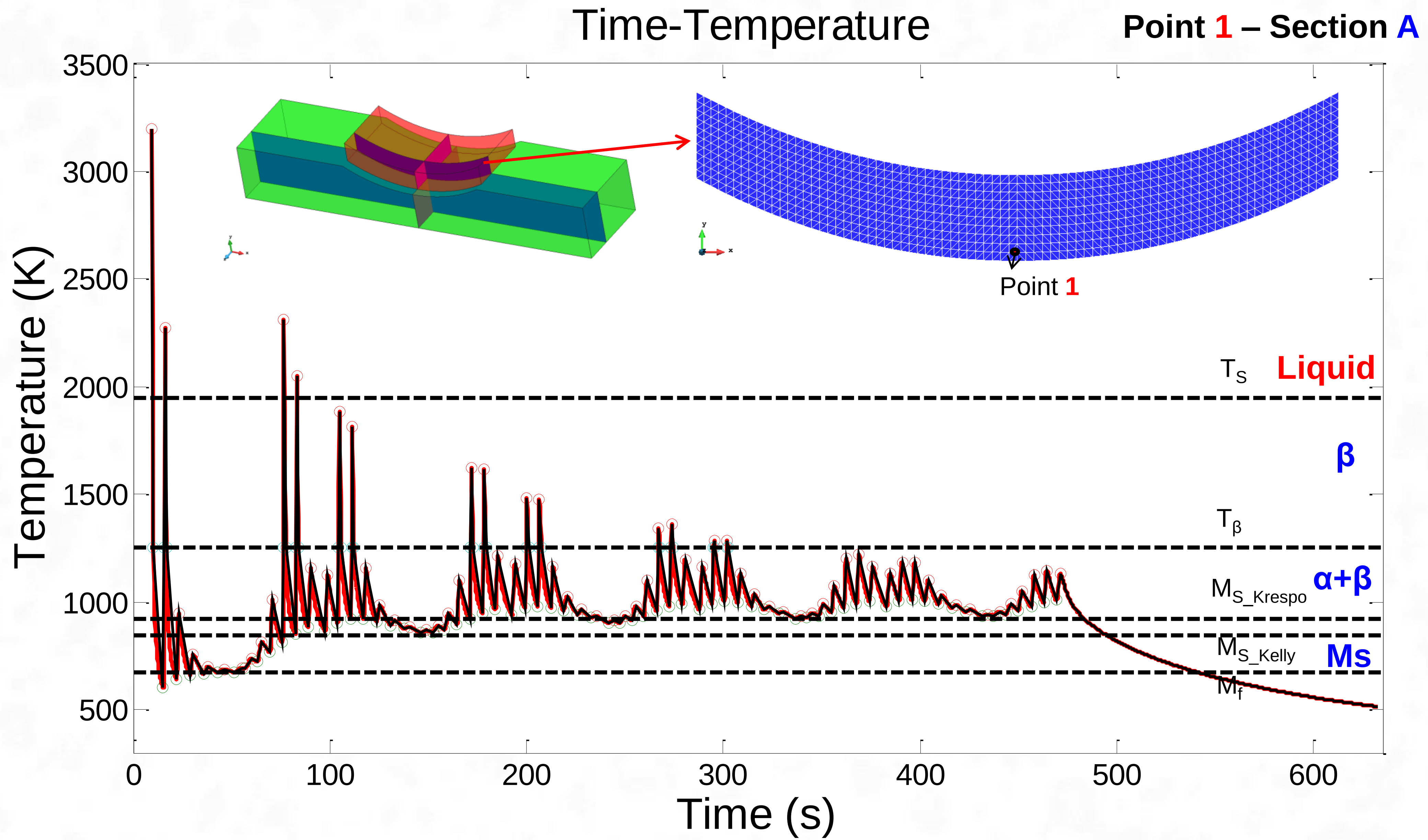
	Depth	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Simu result	h_{DL} (µm)	508	688	709	730	793
	h_{HAZ} (µm) HAZ_β+ $HAZ_{\alpha+\beta}$	1618	1864	2174	2377	2605
Measured	h_{DL} (µm)	450	Not accessible, different zones cannot be recovered			
	h_{HAZ} (µm) HAZ_β+ $HAZ_{\alpha+\beta}$	1501				

Decrease Track Length strategy

Validation at thermocouple for 10 layers

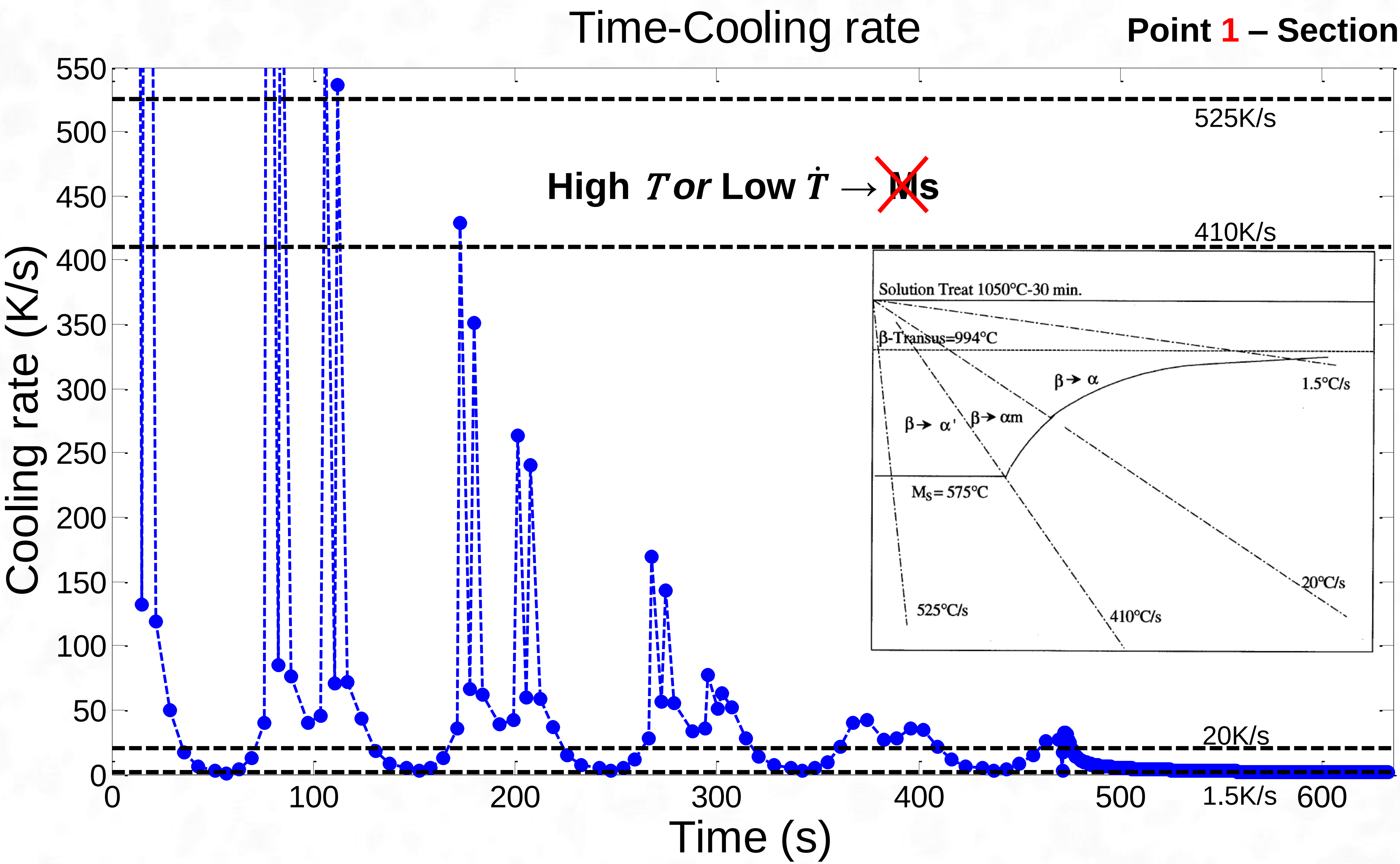


Constant Track Lenght strategy

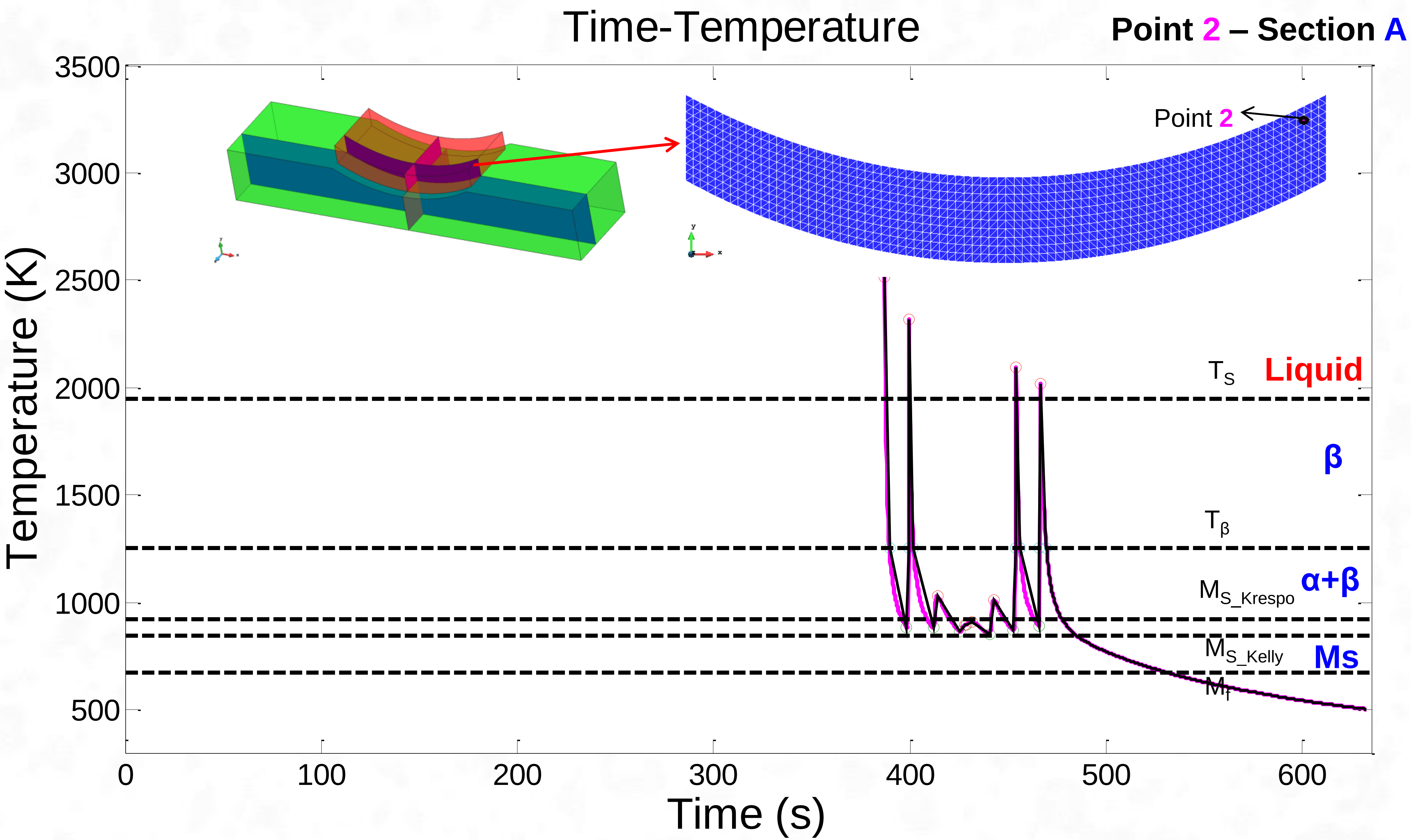


Constant Track Lenght strategy

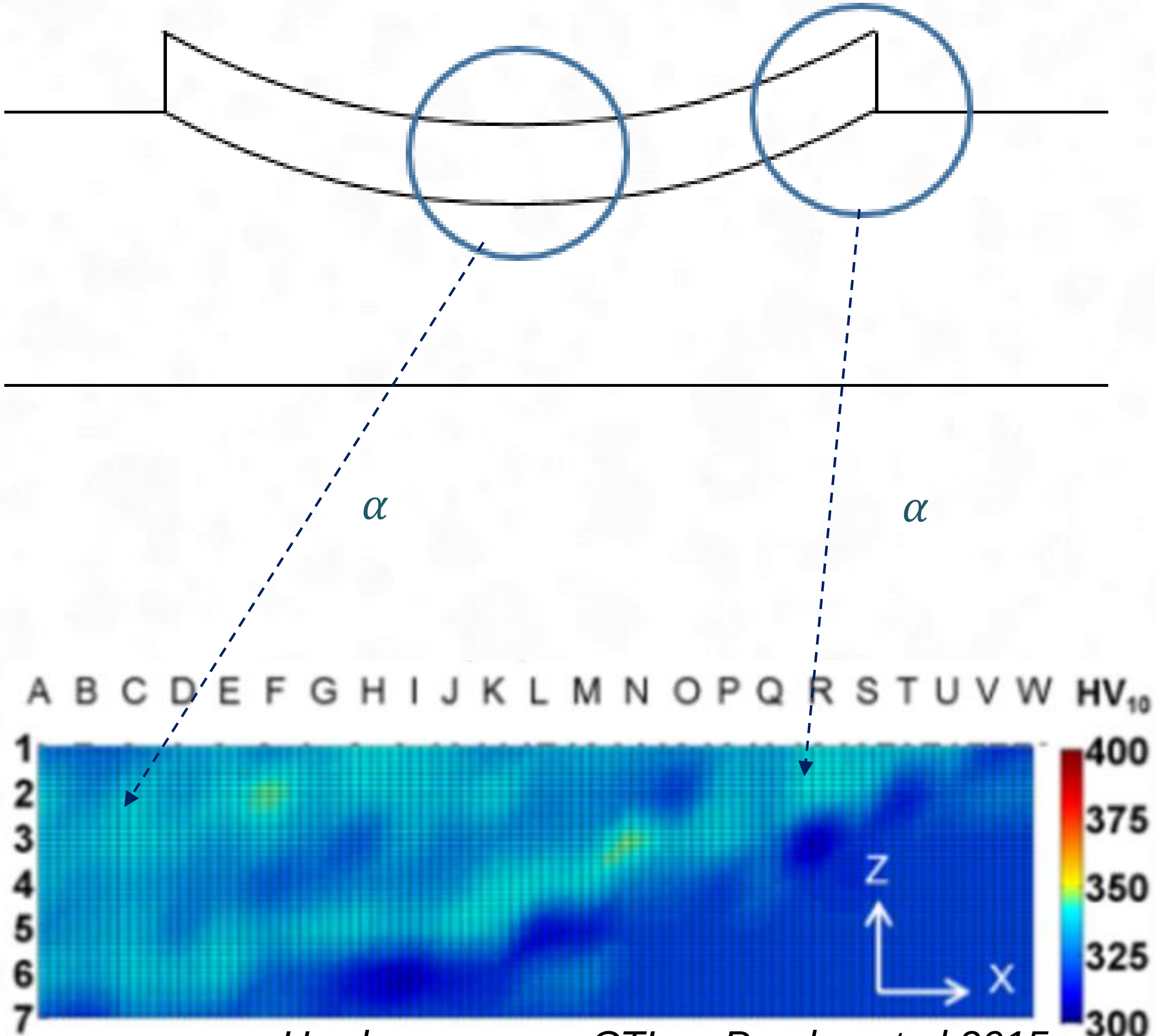
Point **1** **– Section** **A**



Constant Track Lenght strategy

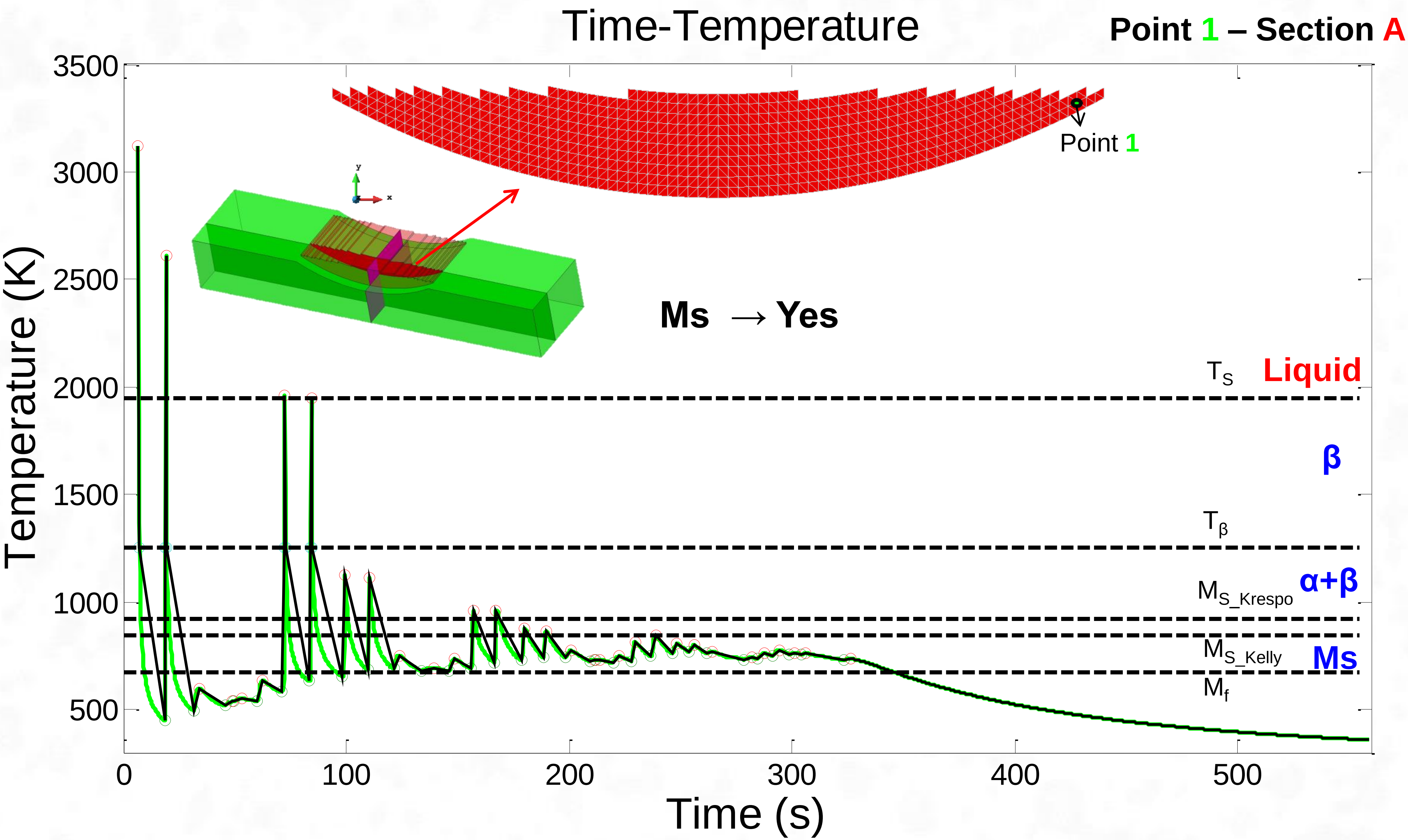


Constant Track Lenght strategy

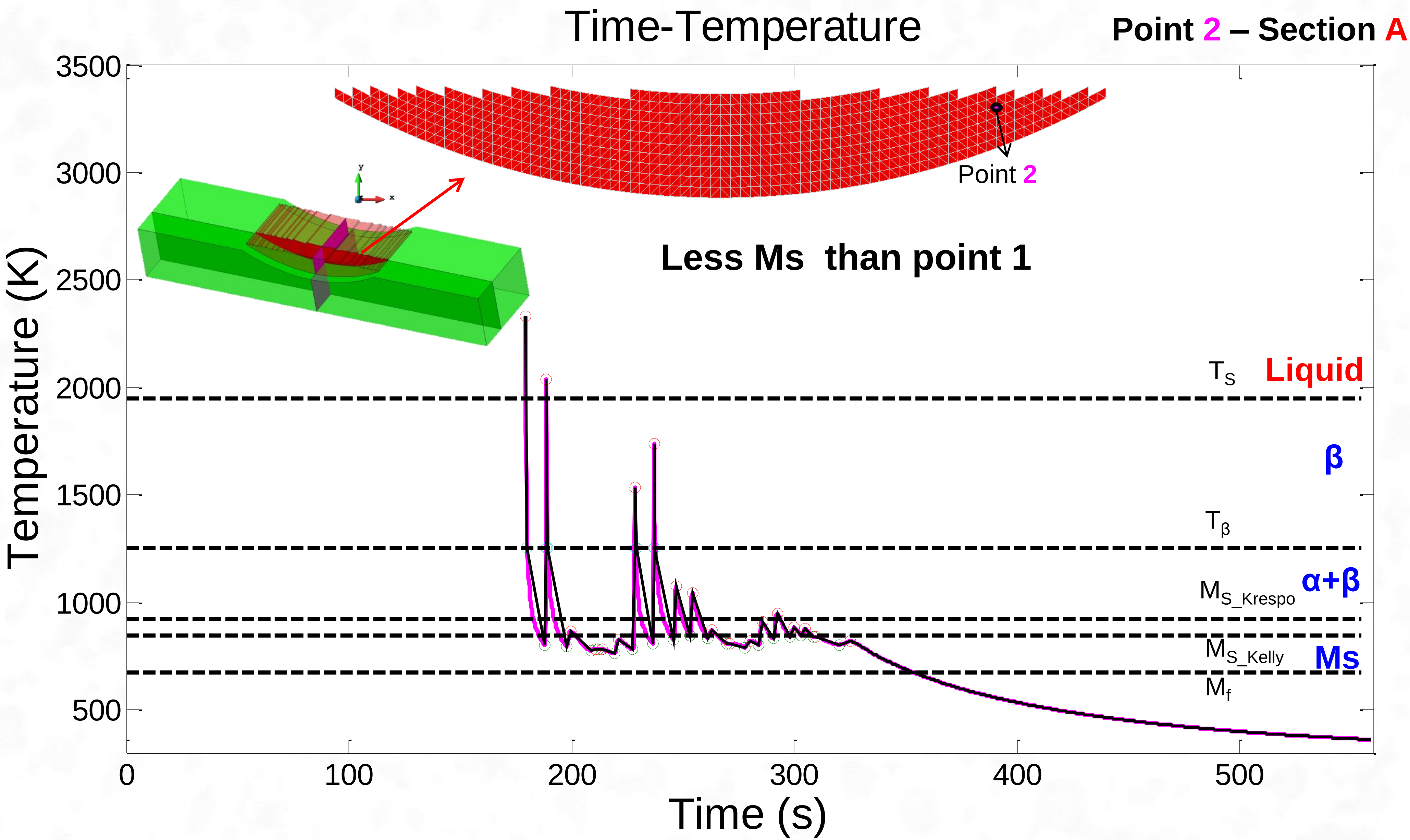


Hardness map – CTL – Paydas et al.2015

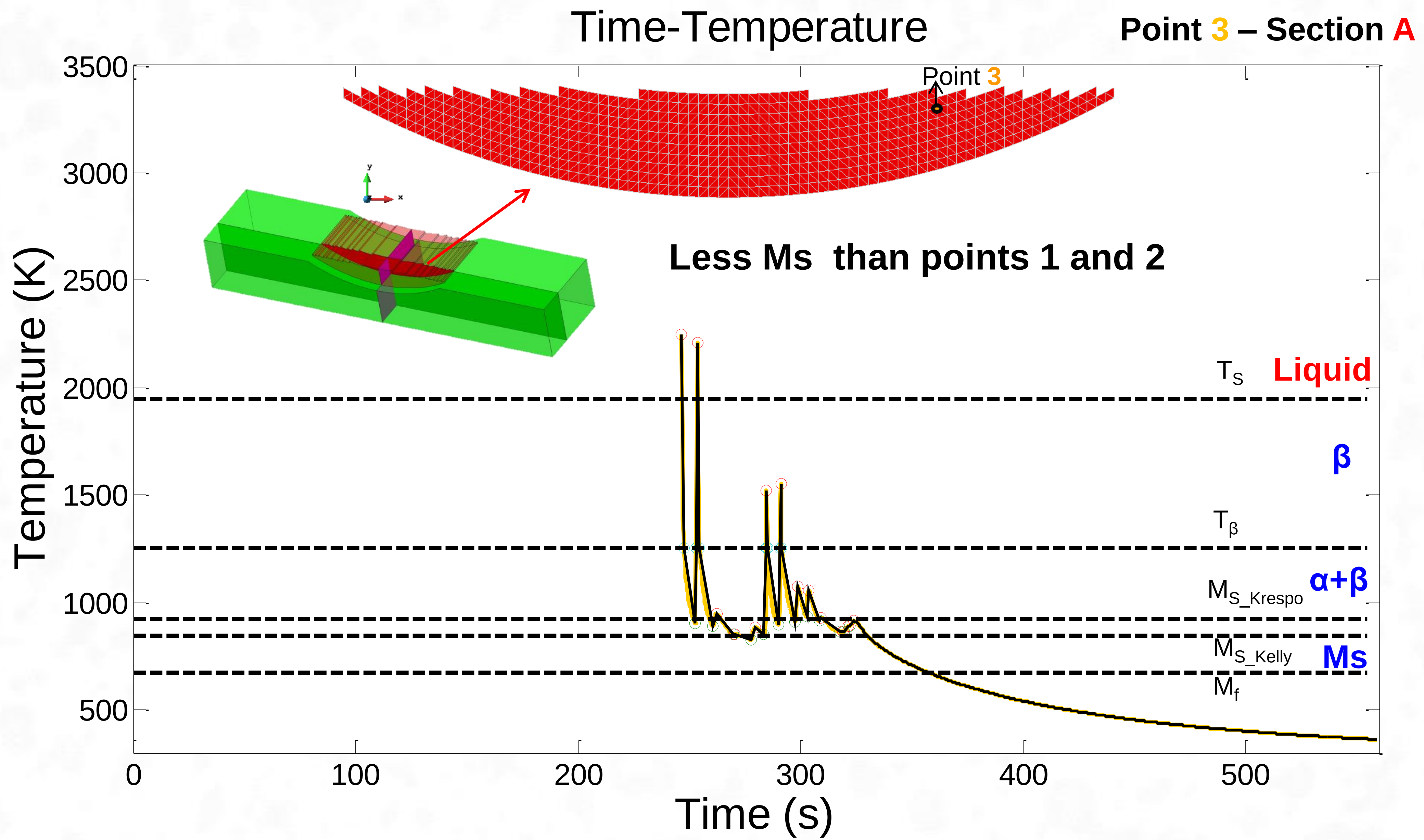
Decrease Track Length strategy



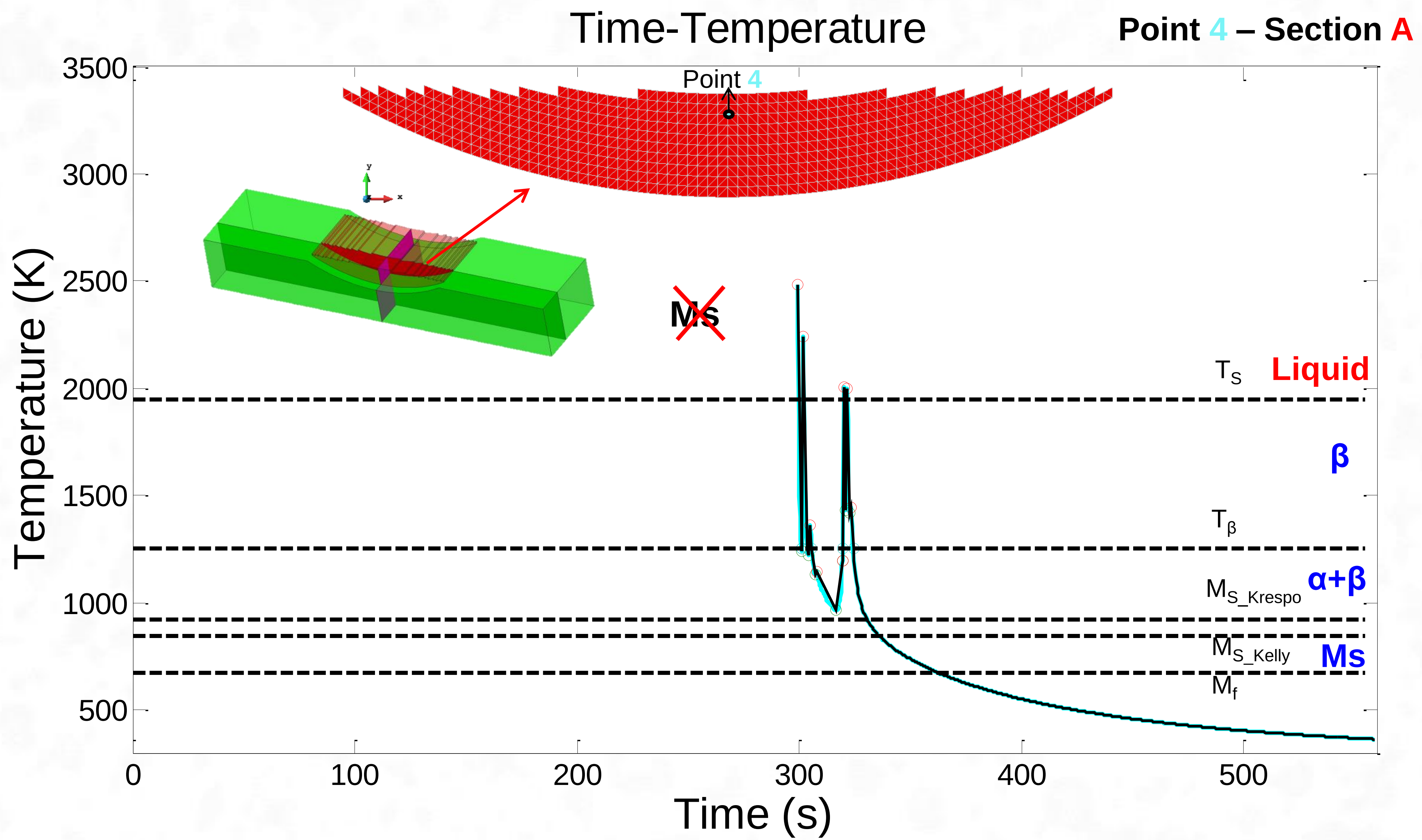
Decrease Track Length strategy



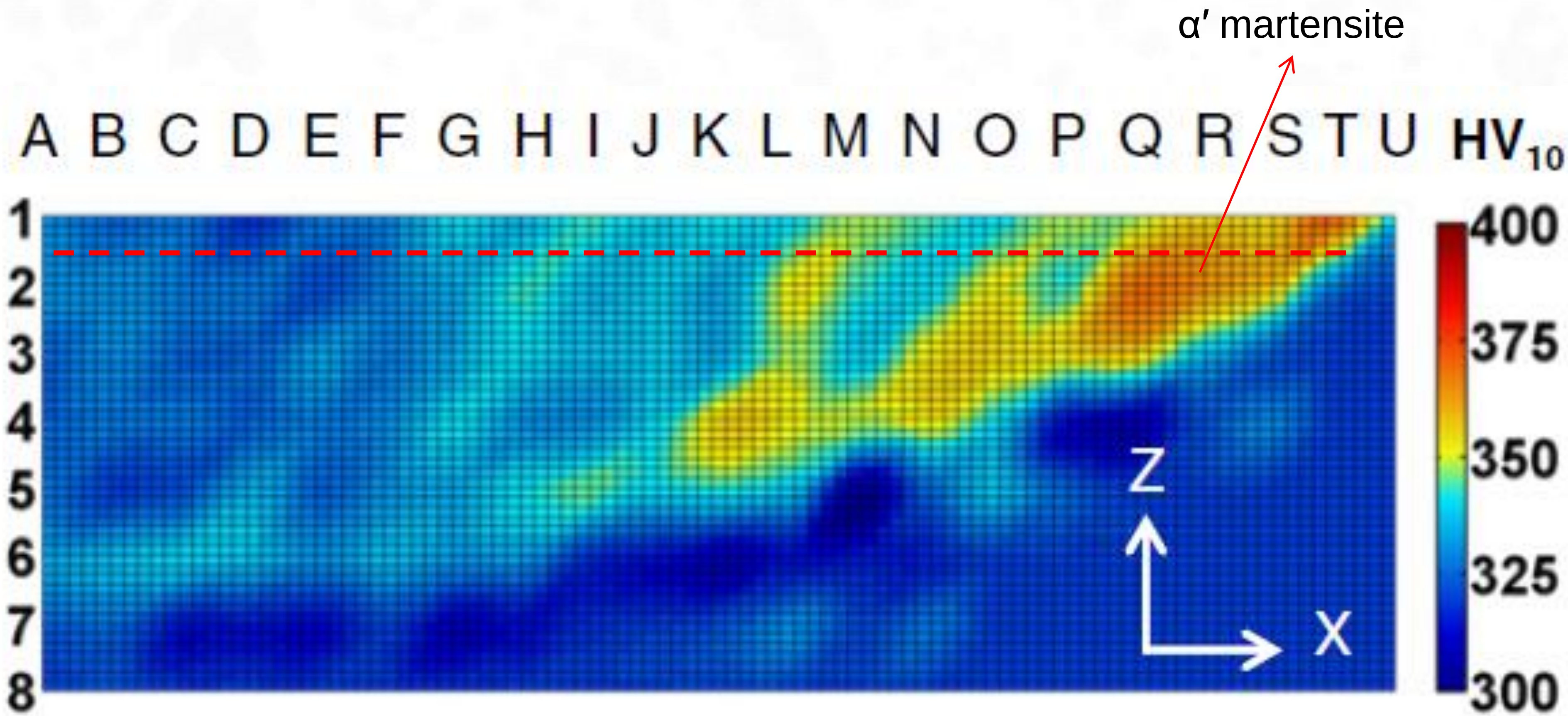
Decrease Track Length strategy



Decrease Track Length strategy



Decrease Track Length strategy



Hardness measurement (Hakan et al. 2015)

Conclusion & Perspectives

Done

Qualitative microstructure prediction // experience

Ms 800°C and Ms for α_m higher

HAZs size within substrate Melt pool size

Prediction in Constant Track Length:

- Homogeneous T° history
- $T_{average}$ > Ms
- $\dot{T}_{\text{at the end}}$ low

➡ basket-wave Widmanstätten structure

Tran et al. Materials & Design 128 (2017)

Prediction in Decrease Track Length:

- Heterogenous T° history
- At some location : $T_{average}$< Ms and $\dot{T}$ high

➡ basket-wave Widmanstätten structure + α’ Martensite

Conclusion & Perspectives

Done

Qualitative microstructure prediction // experience
Ms 800°C and Ms for α_m higher
HAZs size within substrate Melt pool size

On going

- ❑Couple thermo-metallurgical analysis to predict % phase and hardness map. (Esteva)
- ❑Couple thermo-mechanical analysis to predict residual stresses (Jardin, Son)

Need M_f to get quantitative MS through KM
However Module + Experiment available …

END