Microstructure prediction in additive manufacturing

(TA6V, AlSi10Mg, AISI M4 materials)

AM Habraken,Anne Mertens,Laurent Duchêne, Jérome Tchuindjang, Tran Son Hoang, Ruben Jardin, Jocelyn Delahaye, Olivier Dedry, Hakan Paydas, Raoul Carrus
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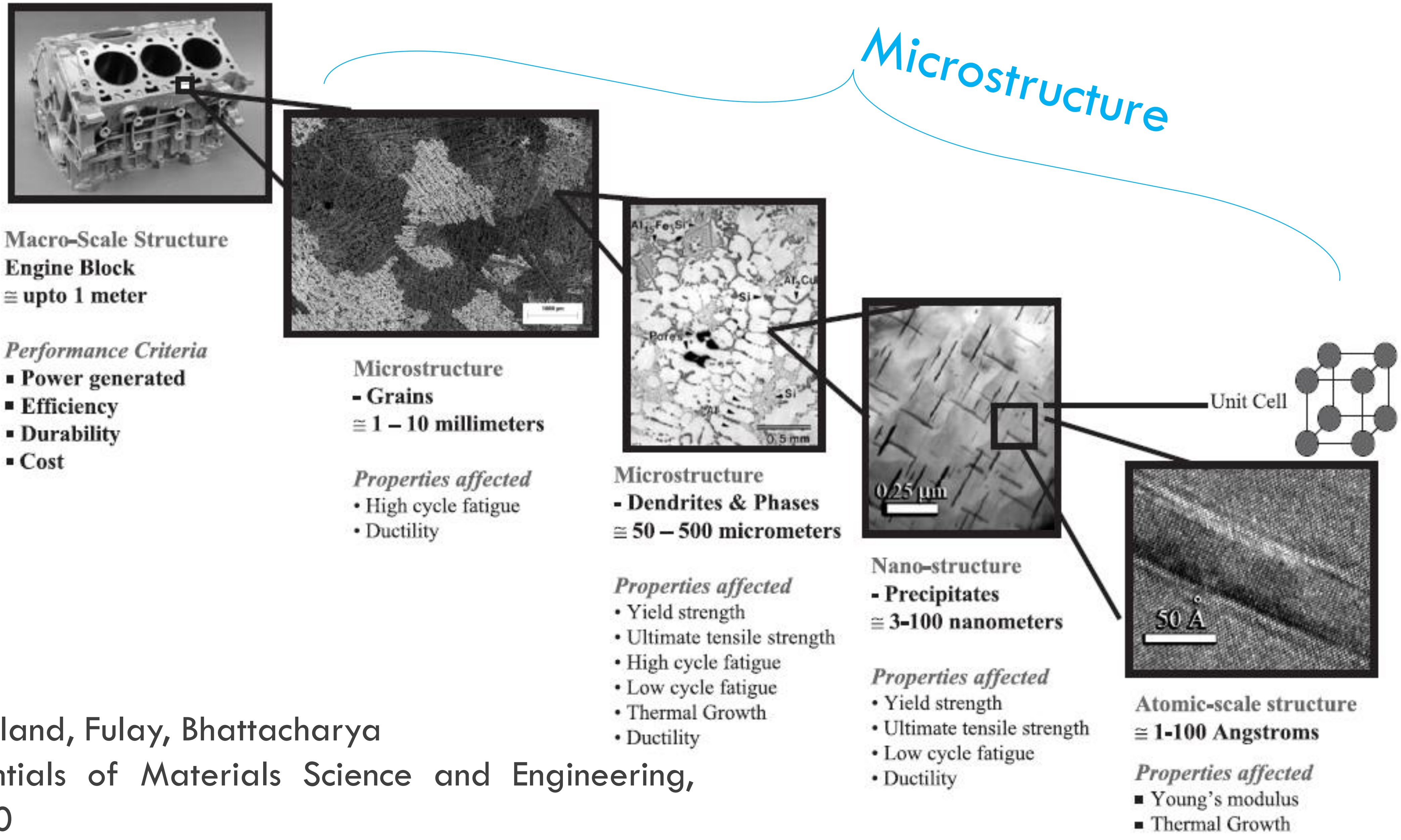
Materials and microstructure



Askeland, Fulay, Bhattacharya
Essentials of Materials Science and Engineering, 2010

Materials and microstructure & Additive Process

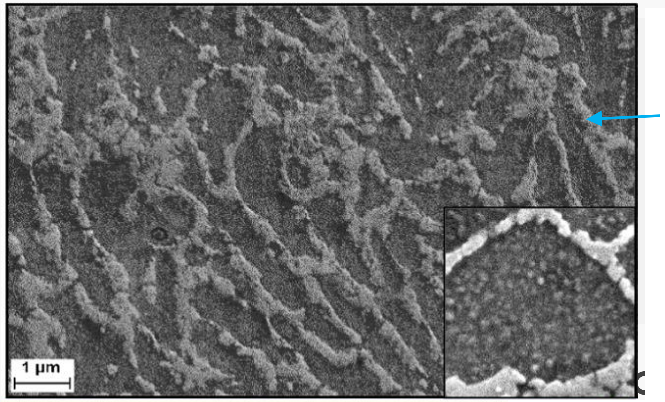
What is the scale of interest ?

What are you looking for ?

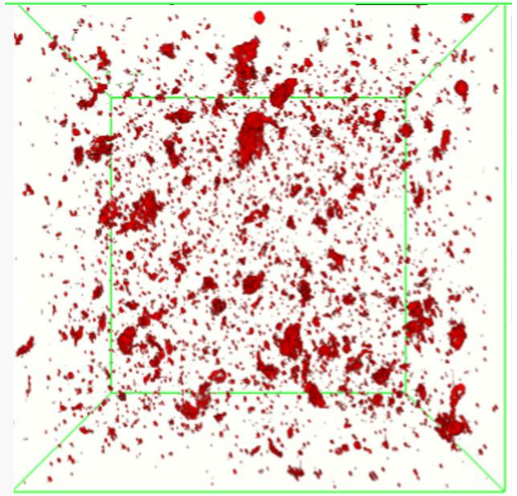
Static rupture, fatigue rupture?

Where is the weak point ?

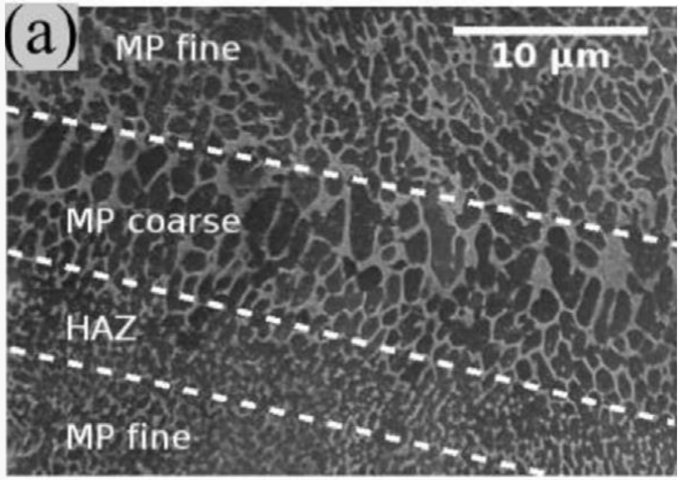
Choice of the model



Si rich phase network SLM AlSi10Mg



Fatigue cracks linked to void size up to 50µm
Static cracks more linked to microstructure (MP)



Cracks in MP fine

MP coarse

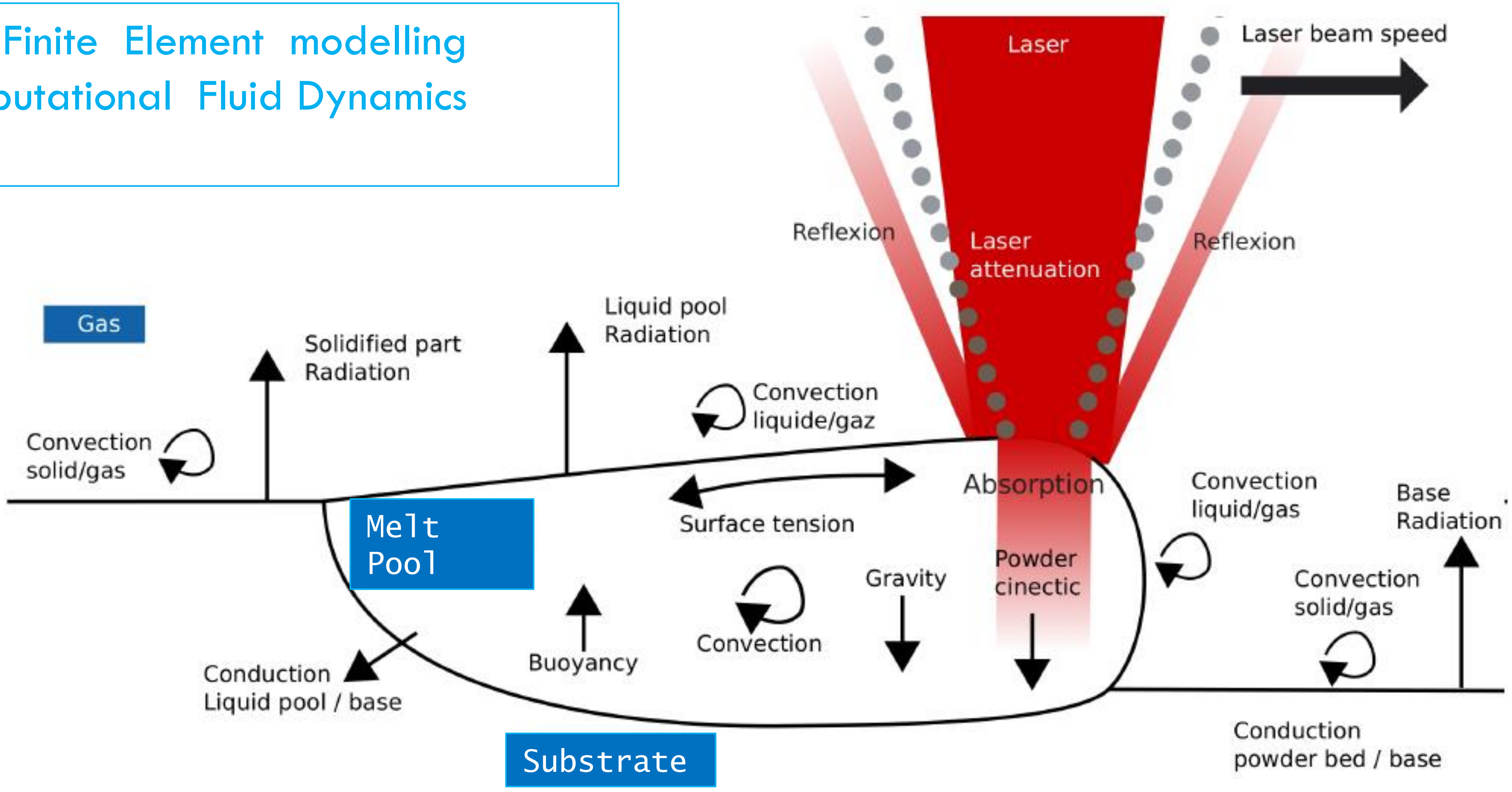
HAZ ???

Santos Macias et al. *Scripta Materialia 170 (2019)*

Delahaye et al. *Acta Materialia (2019)*

Directed Energy Deposition "Easiest" case

For solid Finite Element modelling
For Computational Fluid Dynamics



Marion et al.2015

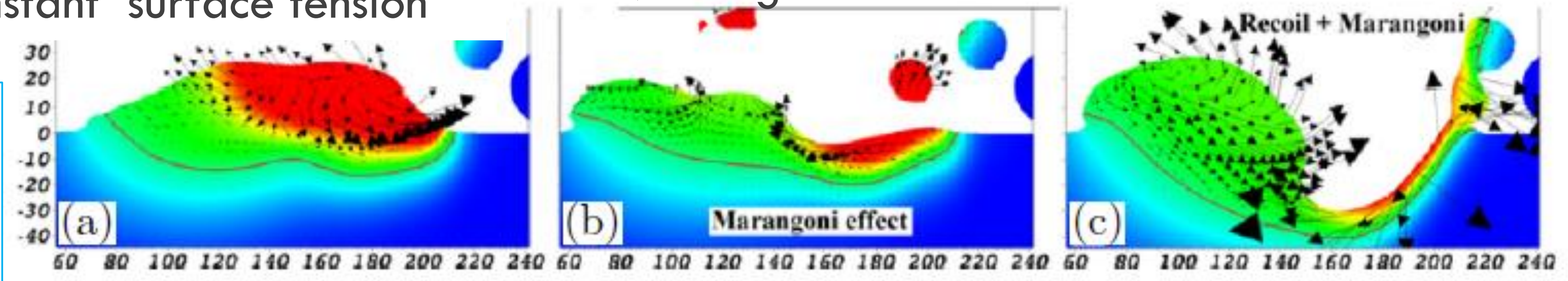
Surface tension, Marangoni, Recoil pressure

Need to model melt pool fluid behavior to predict porosity

Constant surface tension

Variable surf. Tension → Marangoni effect

+ Recoil pressure effect



4000K

293K

Predictions of Temperature field + fluid free surface

S. A. Khairallah, A. T. Anderson, A. Rubenchik, and W. E. King. Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones. *Acta Materialia*, 108:36–45, 2016.

→ convection-related terms can not be ignored

in calculations of the energy balance in the interaction zone

in calculations of the thermal field in the melt pool in the vicinity of the melt pool

Contents

Evolution of the microstructure predictions

Challenges about Additive Manufacturing

About Ti6Al4V and phase prediction

What is the goal with AlSi10Mg?

Why is AISI M4 challenging and interesting?










Contents

? FROM 1990 to 2020 ?

Evolution of the microstructure predictions

PhD (A.M.Habraken, 1989)
Coupled thermo mechanical metallurgical analysis during the cooling process of steel pieces (A.M.Habraken, M. Bourdouxhe, Eur.J. Mec A/Solids11(1992)

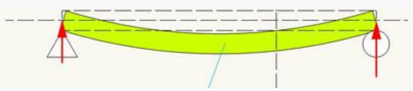
Microstructure = % phases

Finite element simulations
Phenomenological models based on Johnson-Mehl-Avrami-Kolmogorov (JMAK)

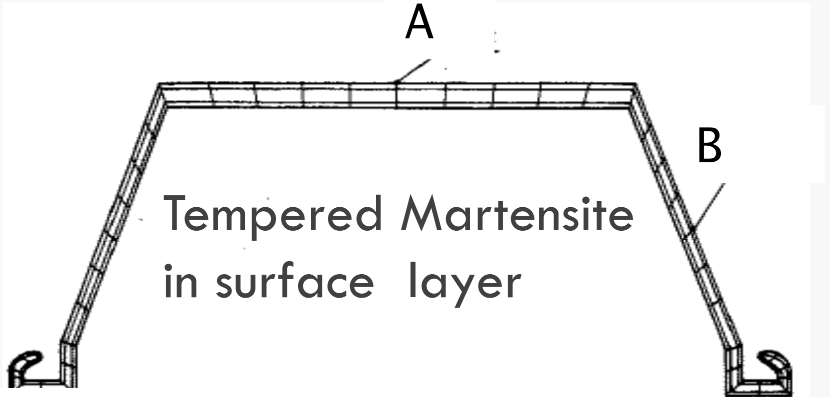
Kinetics of Phase transformation explains depth of martensite and curvature during cooling

Sheetpiles

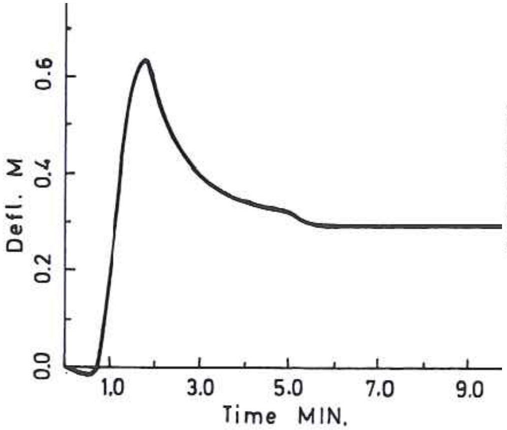
During cooling



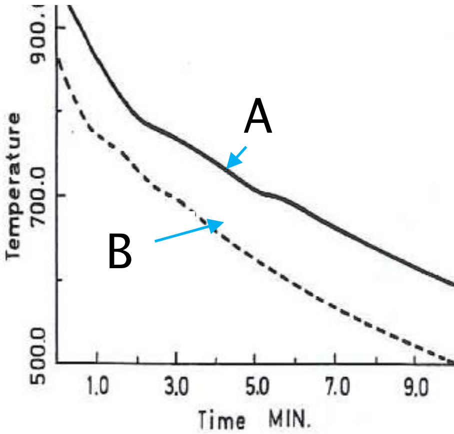
Beam curvature



Deflection



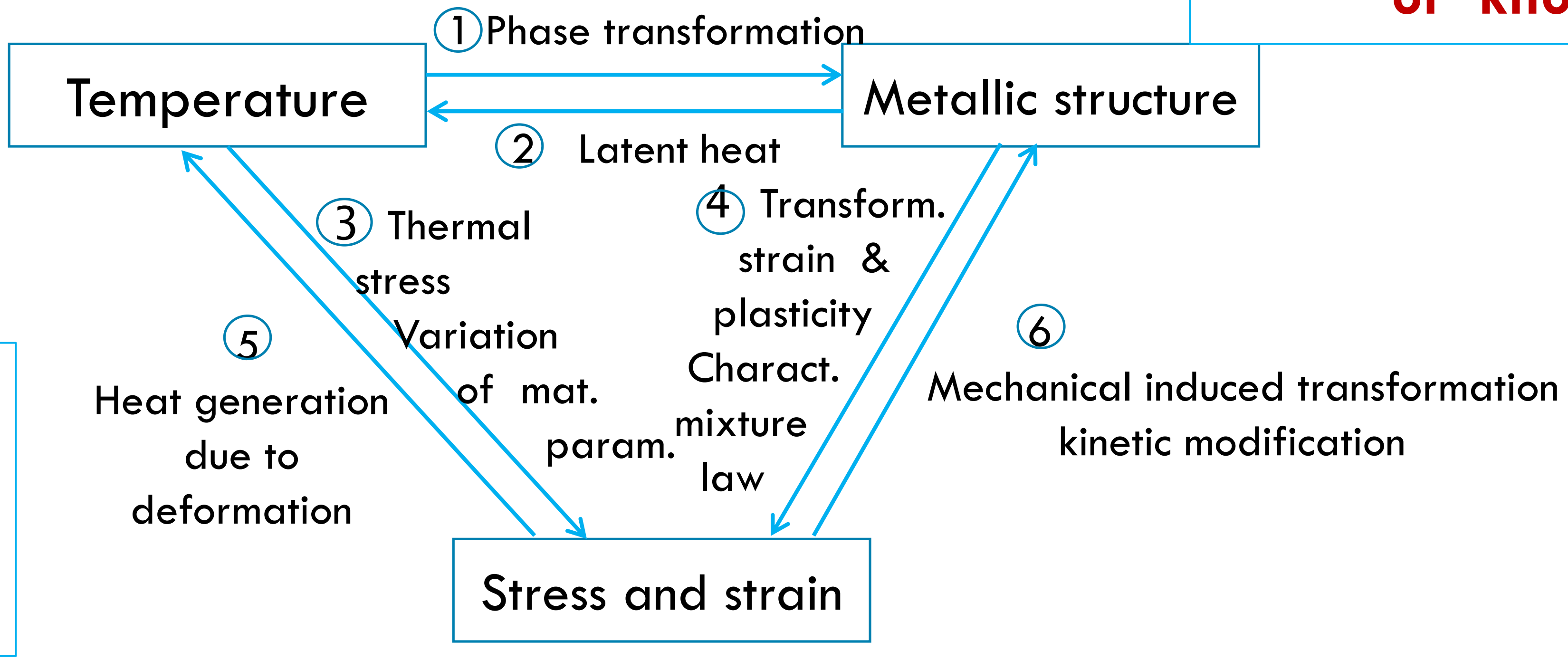
Temperature



Totally coupled thermo metallurgic mechanical finite element simulations

- High temperature rates
- Unknown materials
- Thermal history with remelting, re-heating

Lack of data, of knowledge



Why is it not easily transposed to additive manufacturing ?

Evolution of the microstructure predictions

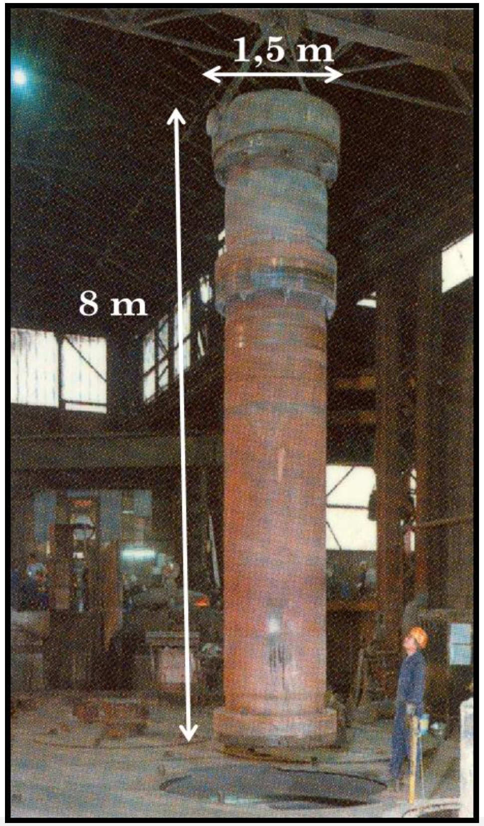
Quite monotonous thermal history
still lack of data…

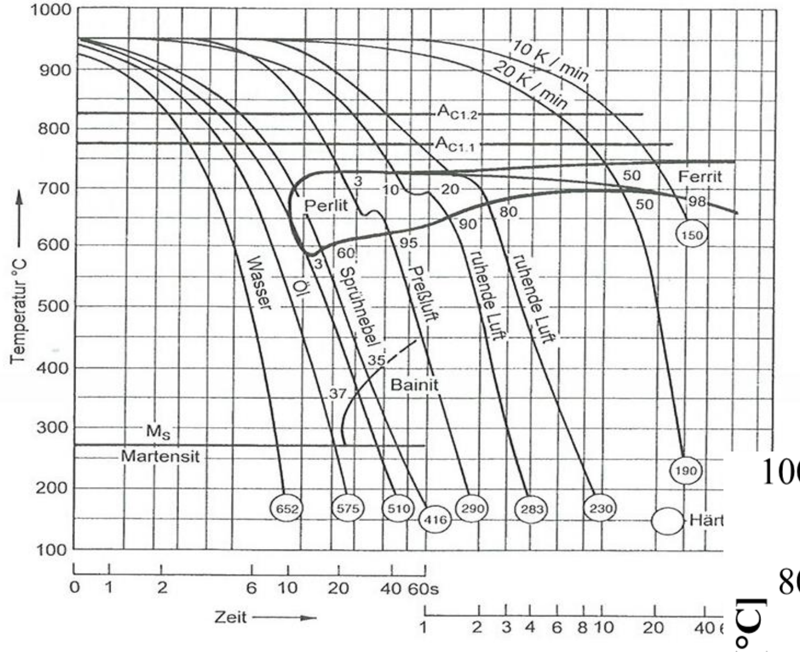
Still effective for some cases

Experiments → TTT, often CCT

JMAK model = isothermal simulations

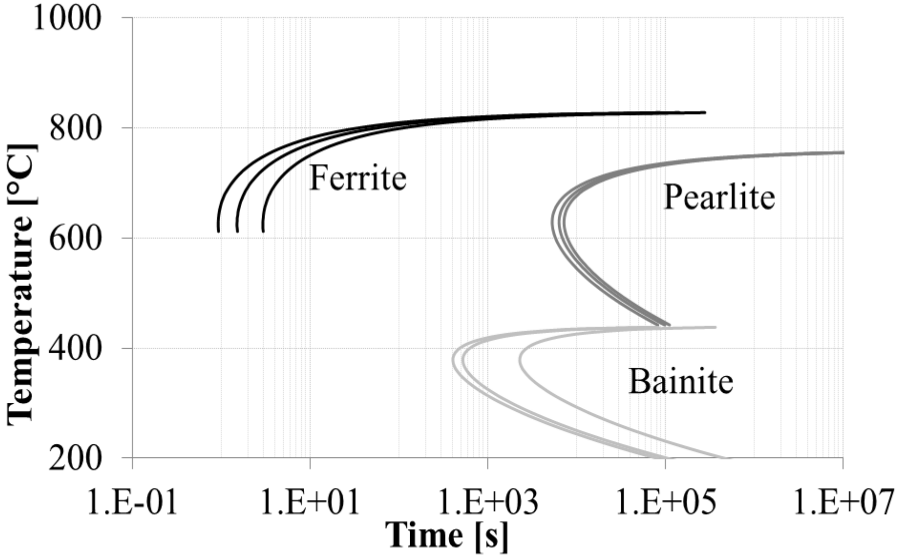
Extension towards anisothermal case





Capacity to recover TTT from CCT then to model any Tp° (t)

High Chromium Steel



→Capacity to predict residual stresses explaining cracks of some bimetallic work rolls

Neira et al. *Int. J. Material Forming (2015)*

Current Evolution of the microstructure predictions

Thermodynamic models and commercial softwares "able" to generate TTT

→ Equilibrium diagrams (Calphad,…)

- by minimization of Gibbs energy (each contribution …)

→ with extended JMAK at anisothermal case → kinetics

Crespo's model
for Ti6Al4V
IntechOpen 2011

→ Kinetics of phase transformations and phase morphology

- by Phase Field approach or Finite elements (slower)

Knowledge of chemical potentials derived from Gibbs energy of the phases, the nucleation force, phase interface velocity, diffusion equations, chemical balance... (Tioual PhD 2019 TITAN application ≠ Ti alloy)

Azizi et al.
for AlSi10Mg
in TMS 2019
Keller et al.
For Ni-based
superalloys
Acta Mat 2017

Finite elements → Tp°(t),
Dictra // Phase Field
→ Microsegregation predictions

Machine learning ??

Contents

Challenges about Additive Manufacturing (simulations)

Long process

→ length of CPU time finite element simulation

→ which tricks ?

→ heterogeneity & complex history of the temperature field

Mixture of liquid and solid state

→ CFD + solid FE ?

→ PI FEM… (Terrapon - Ponthot Bobach PhD ongoing)

High temperature gradient

→ microstructure mechanisms not well identified

→ mixture of length scales

→ lack of material data

High temperature robust camera → big data

Residual stress measurements in depth

Lack of material data

Multi disciplinary field

Hard to measure in similar conditions

3D PI FEM liquid-solid thermo mechanic

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Why is AISI M4 case so challenging and interesting?

2015

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Laser cladding as repair technology for Ti–6Al–4V alloy: Influence of building strategy on microstructure and hardness

H. Paydas [a,*], A. Mertens [a], R. Carrus [b], J. Lecomte-Beckers [a], J. Tchoufang Tchuindjang [a]
[a] University of Liege (ULg), Faculty of Applied Science, Department of Aerospace and Mechanics, Metallic Materials Science Unit, Chemin des Chevreuils, 1 B52/3, B 4000 Liège, Belgium
[b] Sirris Research Centre (Liège), Rue Bois St-Jean, 12, I g, Belgium

2017

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3D thermal finite element analysis of laser cladding processed Ti-6Al-4V part with microstructural correlations

H.-S. Tran [a], J.T. Tchuindjang [b], H. Paydas [b], A. Mertens [b], R.T. Jardin [a], L. Duchêne [a], R. Carrus [c], J. Lecomte-Beckers [b], A.M. Habraken [a,*]

LIÈGE université
uliege.be

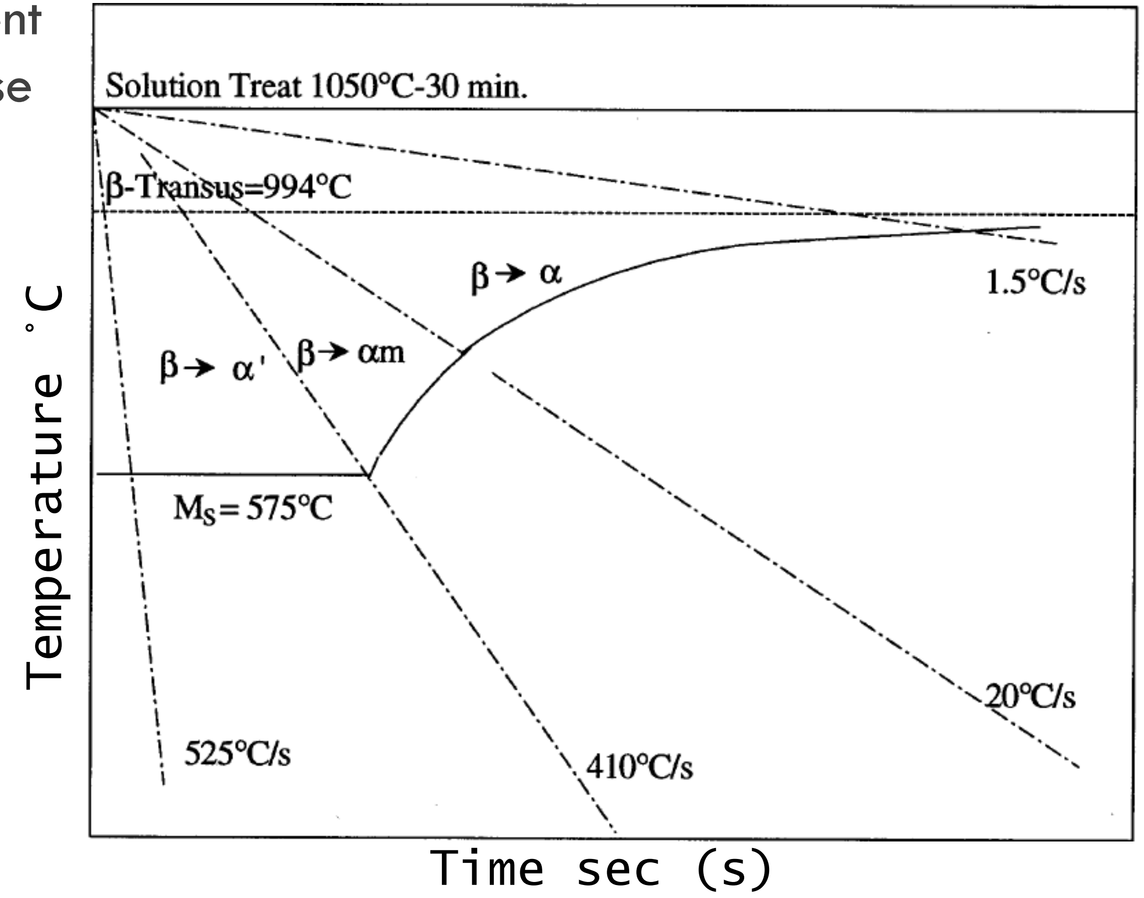
2018
Microstructure prediction of Ti6Al4V processed by Laser Cladding
Master Thesis
Elena Esteva Fabrega

2020 PhD thesis J. Tchuindjang

About Ti6Al4V and phase predictions

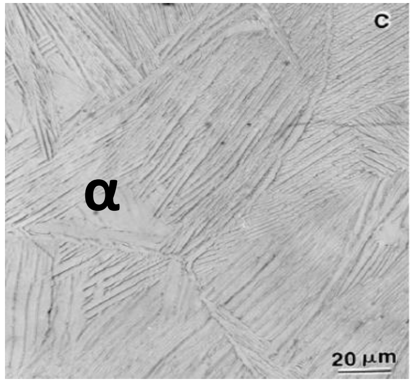
Éléments	Al	V	Fe max.	C max.	O max.	N max.	H max.	Ti
Composition %mass.	5.5 – 6.5	3.5 – 4.5	0.25	0.08	0.13	0.05	0.012	Bal.

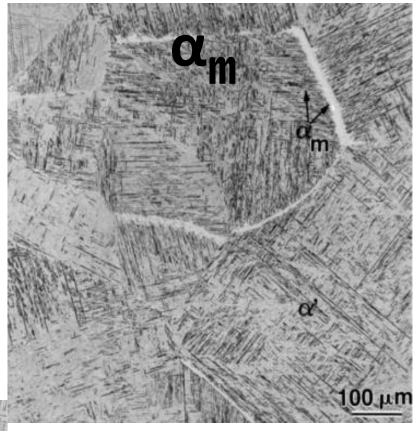
Parent phase β

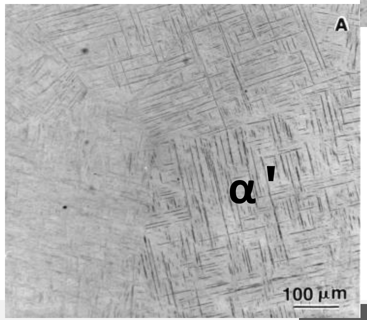


T. Ahmed, H.J. Rack, Materials Science and Engineering: A 243 (1998) 206–211.

Microstructure evolution



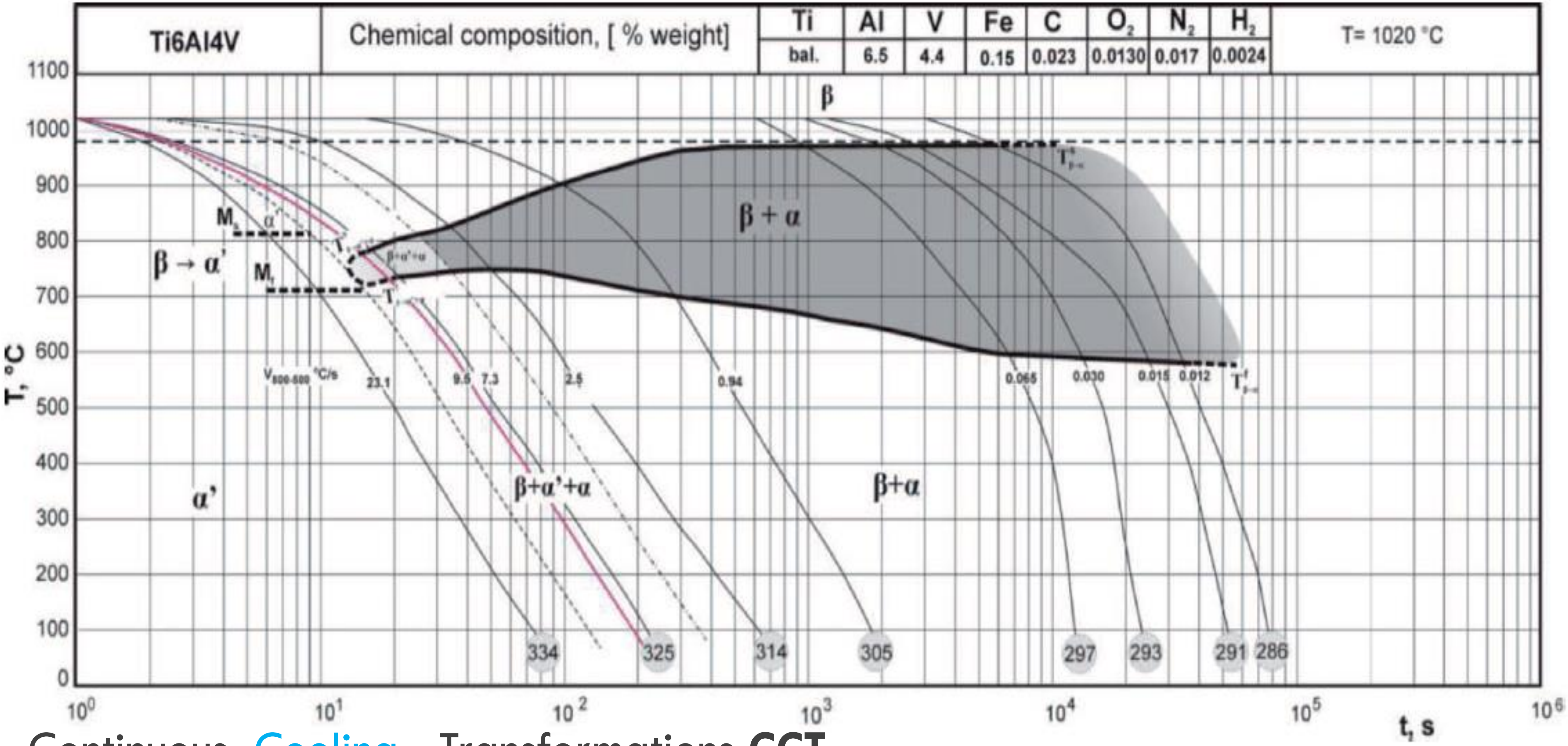




1998
Toward a
Continuous
Cooling
Transformations
CCT

About Ti6Al4V and phase predictions

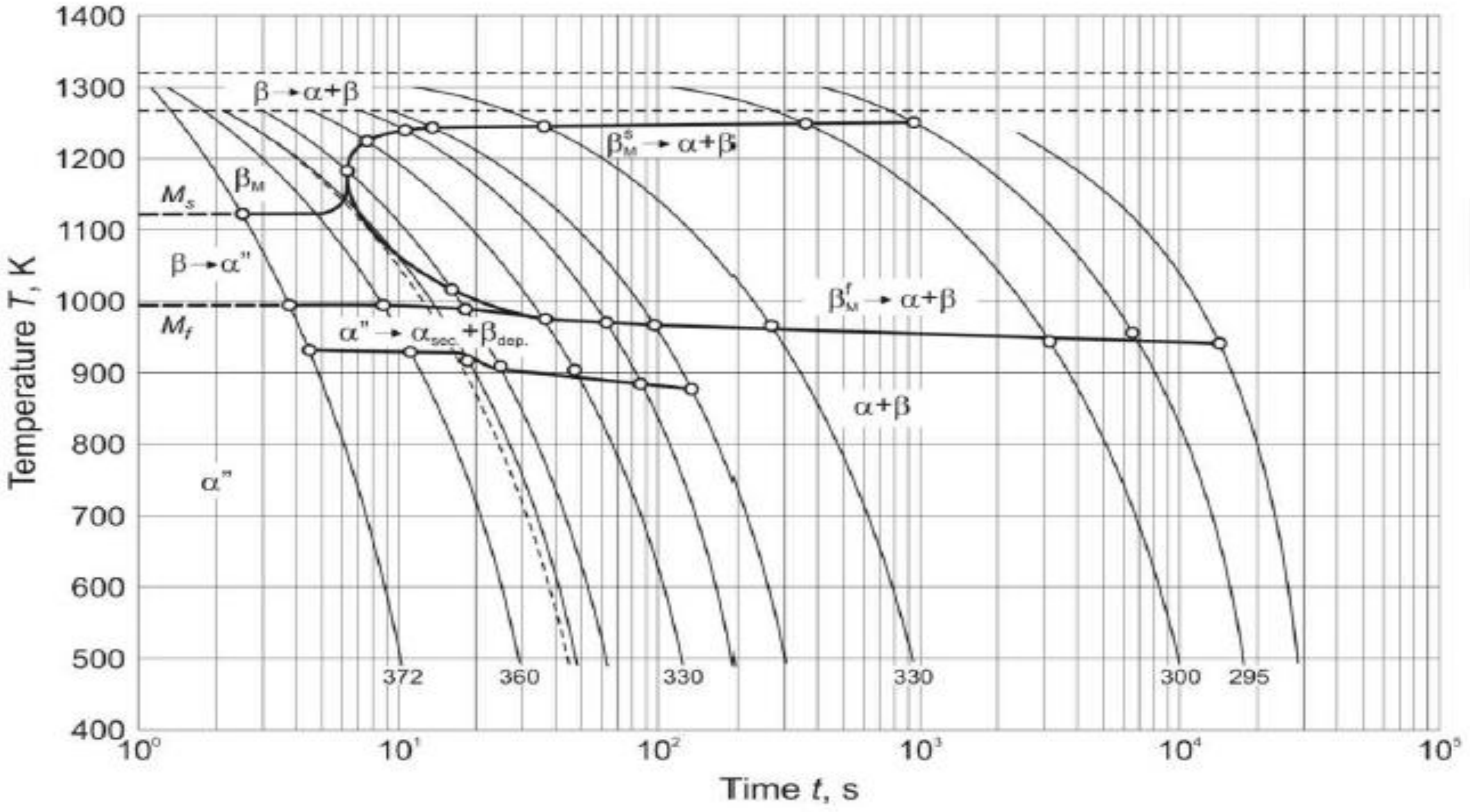
R. Dąbrowski, Archives of Metallurgy and Materials 56 (2011) 703–707.



Continuous Cooling Transformations **CCT**

About Ti6Al4V and phase predictions

J.Sieniawski et al. Intech Open 2013



About Ti6Al4V and phase predictions

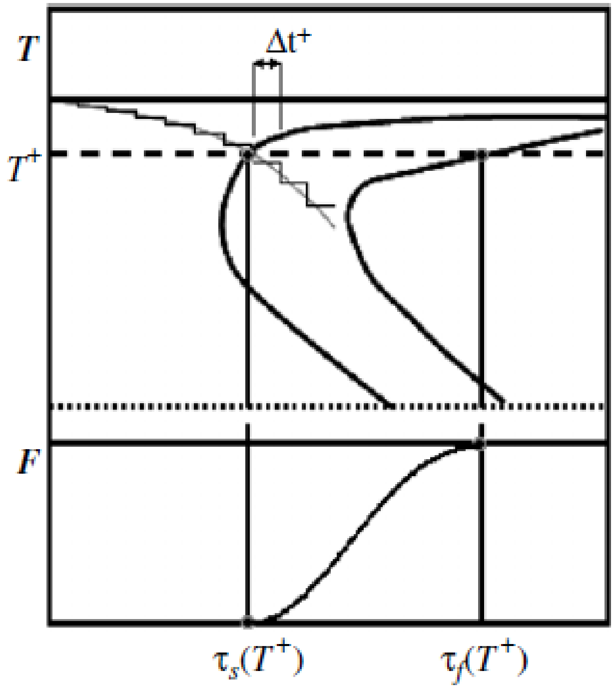
Diffusional transformation (α'→α+ β, β↔ α): JMAK Model + additivity rule

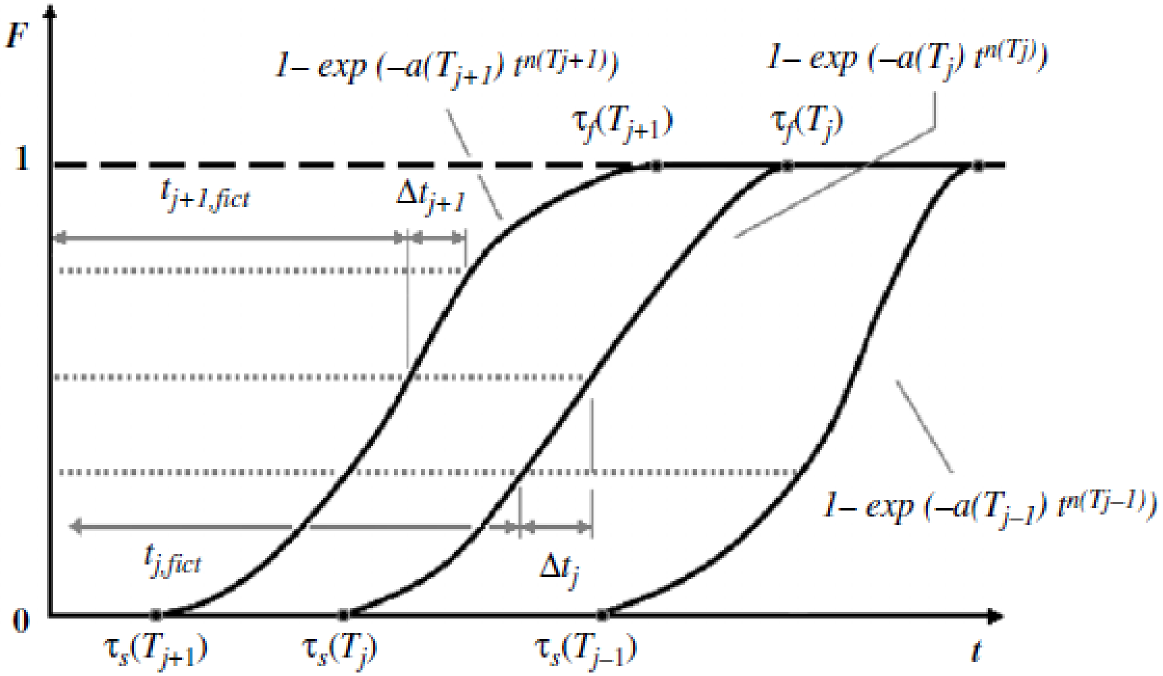
$$f_{\alpha'}(T + dT) = 1 - [1\text{-exp}[-k(t^f + \Delta t)^n]](1 - f_{\alpha'}^{eq})$$

f phase fraction

k,*n* JMAK coefficients (depending on T)

t^f = fictious time which would have resulted in fraction *f* of previous timestep at $T + dT$





P. Carlone et al. Computers and Mathematics with Applications (2010)

About Ti6Al4V and phase predictions

Displacive transformation (β→α'): Koisitinen – Marburger model

$$f_{\alpha'}(T) = f_{\alpha'}(T_0) + (f_{\beta\, T0)} - f_{\beta r})[1\text{-}\exp[-\gamma(M_s - T)]]$$

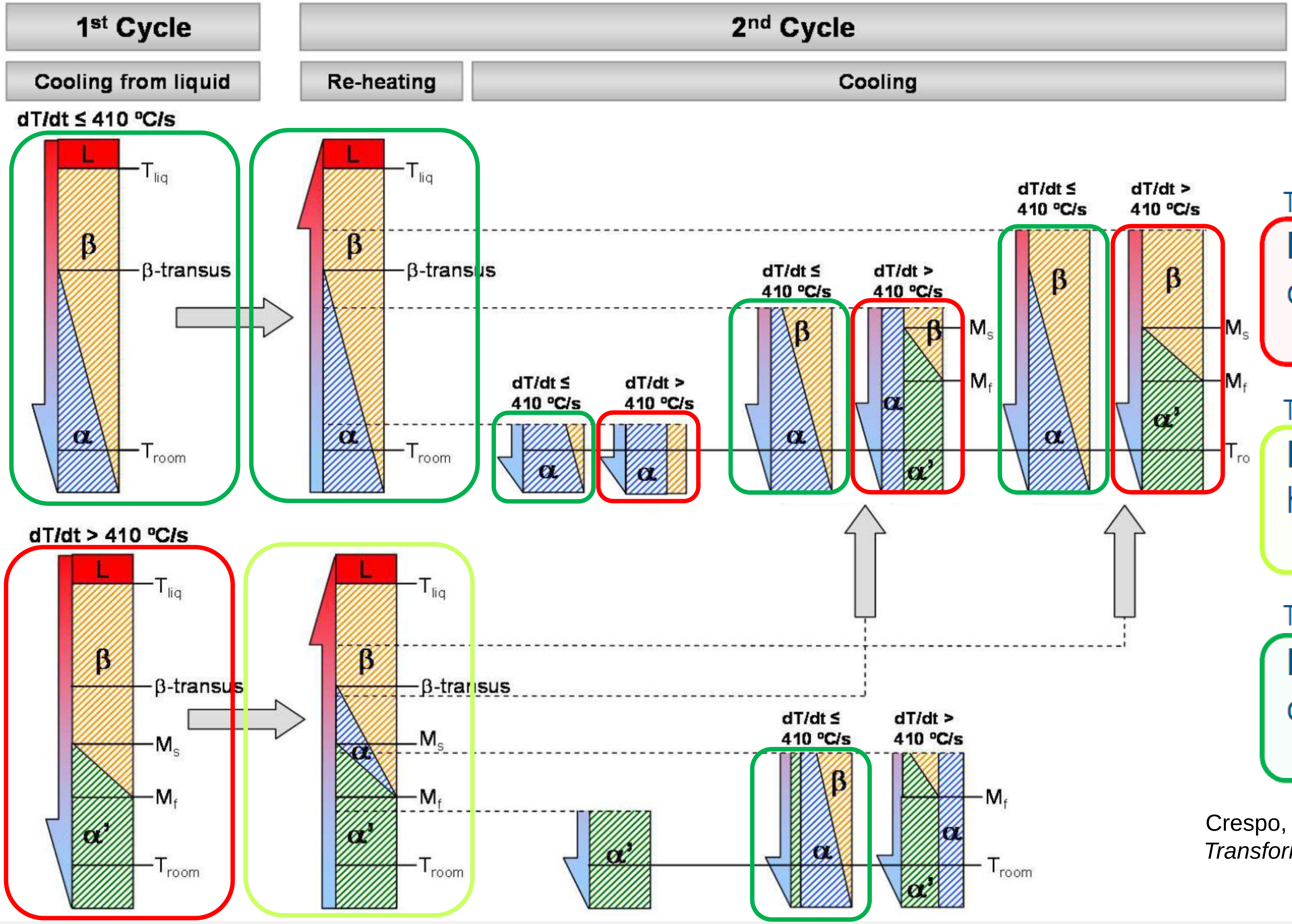
T_0 temperature at which the martensitic transformation starts defining the quantity of parent phase. If the transfo. end tp° known M_f then γ is known

Effect of T $\dot{T}$
of composition of parent phase
→ Need of thermodynamics
→ Difficult in all integration points of a FE mesh

For additive simulations values vary in the literature, for cooling:

- (Tan et al. 2015) M_s =1073 K
- (Kelly SM 2004) M_s = 848 K
- (Charles Murgau C et al. 2012) M_s = 898 K
- (Crespo A, et al. 2010) M_s = 923 K M_f = 673 K
- (Jovanovic *et al.* 2006) M_f = 298 K

About Ti6Al4V and phase predictions



JMAK for diffusional transf.

Koistingen-Marburger for displacive transf.

No α_m

No Reverse Diffusive transf. of α'

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 ≤ 410 °C/s)

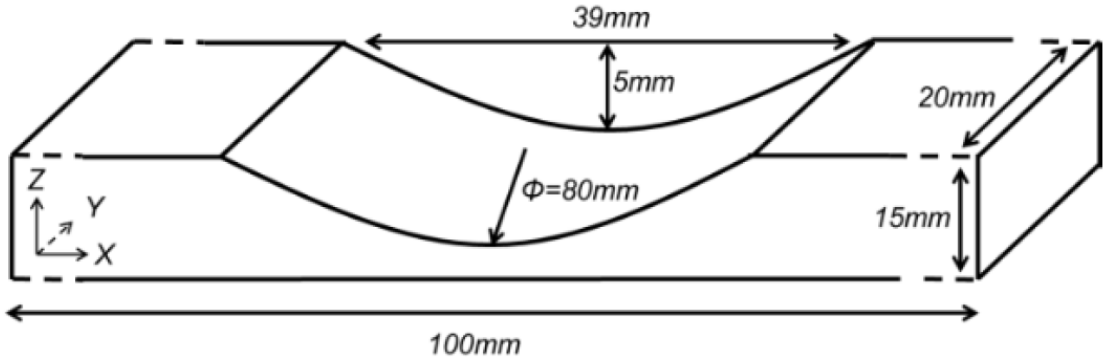
$$\beta \leftrightarrow \alpha$$

Crespo, A.,*2011 Modelling of Heat Transfer and Phase Transformations in the Rapid Manufacturing of Titanium Components (IntechOpen)*

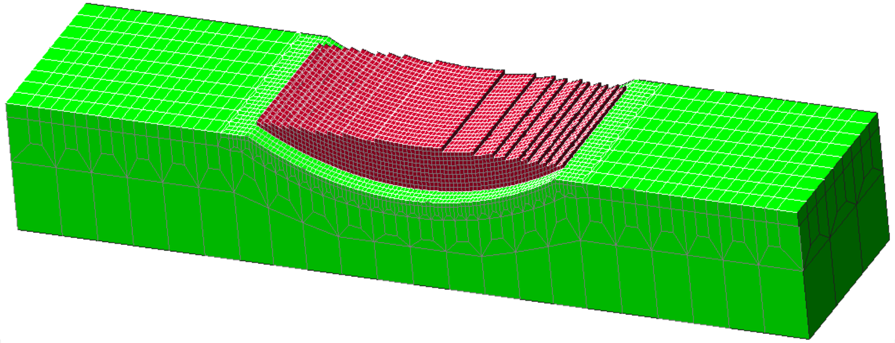
Experiments

Laser cladding for Ti6Al4V alloy: influence of building strategy on microstructure and hardness.

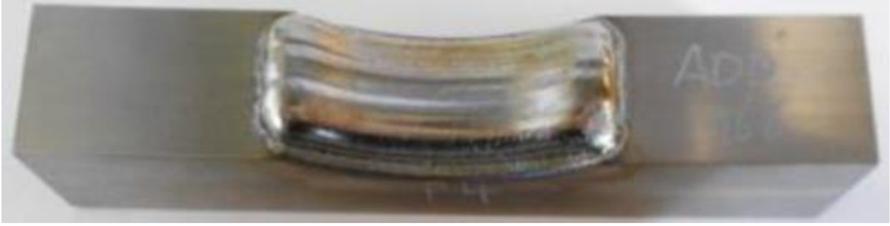
Paydas,et al. Materials and Design 2015.

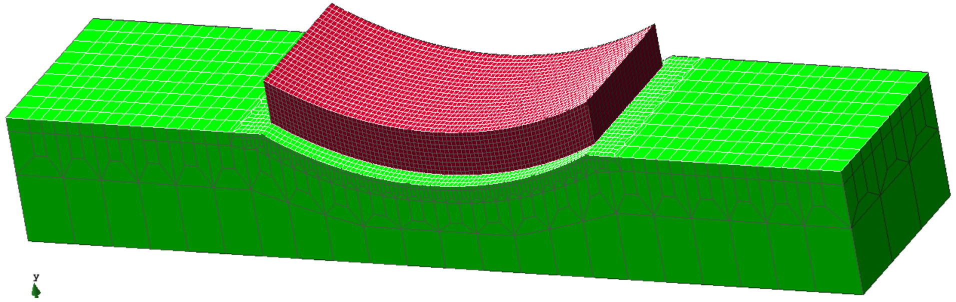


Decreasing Track Length (DTL) strategy



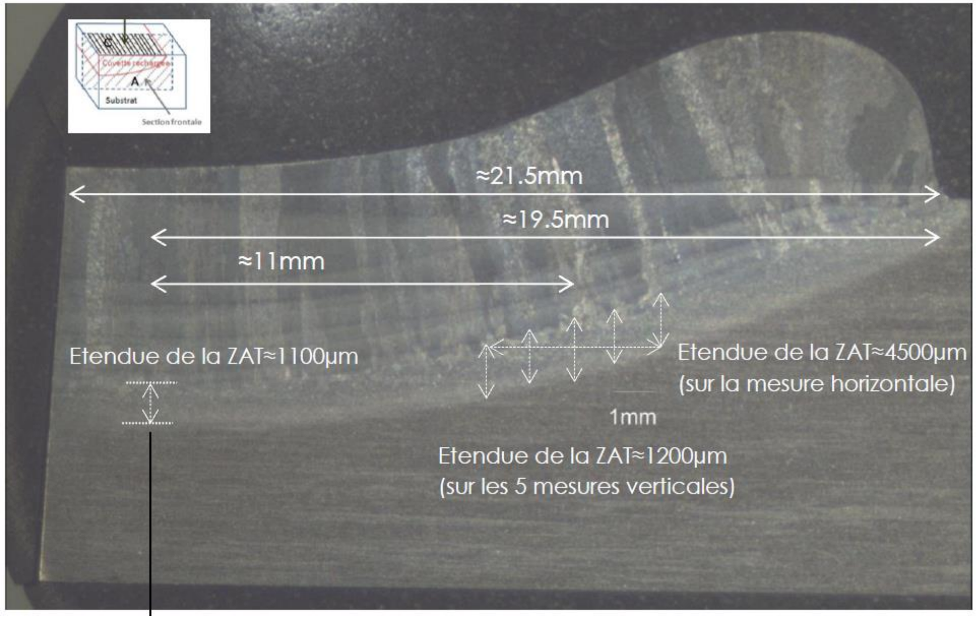
Constant Track Length (CTL) strategy

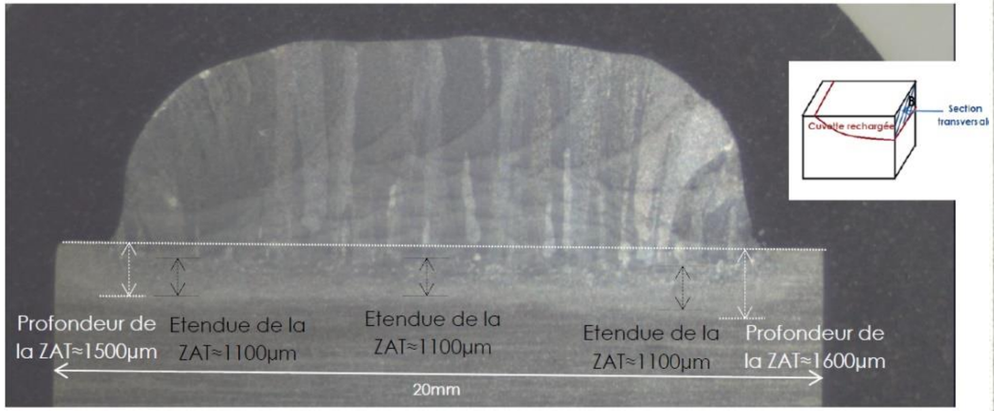




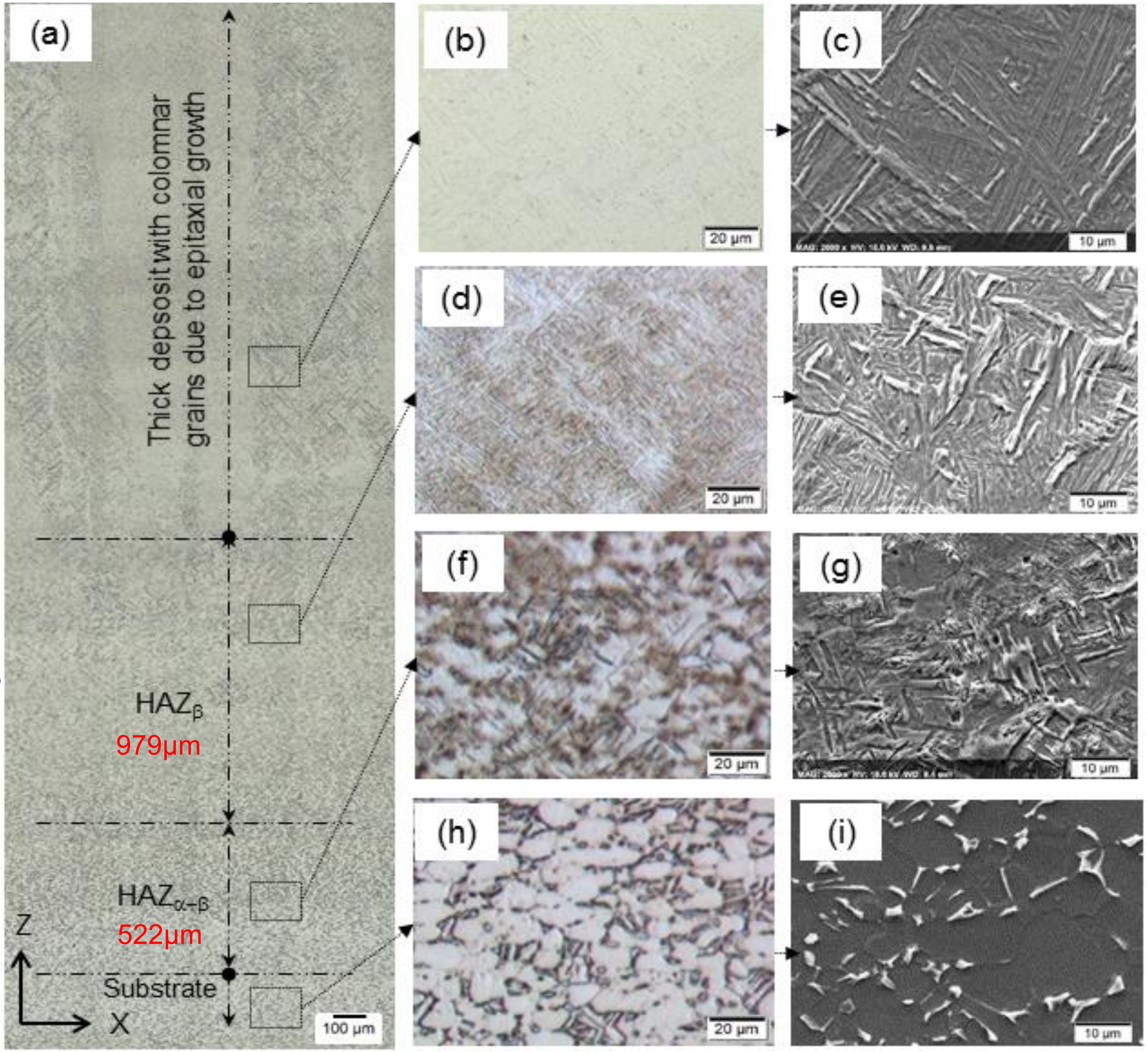
Tran et al. Materials & Design 2017

Experimental data





Final microstructure in CTL

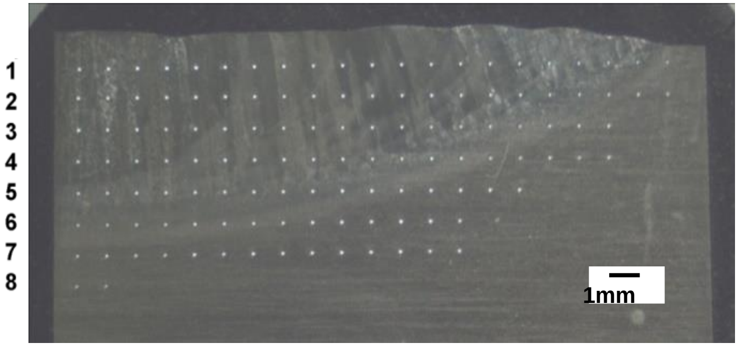


Paydas et al. Materials and Design 2015.

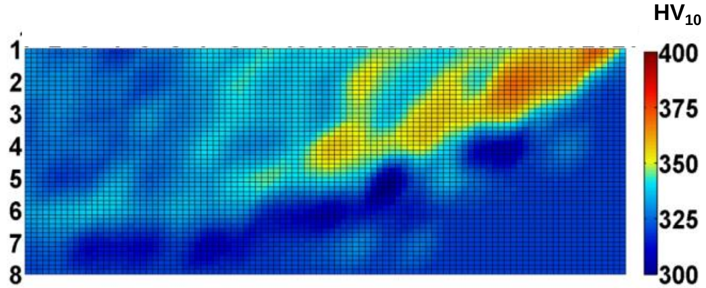
Results of indentation campaign

(a) Decrease Track Length (DTL)

(b)

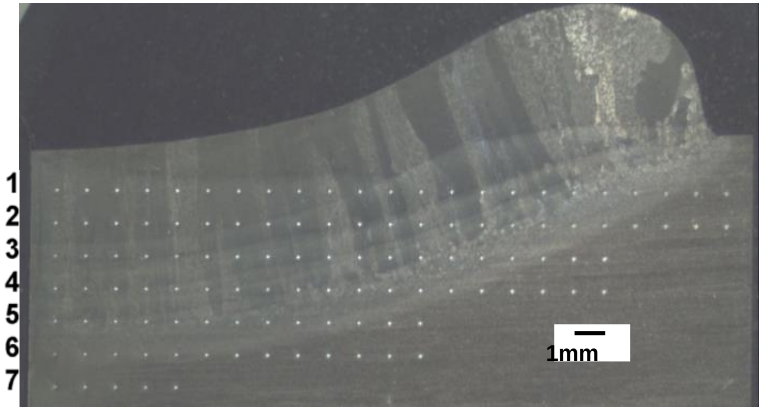


(c)

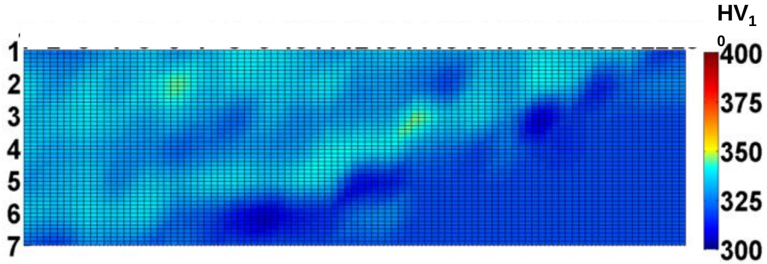


(d) Constant Track Length (CTL)

(e)



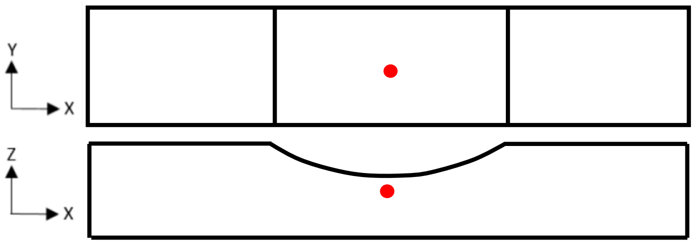
(f)



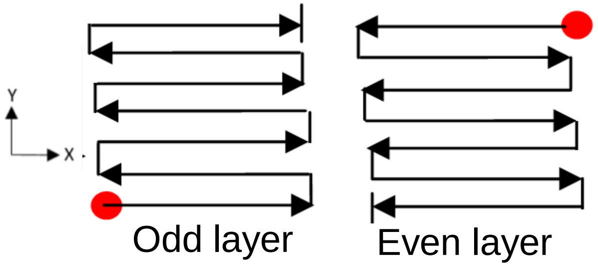
Hardness maps and corresponding hardness indentation grids

Paydas et al. Materials and Design 2015.

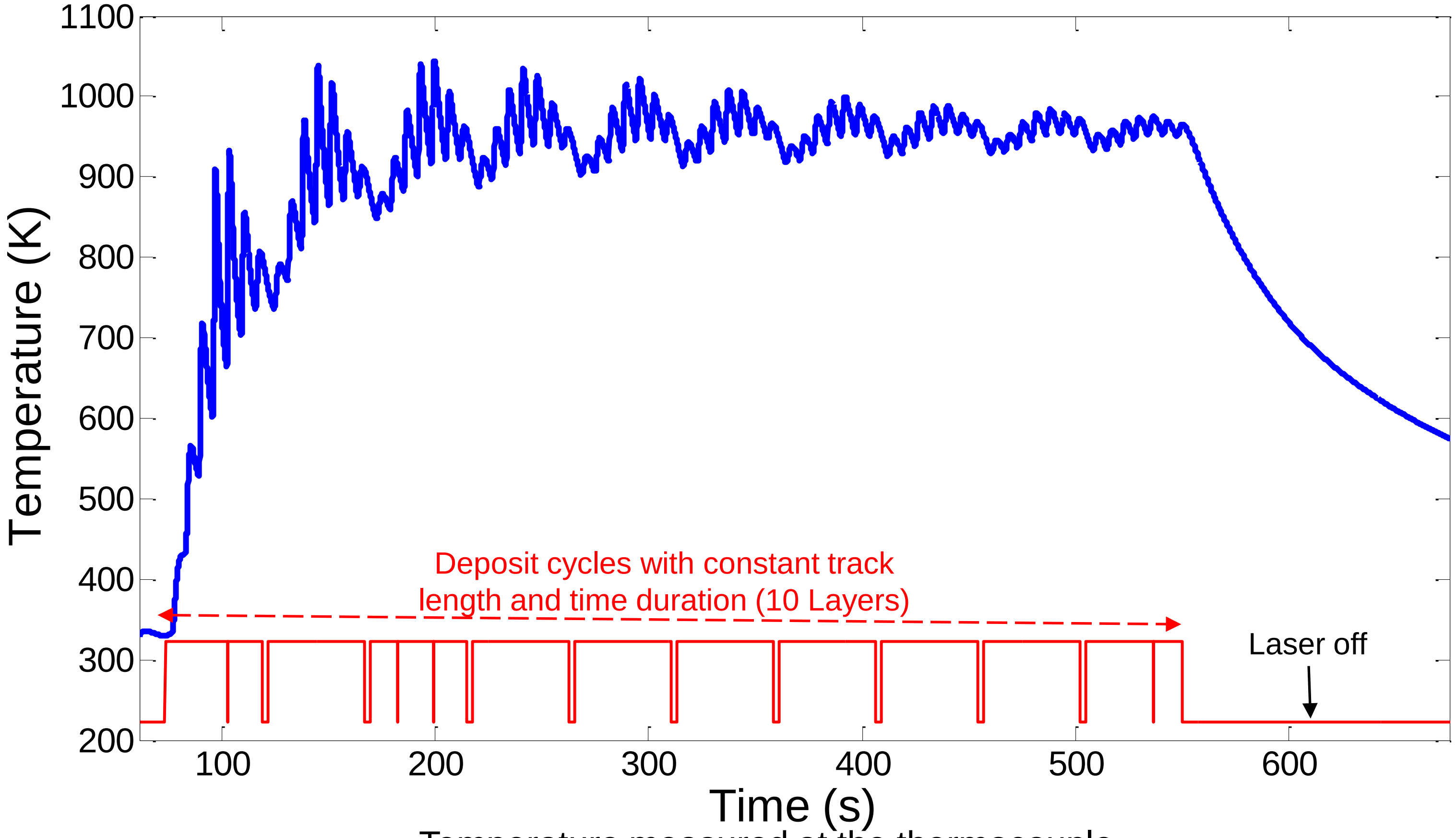
Temperature measurement



Geometry of the machined substrate



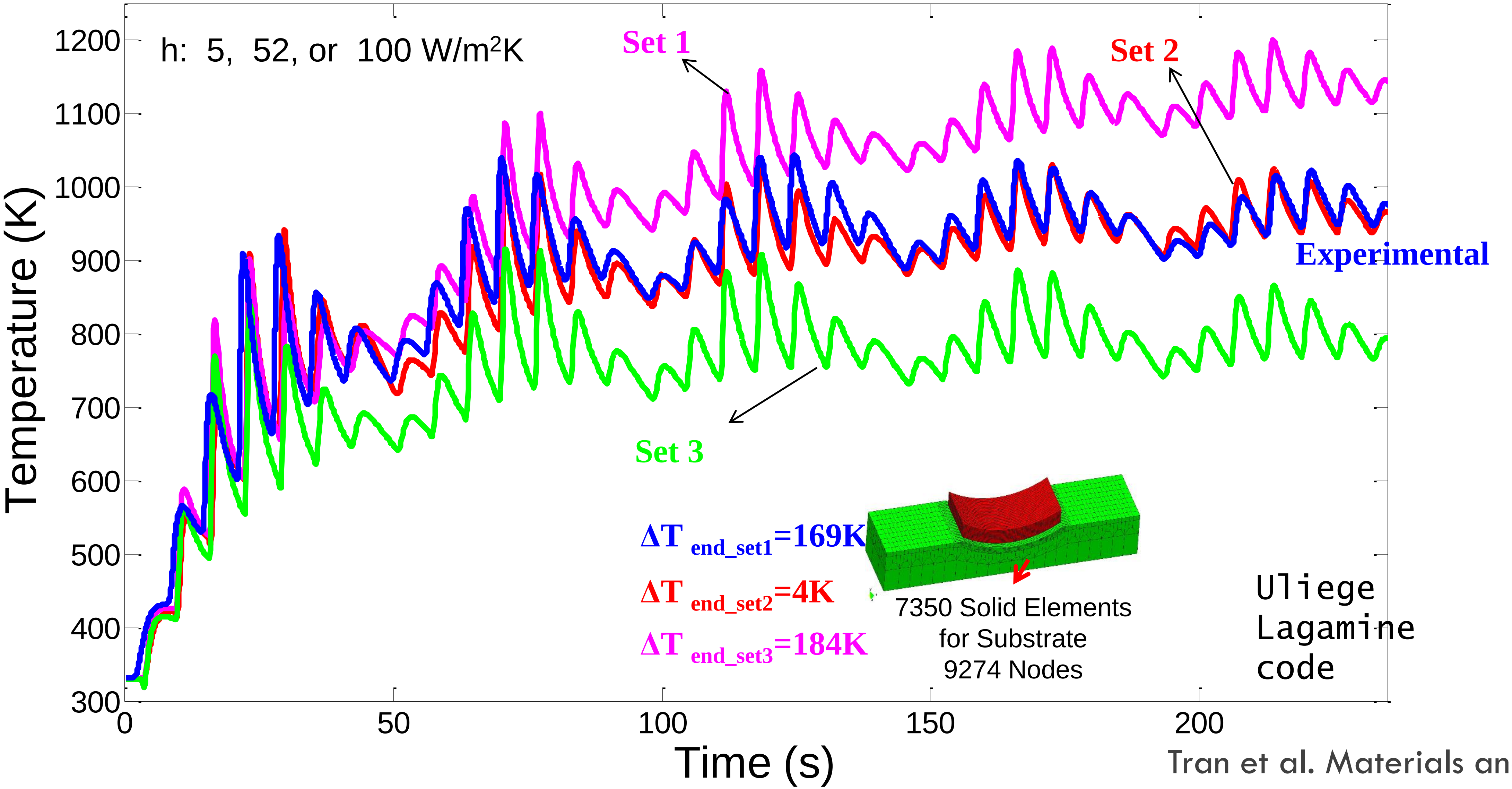
Path of laser beam (7 tracks/layer)



Temperature measured at the thermocouple

Constant Track Length strategy

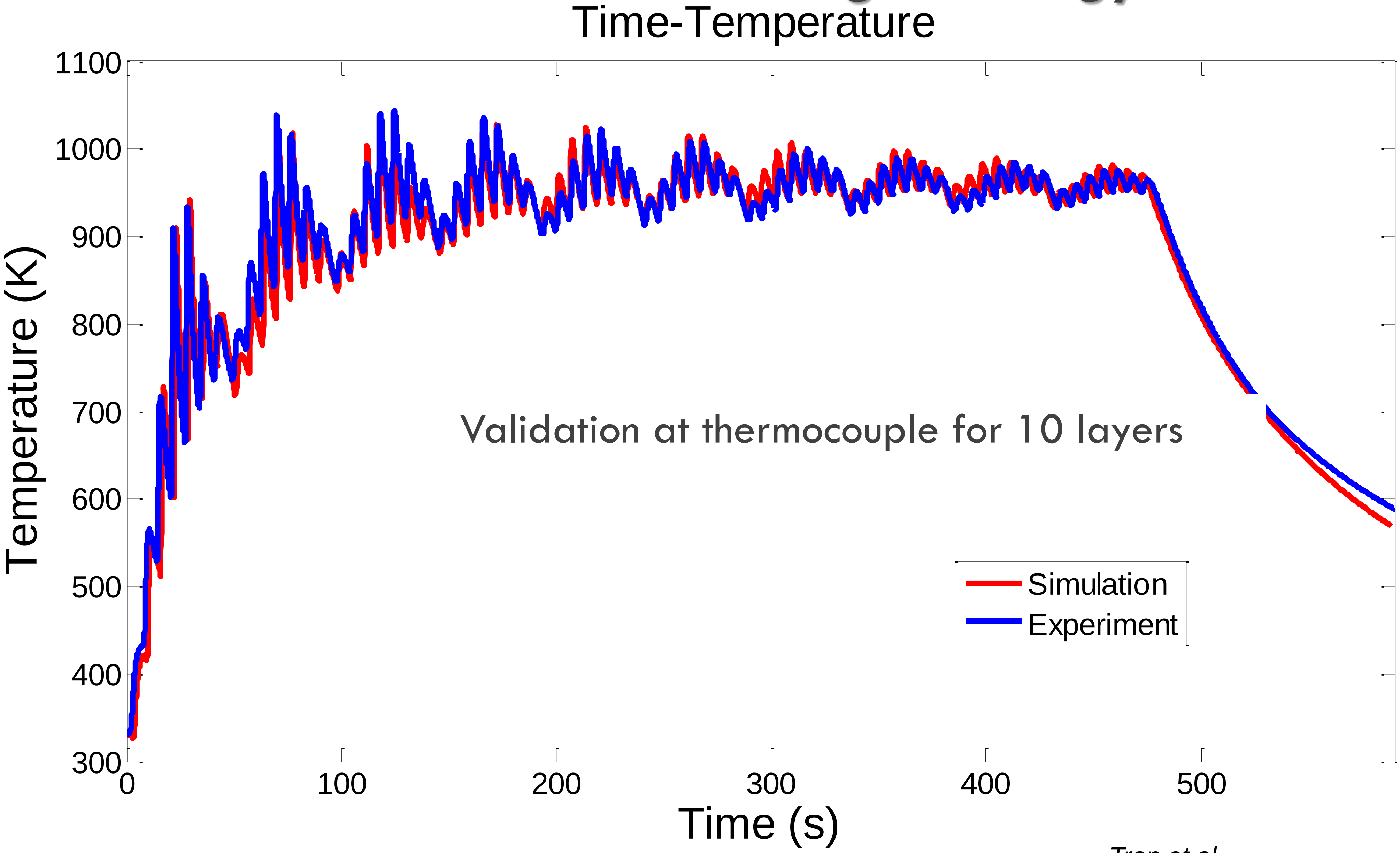
FE inverse modelling to identify convection coefficient Sensitivity analysis: T° at thermocouple



Thermal history at the thermocouple due to the first five layers

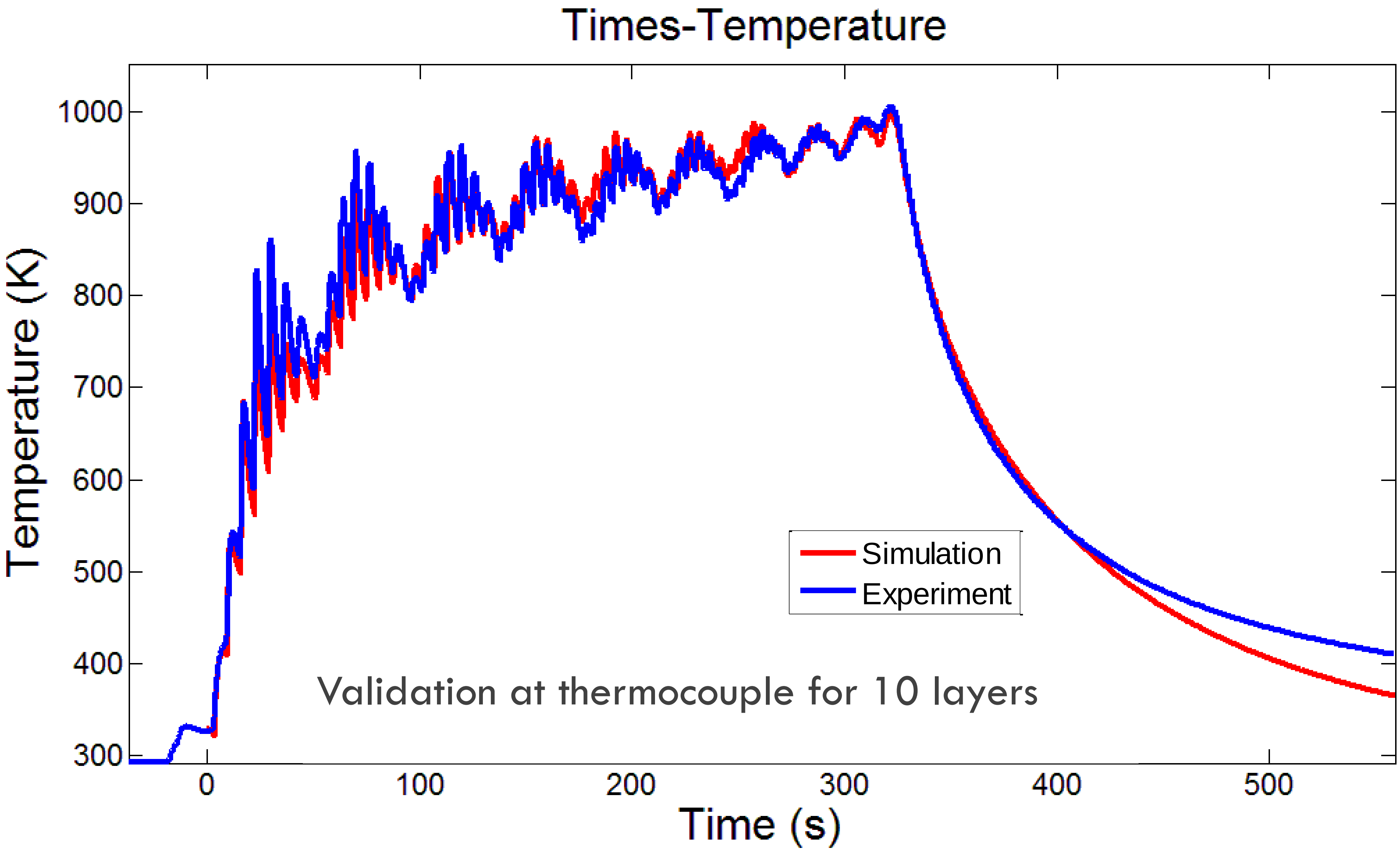
Tran et al. Materials and Design 2017

Constant Track Length strategy



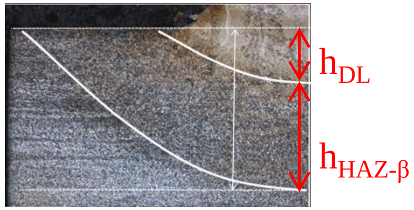
Tran et al.
Materials and Design 2017

Decrease Track Length strategy

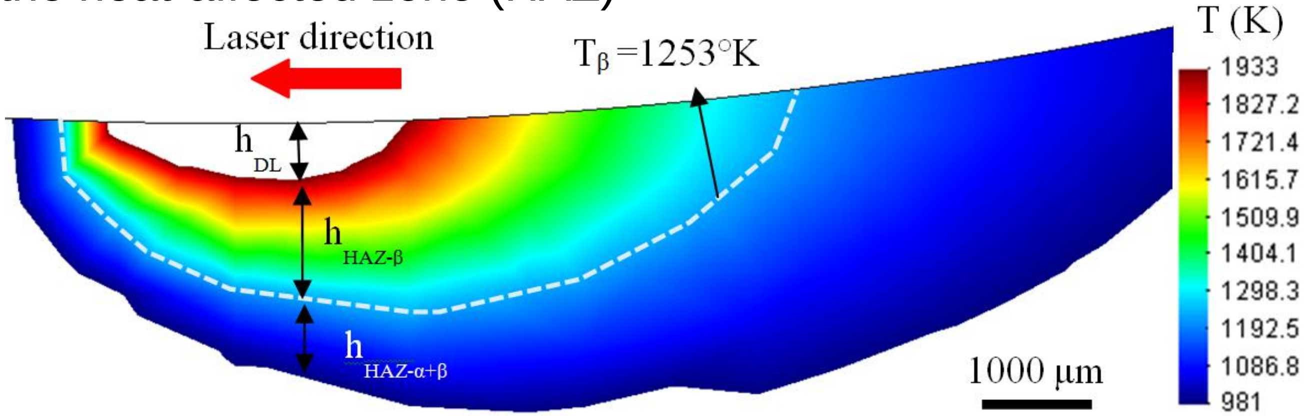


Constant Track Length strategy

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



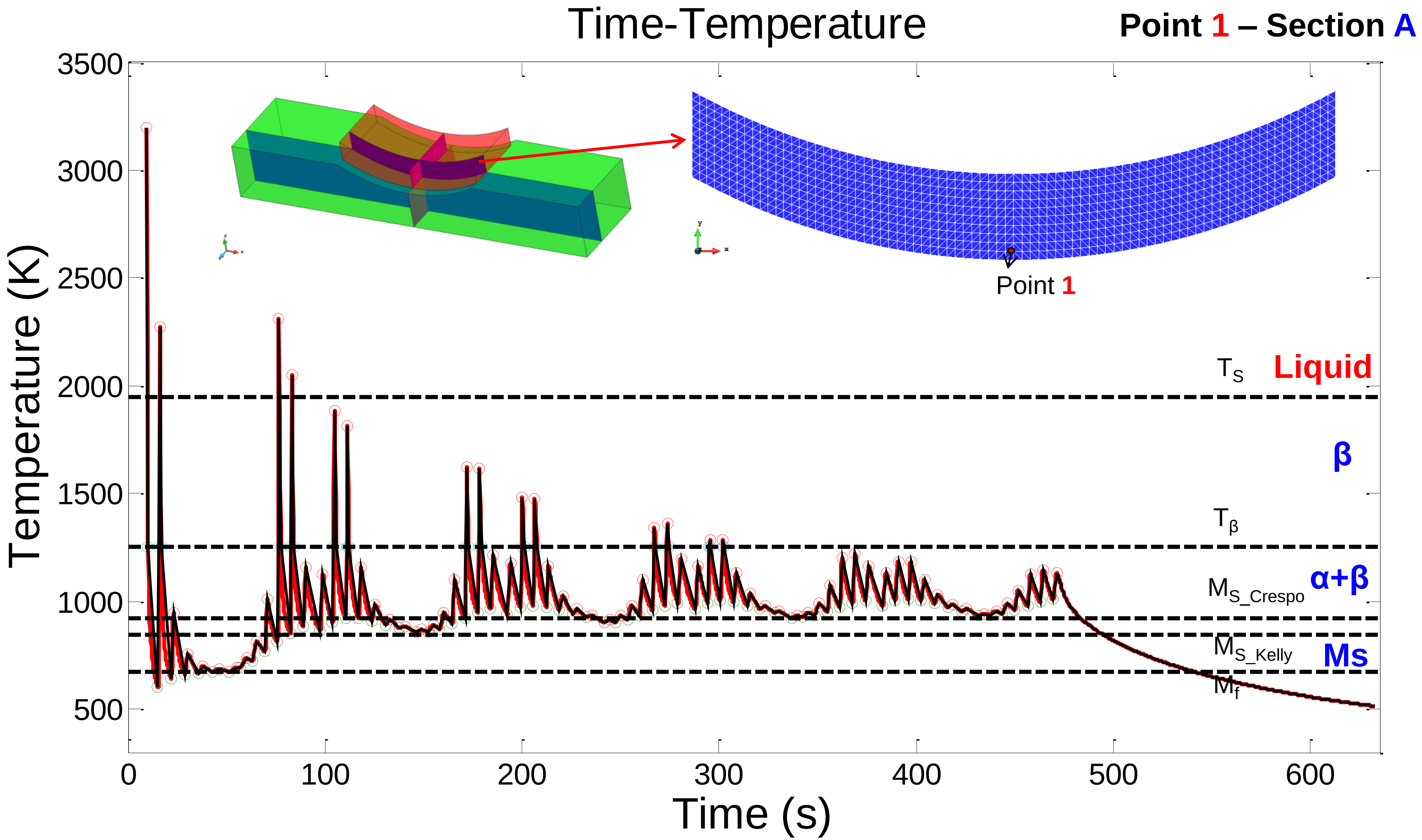
Depth of Fusion zone



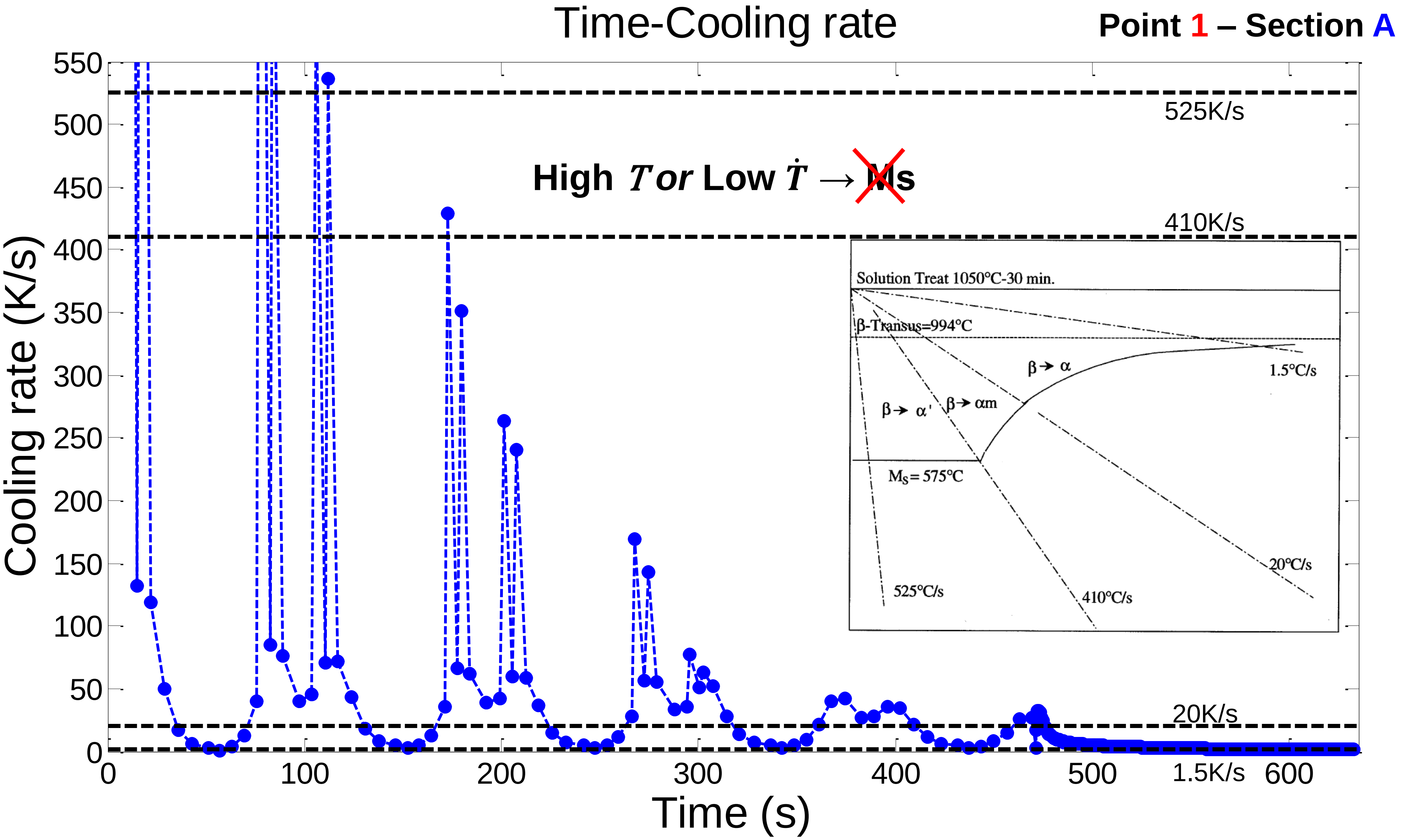
2D view of thermal field within HAZ

Validation	Depth	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Simulation 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				

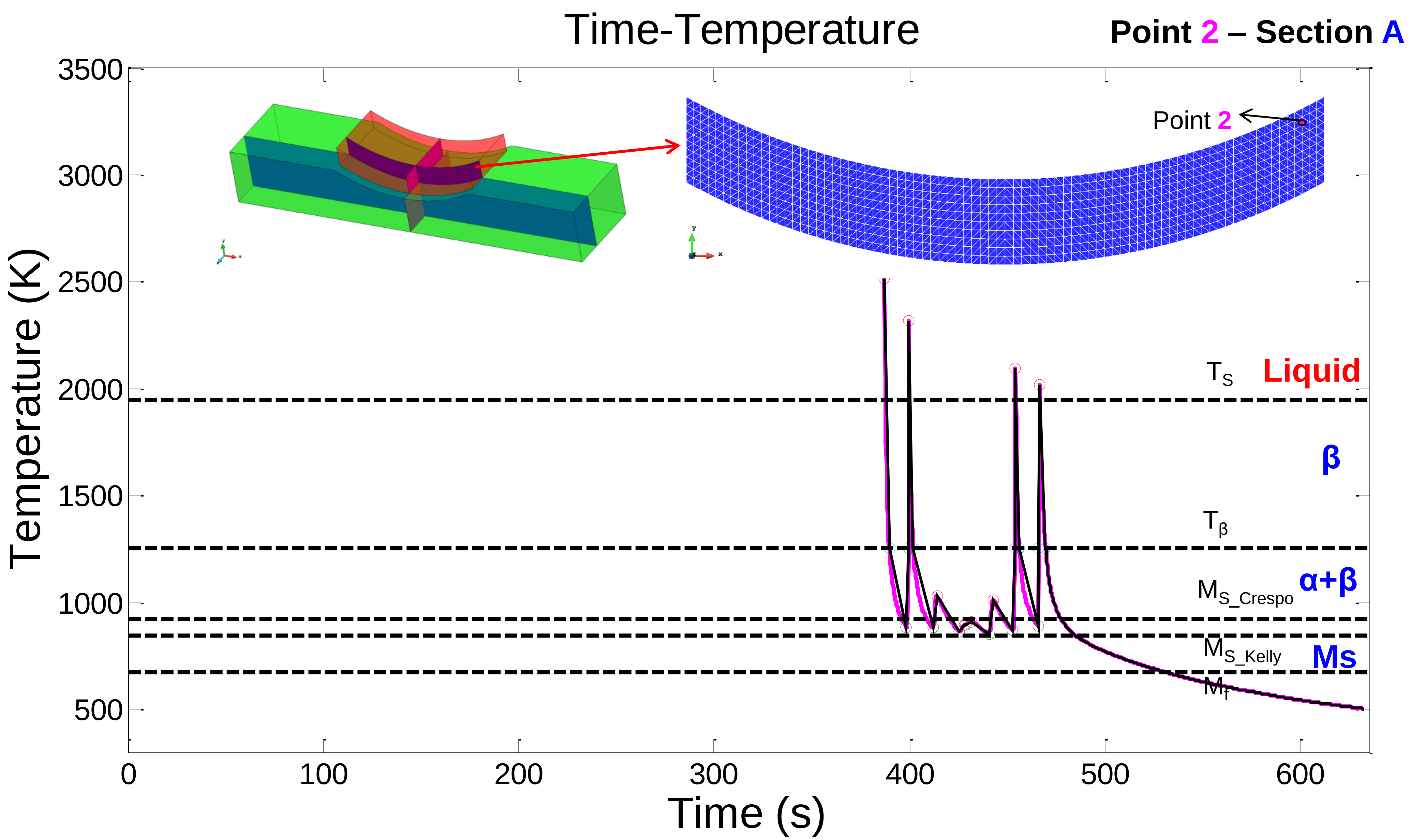
Constant Track Length strategy



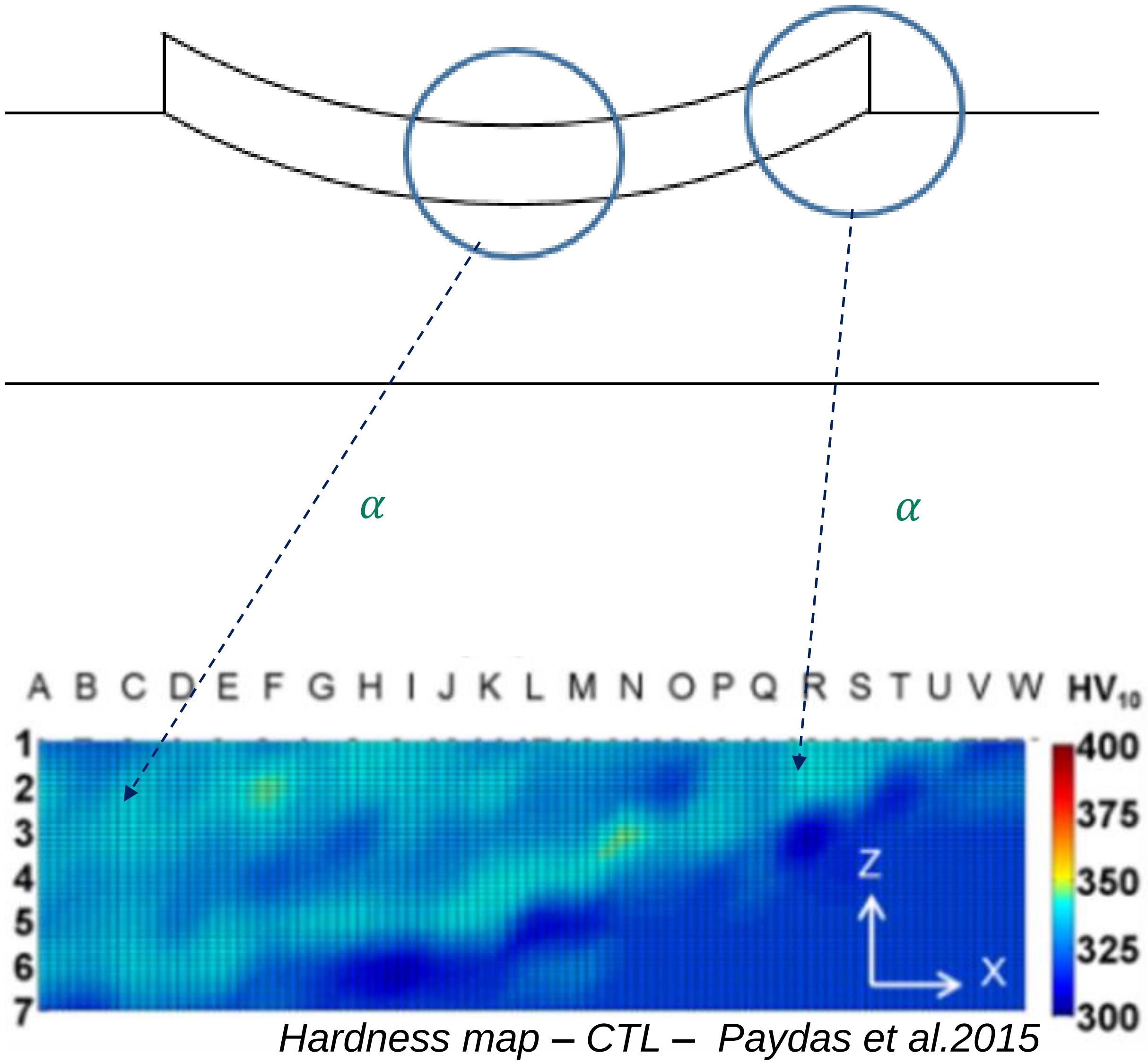
Constant Track Length strategy



Constant Track Length strategy

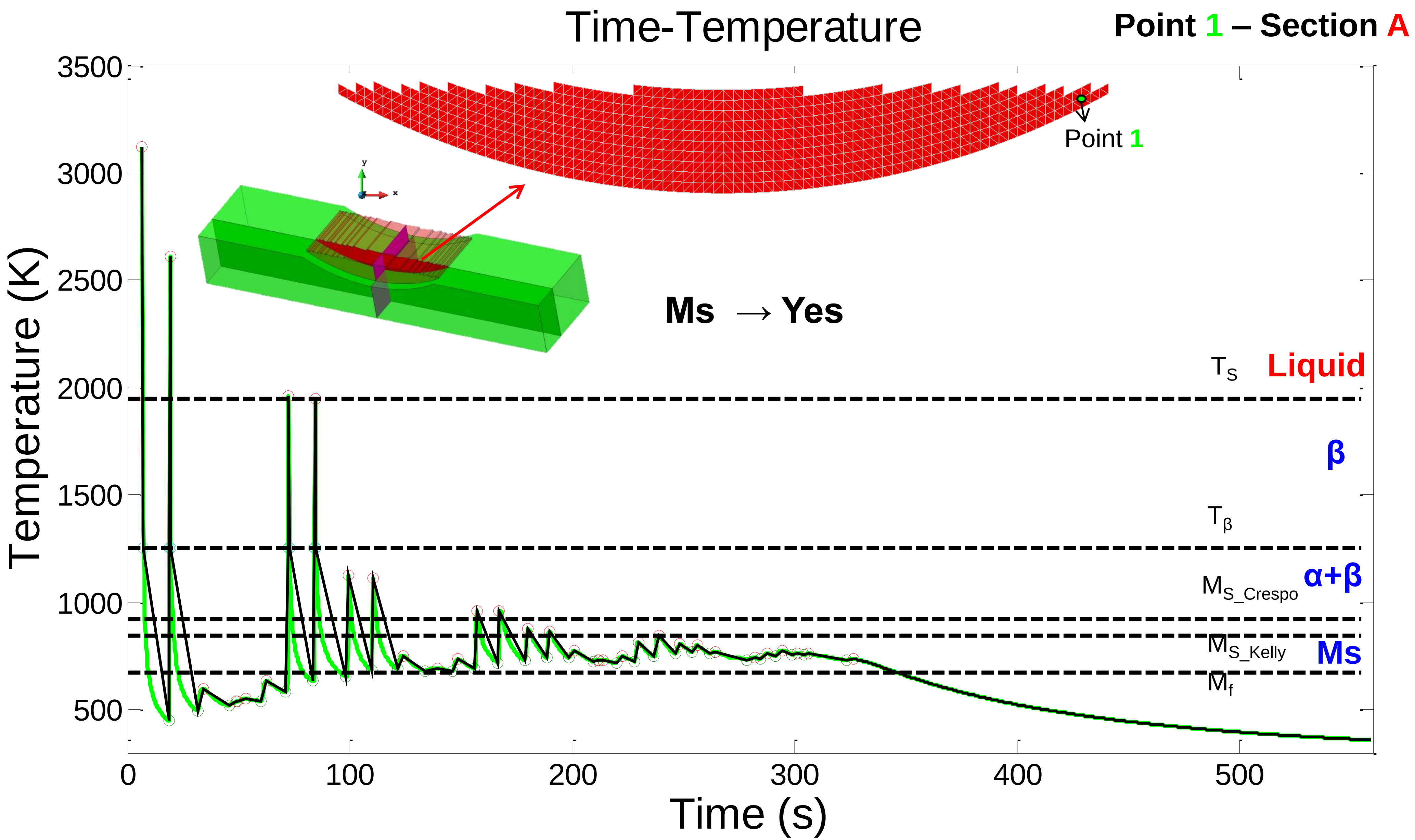


Constant Track Length strategy

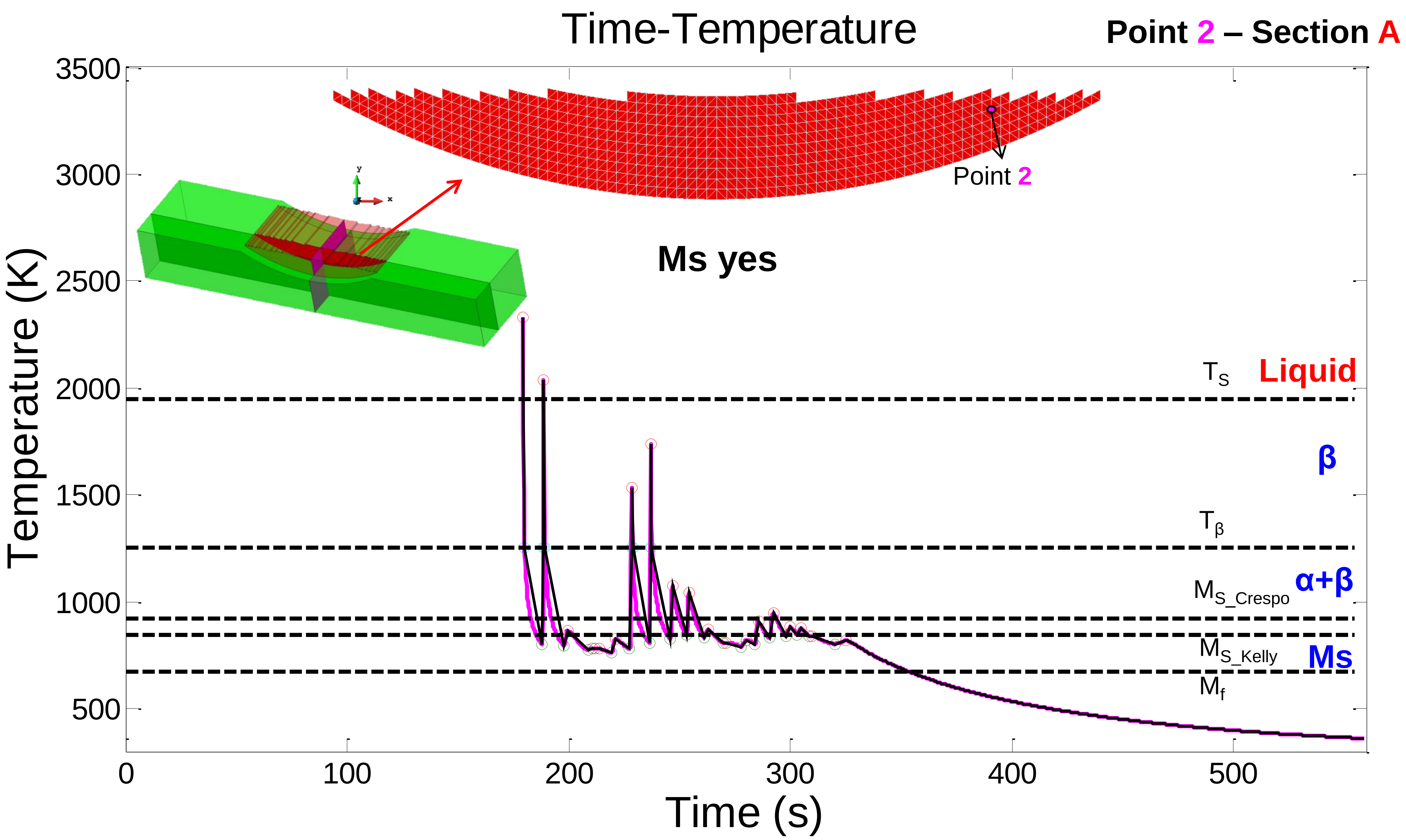


Hardness map – CTL – Paydas et al.2015

Decrease Track Length strategy

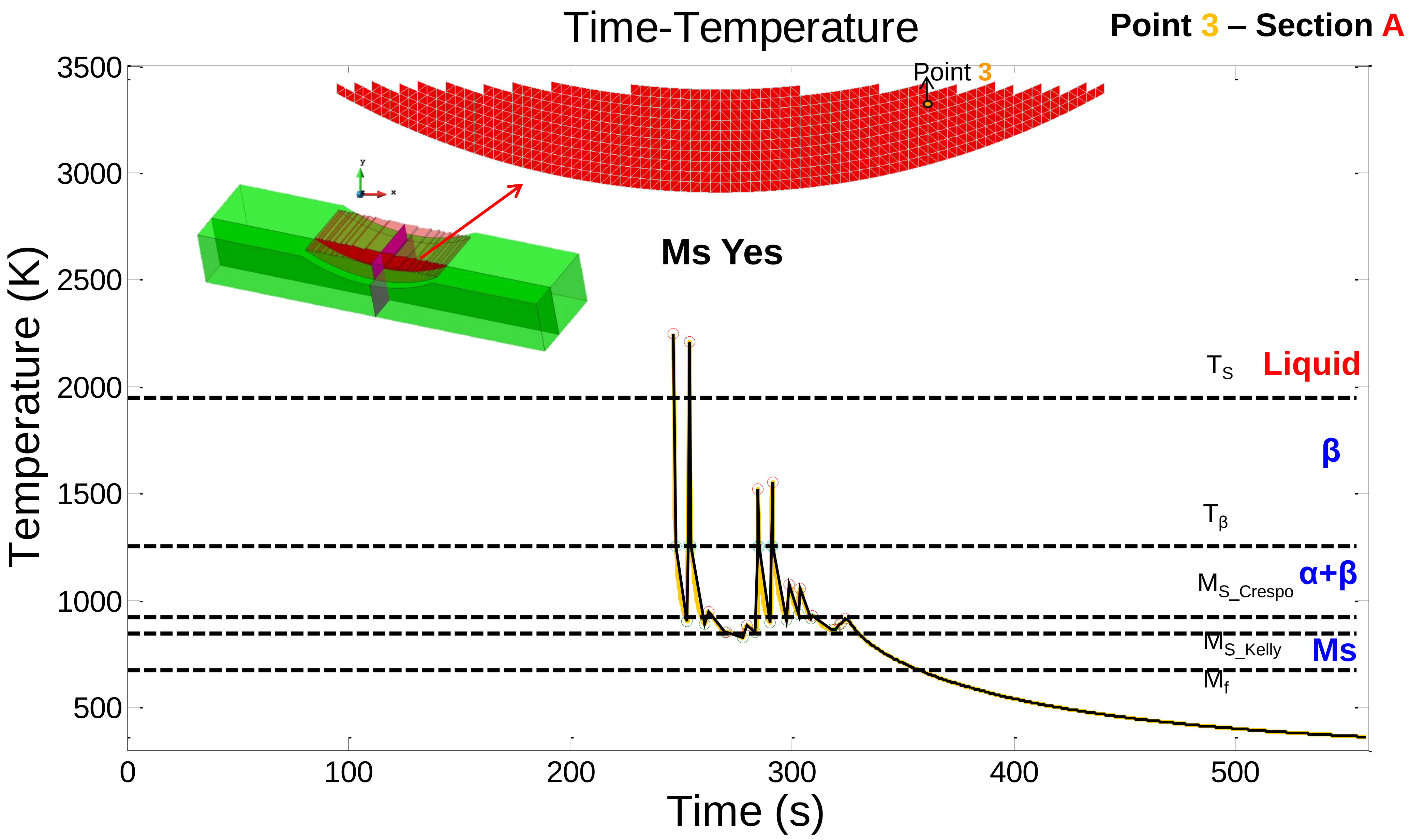


Decrease Track Length strategy

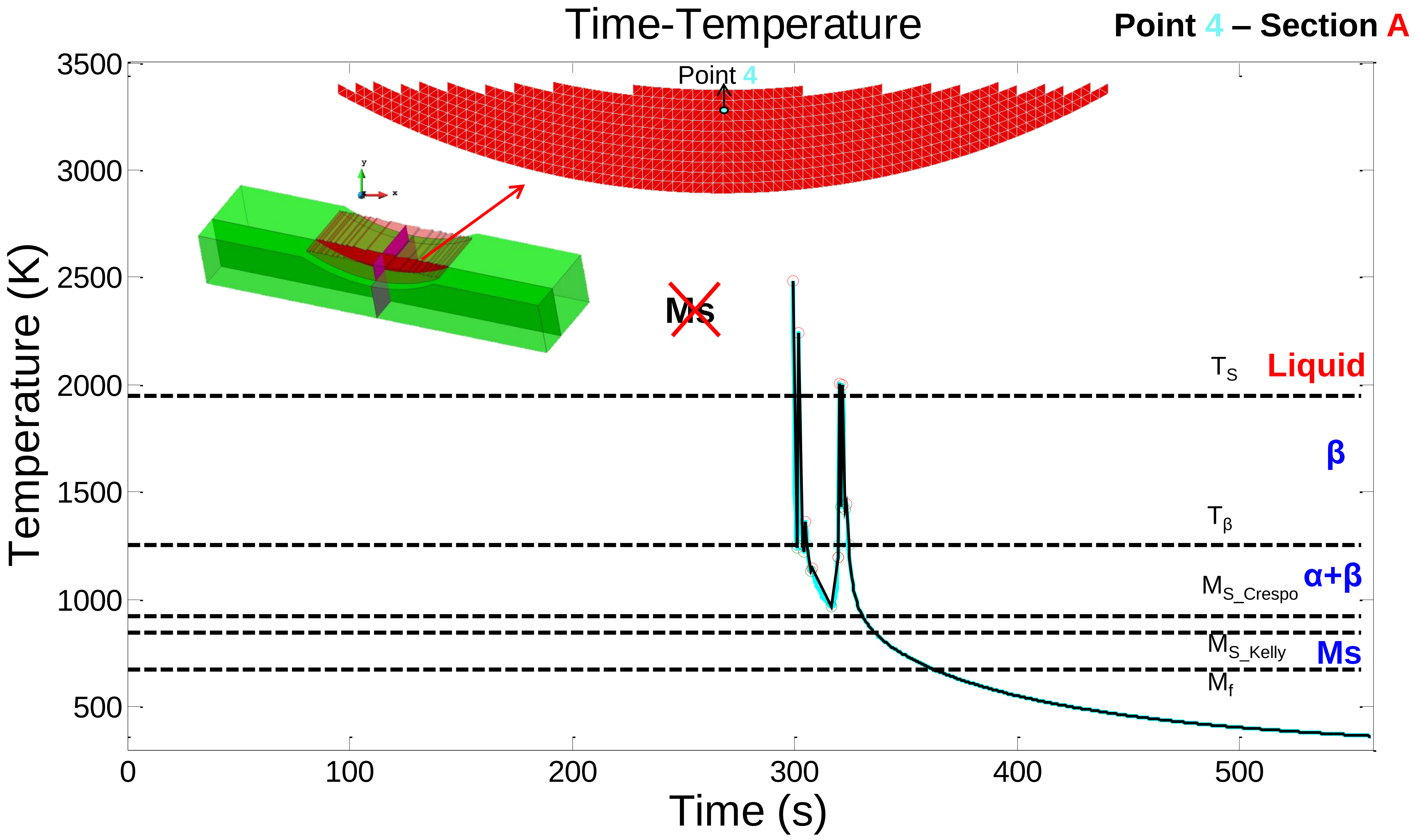


Decrease Track Length strategy

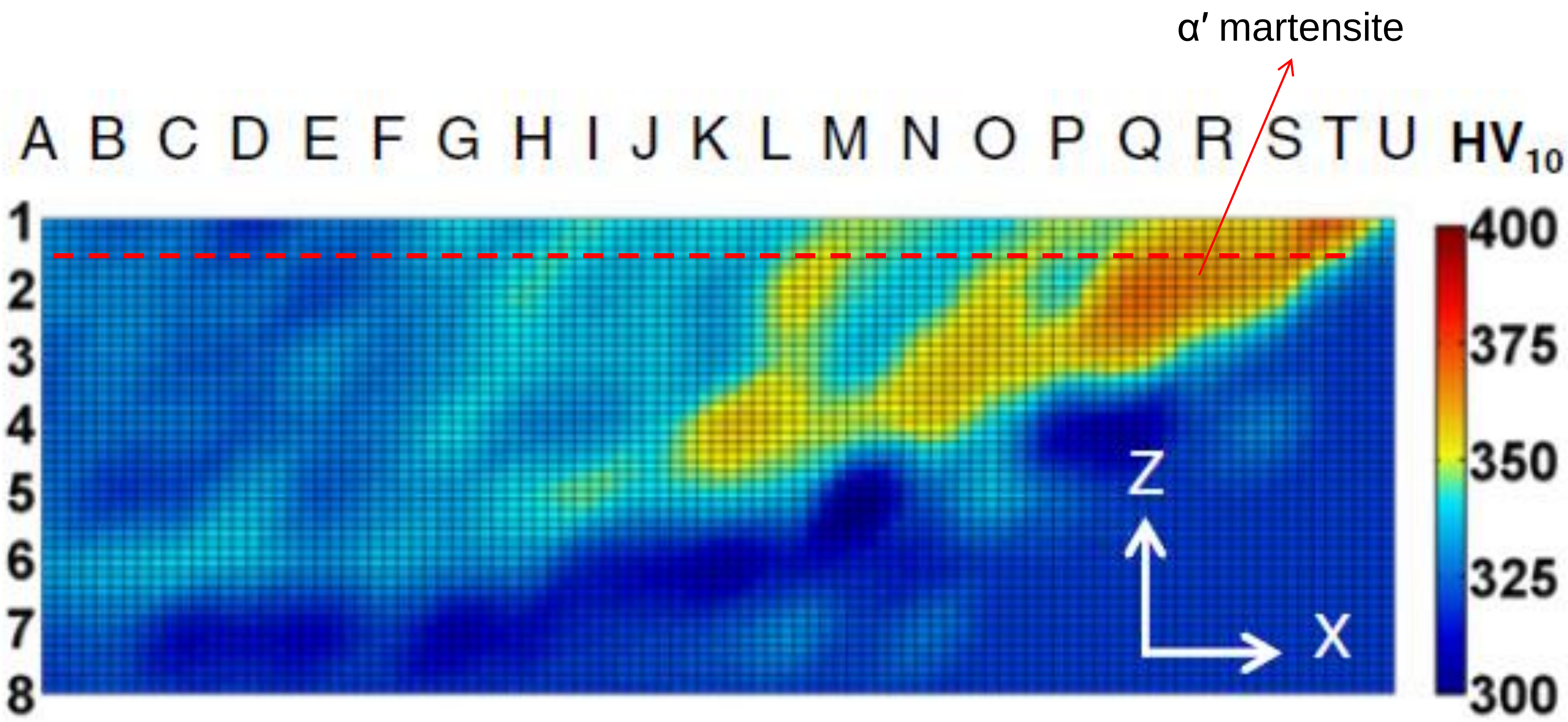
Point 3 – Section A



Decrease Track Length strategy



Decrease Track Length strategy



Hardness measurement (Hakan et al. 2015)

Tran's Conclusion 2017

Qualitative microstructure prediction with Kelly Ms value// experience

M_s 800°C and 848°C M_s for α_m

HAZ size in substrate validated

Prediction in Constant Track Length:

- Quite Homogeneous T° history
- $T_{average} > M_s$ when $\dot{T}$ high
- at the end $T <$ Ms but $\dot{T}$ low

→ **Basket-weave Widmanstätten structure**

Prediction in Decrease Track Length:

- Heterogenous T° history
- At some points :

$T_{average} <$ Ms $+ \dot{T}$ high

→ **Basket-weave Widmanstätten structure + α' Martensite**

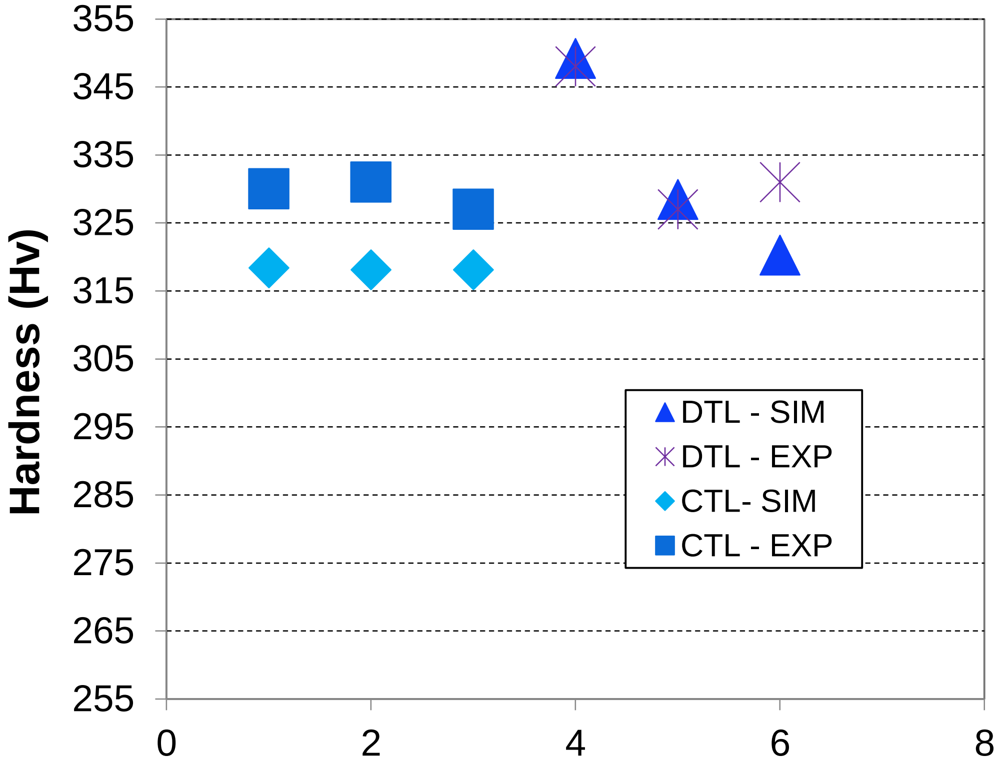
Crespo vs Esteva Master 2018 thesis (→quantitative)

		Crespo	Esteva
	Liquidus	1650 °C	1660 °C
Cooling	Boundaries rates	$\dot{T}$ < -410°C/s	$\dot{T}$ < -410°C/s -410°C/s < $\dot{T}$ < -20°C/s $\dot{T}$ > -20°C/s
	Ms, Mf	650 °C, 400 °C	655 °C, 355 °C
	α_m existance	No	Yes
Heating	Equation α′ → β and α	JMAK	K-M

Obtained Hardness values (Esteva)

Mixture Law:

$$Hardnes = f_\beta \cdot h_\beta + f_\alpha \cdot h_\alpha + f_{\alpha'} \cdot h_{\alpha'} + f_{\alpha_m} \cdot h_{\alpha_m}$$



	POI	Hardness error [%]
DTL	POI 1	0,3
	POI 2	0,4
	POI 3	3,3
CTL	POI 1’	3,6
	POI 2’	3,7
	POI 3’	3,7

Not too bad

however other SLM exp. could not fit with these M_s M_f choices

Experimental data obtained from H.Paydas et al. (2015)

Phases hardness values obtained from Pederson (2002) and Crespo (2010).

About Ti6Al4V and phase prediction

Themodynamics approaches must be further developed
to get better knowledge about Transformations (start, end, kinetics) for various compositions as well as element diffusion under complex Tp° history
(TITAN code T=cte… PhD Tioual Nancy supervised by Benoit Appolaire 2019)…
+ links with Phase fields

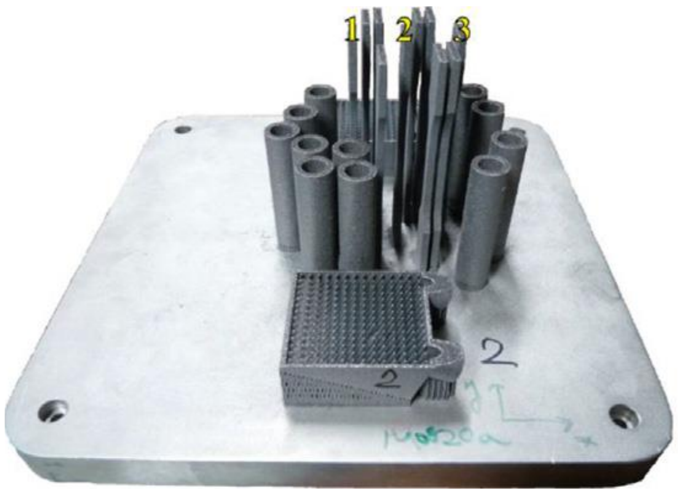
Post processing of T(t), computed by Finite elements, by Crespo type model based on previous results could predict microstructure

→ Coupling is important or machine learning….

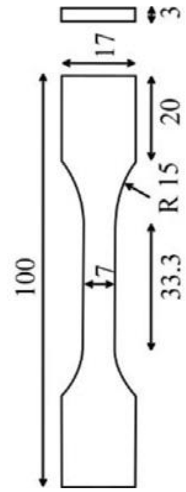
Contents

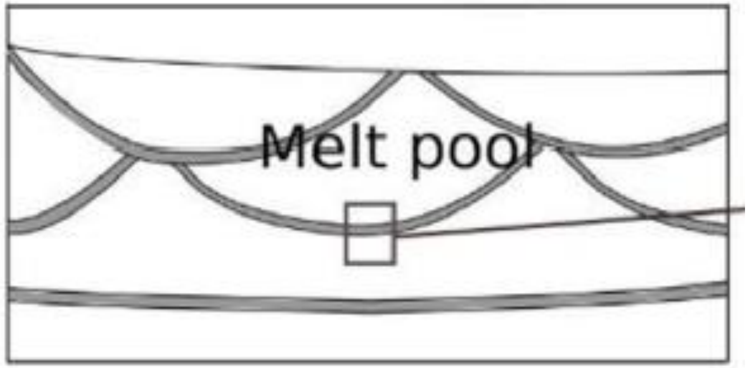
Goal= study of static rupture in AlSi10Mg-SLM, (…delaying it…)

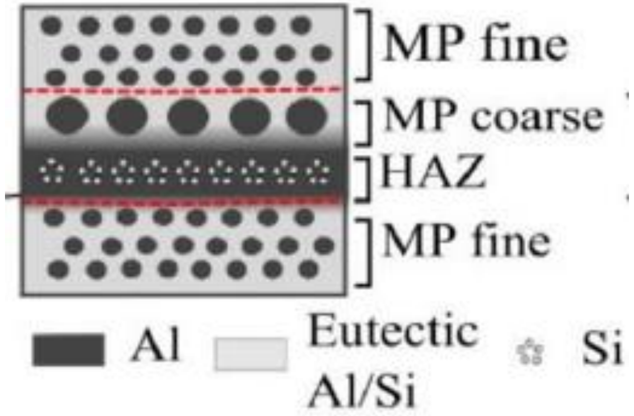
J. Delahaye et al. Acta Materialia 2019

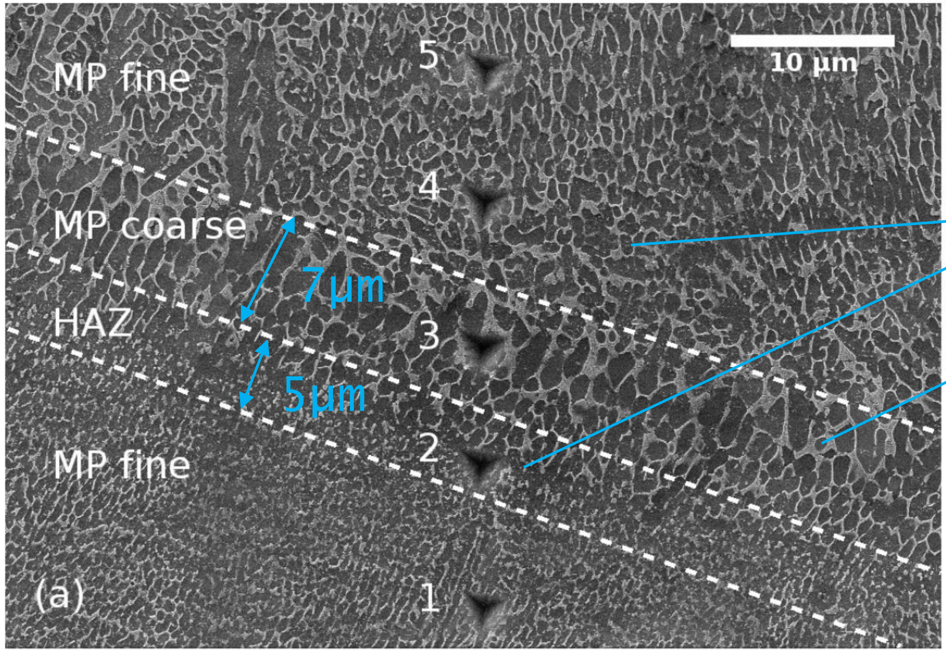


(b)









Average cell size

0.7 µm

1 µm

Si in solution solid inside the cell: MP fine =Mp coarse =HAZ

SLM process

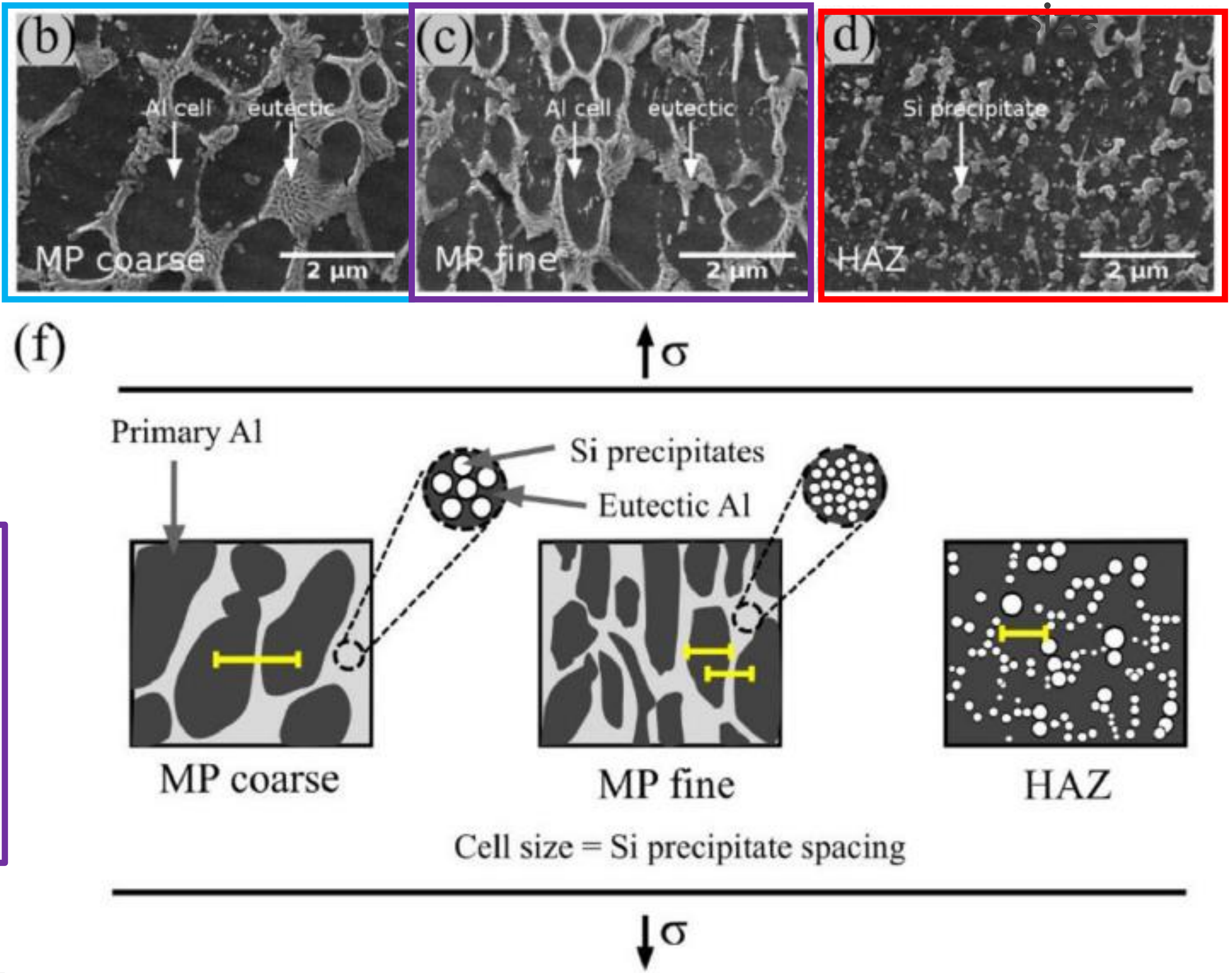
Laser Power, P [W]	175
Beam travel speed, v [m/s]	0.195
Absorbed power coefficient, [–]	0.35

Non optimal parameters but parameters enhancing HAZ size

Goal= study of static rupture in AlSi10Mg-SLM, (…delaying it…)

melt pool boundary = MP coarse

'increased' cell size and thick eutectic with large precipitates



HAZ = eutectic network broken, Si coarse precipitate,

HAZ cell size =MPF cell size

melt pool core = MPfine

'Small' cell size and thin eutectic with small precipitates

Goal= study of static rupture in AlSi10Mg-SLM, (…delaying it…)

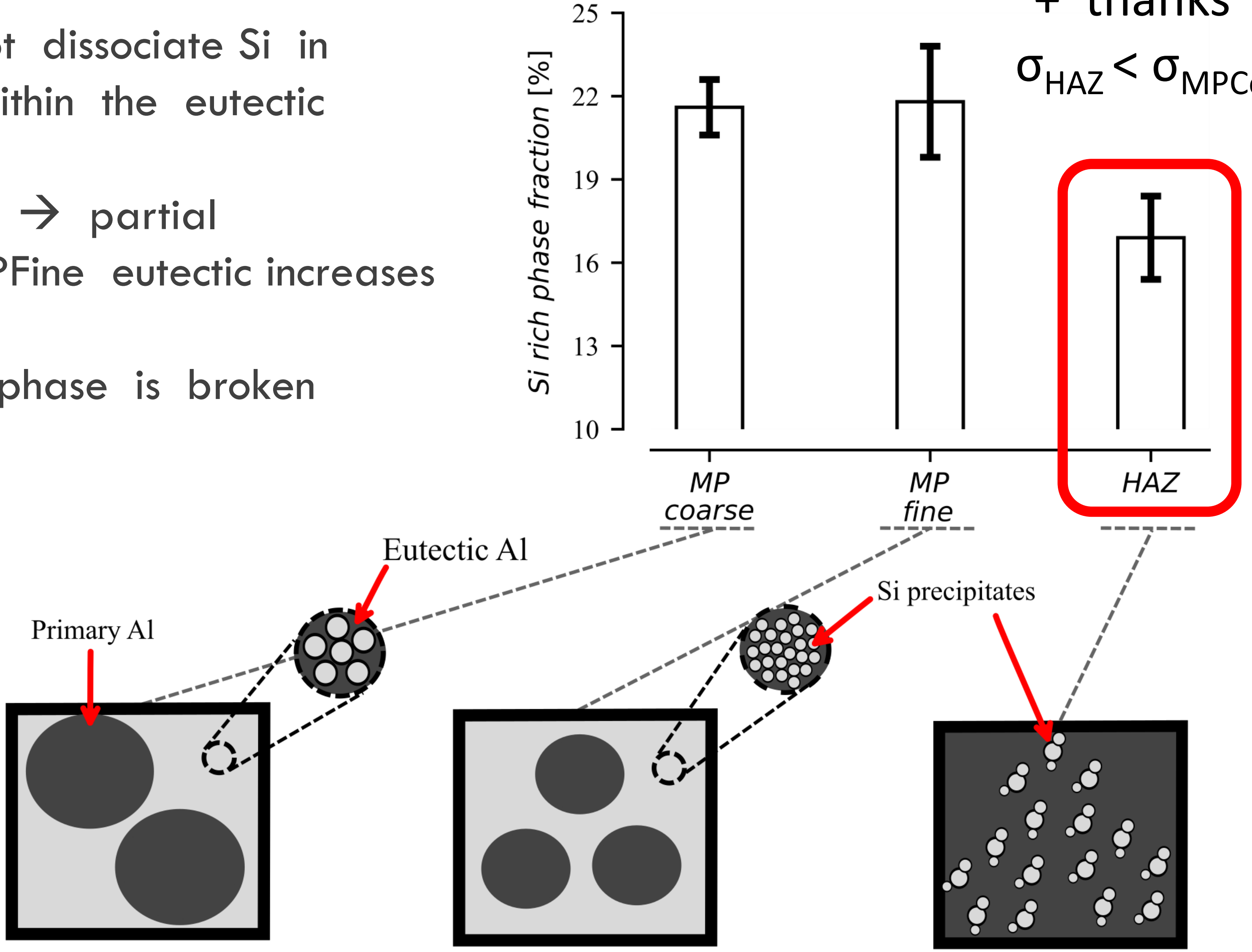
Measurements do not dissociate Si in precipitate and Si within the eutectic

Lower value in HAZ → partial decomposition of MPFine eutectic increases Si precipitate size

Network of eutectic phase is broken

+ thanks to hardness

$\sigma_{HAZ} < \sigma_{MPCorse} < \sigma_{MPFine}$



Goal= study of static rupture in AlSi10Mg-SLM,

(…delaying it…)

HAZ is the risky zone →optimal parameters should decrease its size

Use of

Rosenthal equation (‘direct’, a lot of assumptions)→temperature history → cell parameters

or

Finite element simulations (heavier, more details tp° hstory, need input data)

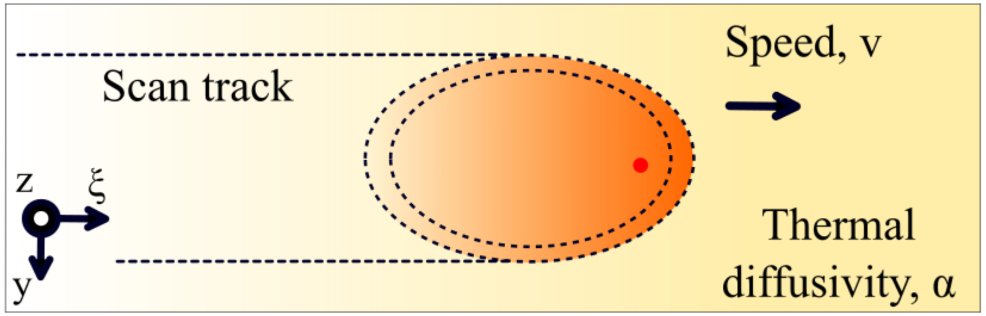
Process parameters → temperature history → cell parameters

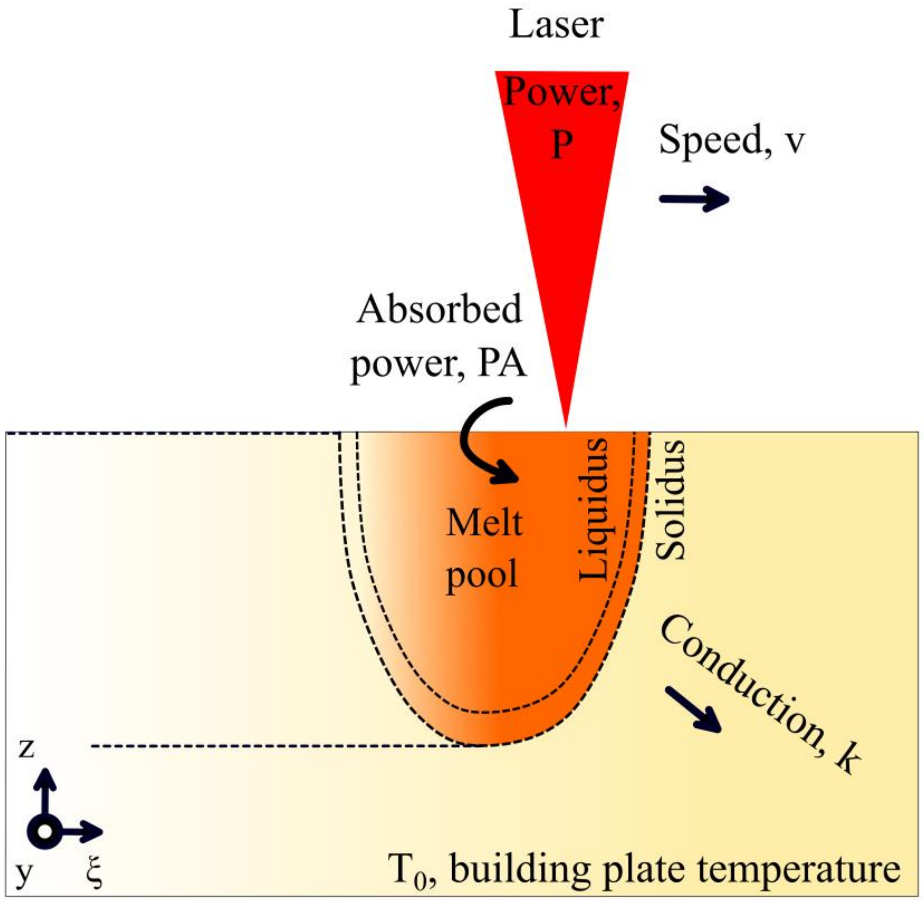
Thermal field during SLM – Rosenthal's equation

P laser power
c absorbed power coefficient
T0 building plate temperature
k thermal conductivity
α thermal diffusivity

$$T = T_0 + \frac{Pc}{2\pi R k} e^{\frac{-\nu(\xi + R)}{2\alpha}} \quad R = (\xi^2 + y^2 + z^2)^{\frac{1}{2}}$$

Moving coordinate system :
$\xi = x - \nu t$





Thermal field and link with cell size

Thermal history during SLM – Rosenthal's equation[1]:

$$T = T_0 + \frac{Pc}{2\pi Rk} e^{\frac{-\nu(\xi+R)}{2\alpha}} \quad R = (\xi^2 + y^2 + z^2)^{\frac{1}{2}}$$

Cell size vs cooling rate – Matyja's equation[2]:

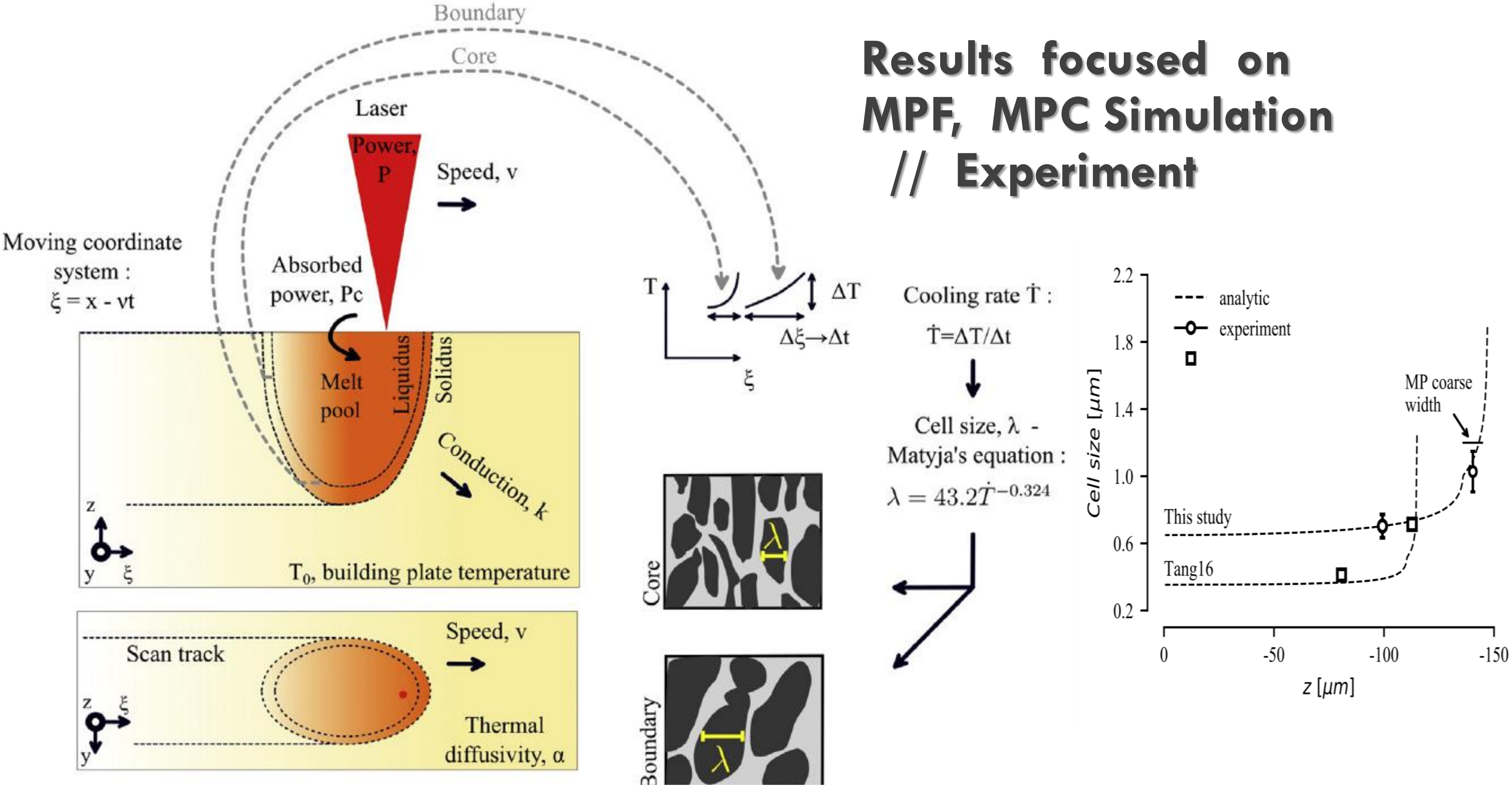
$$\lambda = 43.2\dot{T}^{-0.324}$$

Parameter used in Rosenthal's equation:

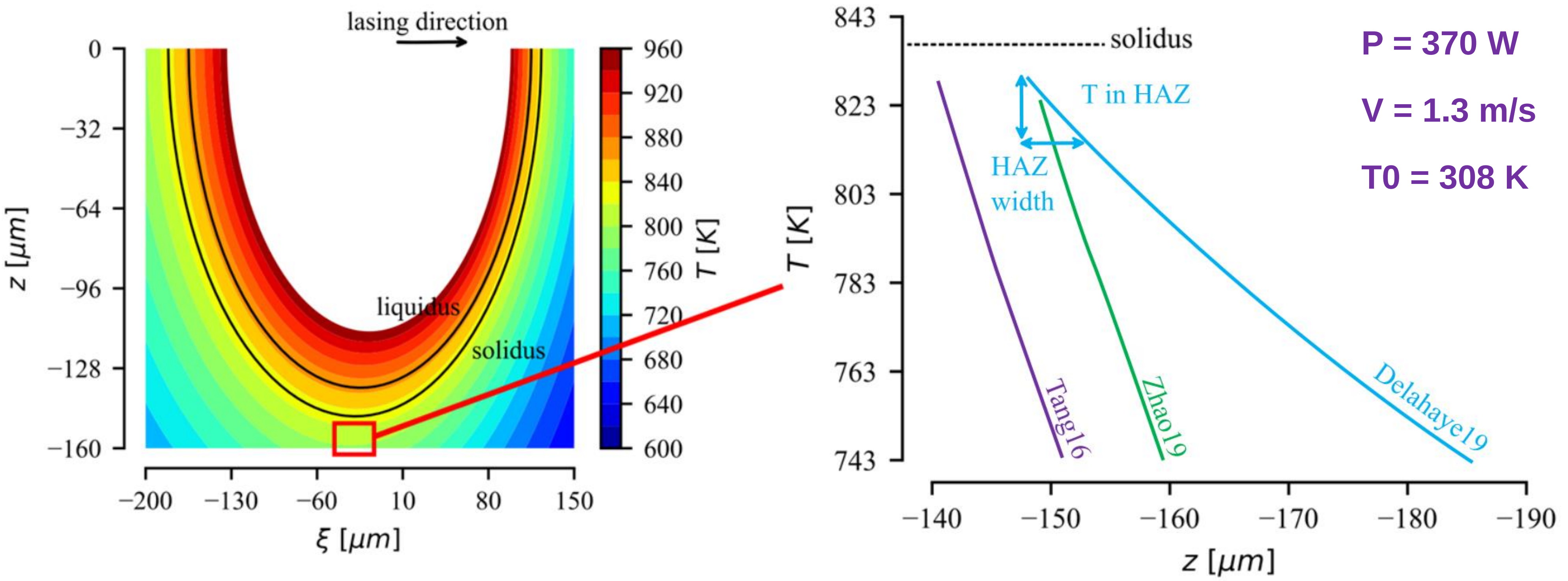
Parameter	this study	Tang16[3]
Conductivity, k $[W/mK]$	150	150
Diffusivity, α $[m^2/s]$	6.2^{-5}	6.2^{-5}
Liquidus, T_{liq} $[K]$	867	867
Solidus, T_{sol} $[K]$	831	831
Building Plate temperature, T_0 $[K]$	473	308
Laser Power, P $[W]$	175	370
Beam travel speed, ν $[m/s]$	0.195	1.3
Absorbed power coeffiecient, $[-]$	0.35	0.35

[1]D. Rosenthal, Weld. J. 20 (1941) 220–234.
[2]H. Matyja, Journal of the Institute of Metals 96 (1968) 30–32.
[3]M. Tang, P.C. Pistorius, S. Narra, J.L. Beuth, JOM 68 (2016) 960–966.

Results focused on MPF, MPC Simulation // Experiment



Results focused on HAZ Simulation // Experiment



P = 370 W
V = 1.3 m/s
T0 = 308 K

P = 175 W
V = 0.195 m/s
T0 = 473 K

P = 390 W
V = 1.3 m/s
T0 = 308 K

Process parameters modifies HAZ width:

5 μm (Delahaye Acta Mat 2019) - fracture strain 1.8%

2 μm (Tang JOM 2017) - fracture strain 12.5%

2 μm (Zhao Mat. Sc. & Eng. A 2019)- fracture strain 11% but different loading direction and mechanism

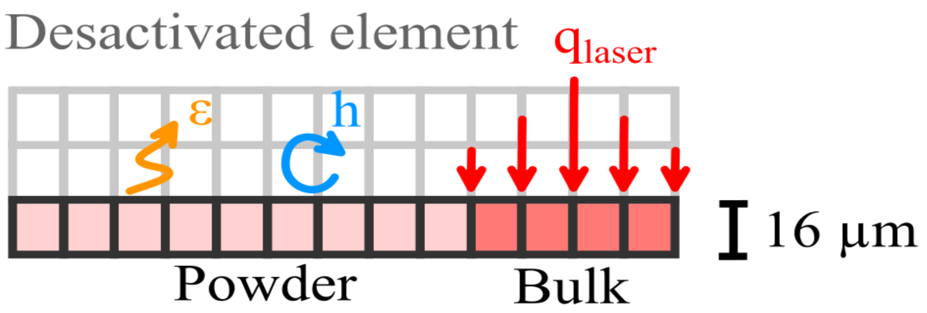
What about the interest of FE Simulation

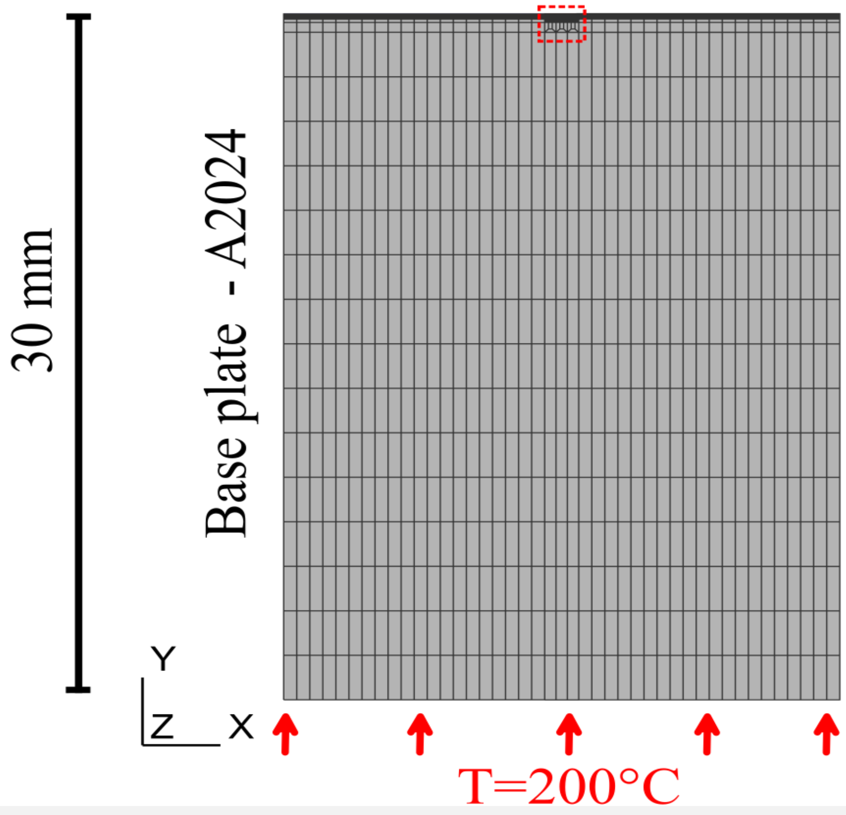
Heat conduction equation :

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+Q_{x,y,t}=\rho C_p\frac{\partial T}{\partial t}$$

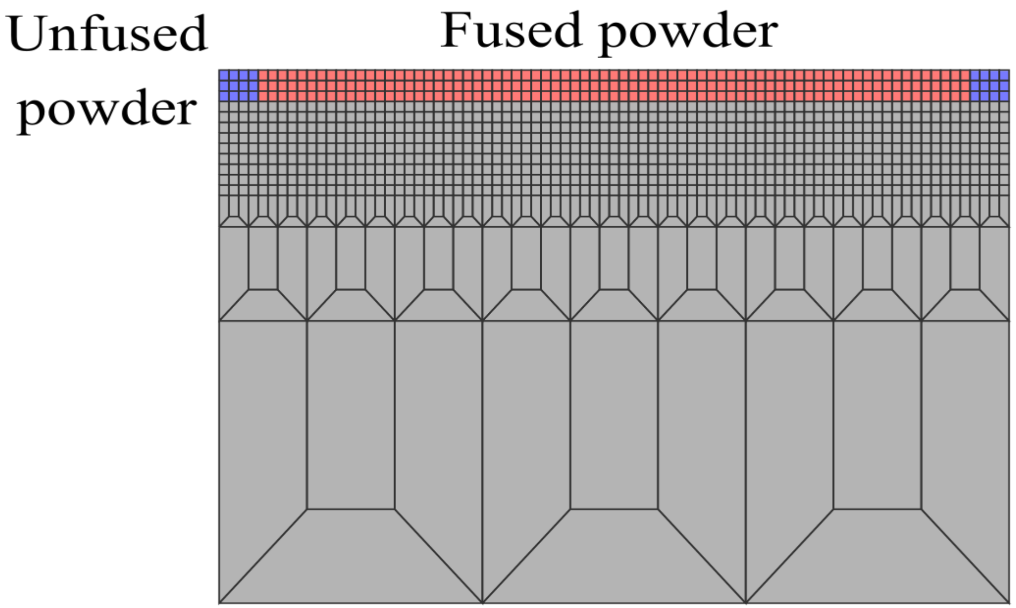
Convection / radiation heat loss :

$$-k\left(\nabla T.n\right)=\ q_{\text{laser}}-h\left(T-T_0\right)-\epsilon\sigma\left(T^4-T_0^4\right)$$





Finer Mesh :

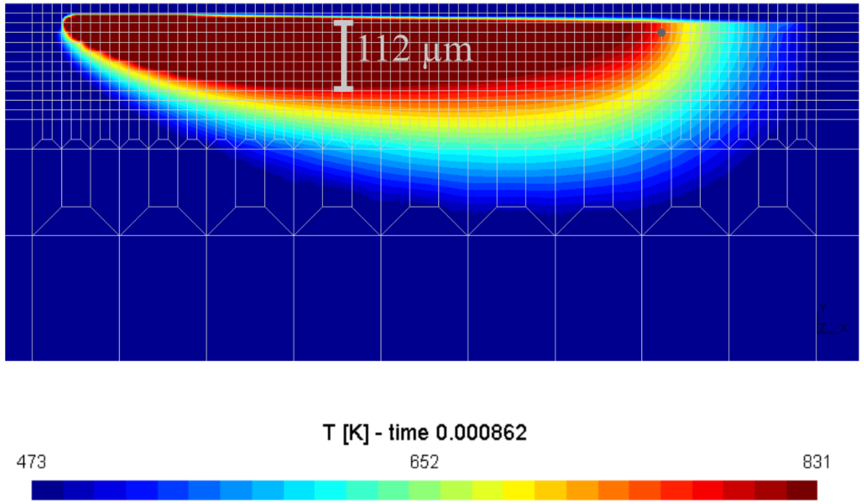


What about the interest of FE Simulation ?

1. Validation and identification (1 layer) :

Melt pool depth :

Exp. : 90-120 µm (part supplier)



Thermo-physical properties :

—Bulk : Cp(T), ρ(T) and k(T) measured in MMS on SLM samples

—Powder : k(T) Sih and Barlow's model[1]

—Constant ε

Moving Gaussian heat source :

—Tuning laser absorptivity A to calibrate

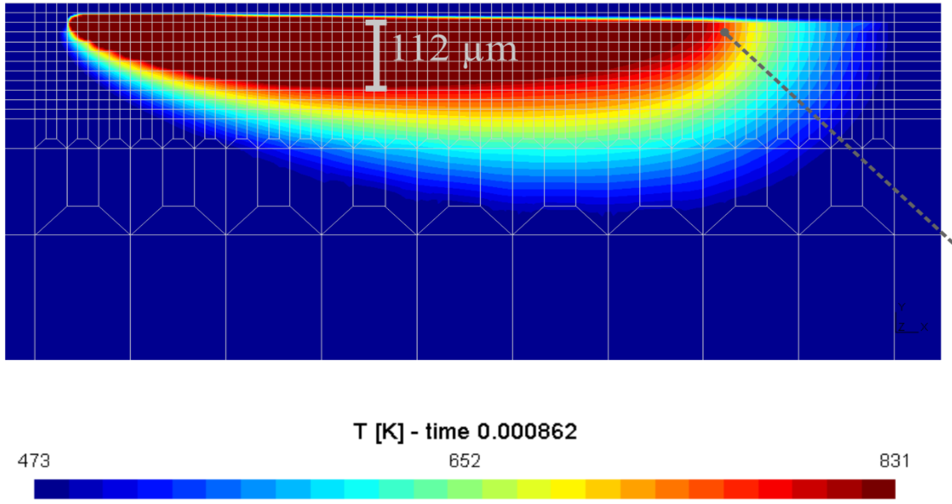
—Non-physical meaning of A(~0.02) for 2D thermal model (3D model A~0.35)

[1] Sih et al. Particul. Sci. Technol. 22 (2004)

What about the interest of FE Simulation ?

Melt pool depth :

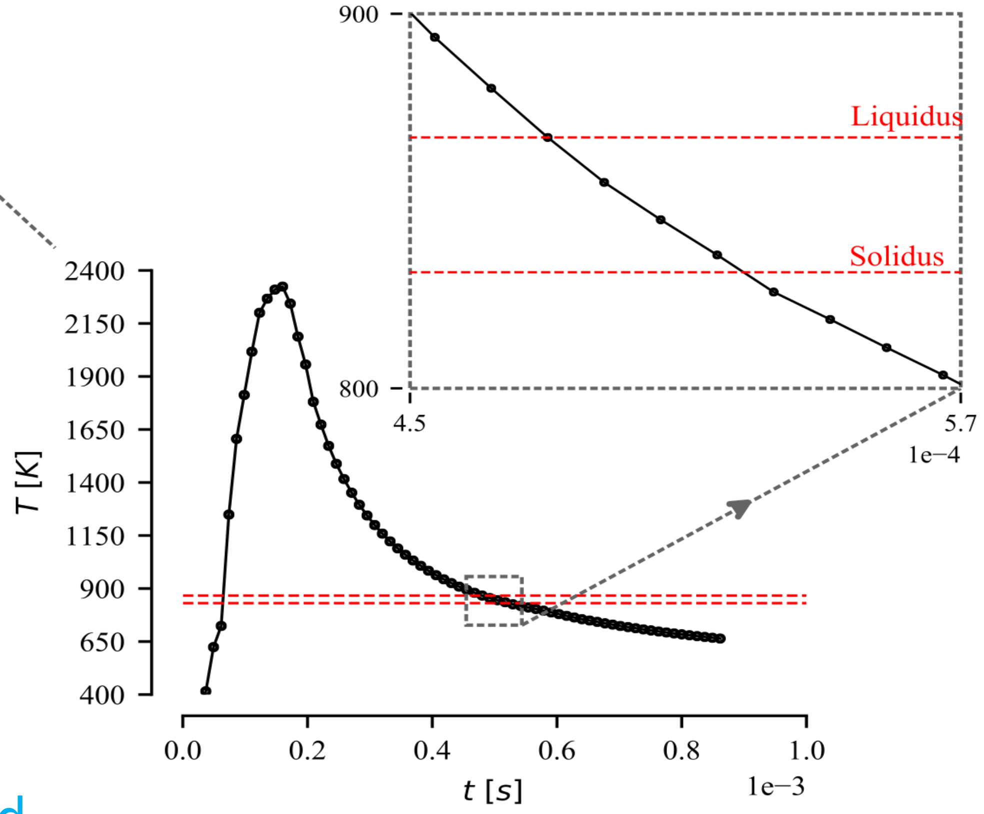
Exp. : 90-120 μm (part supplier)



Cooling rate :

$\dot{T}_{exp} = 10^6 K.s^{-1}$(microstructure + Matyja's eq)

$\dot{T}_{sim} = 0.9x10^6 K.s^{-1}$



Thermal history presents different cycles due to multiple layers

→ T(t) feeds a Phase Field model

→ phases kinetics and Si diffusion can will be studied

→ Ongoing PhD

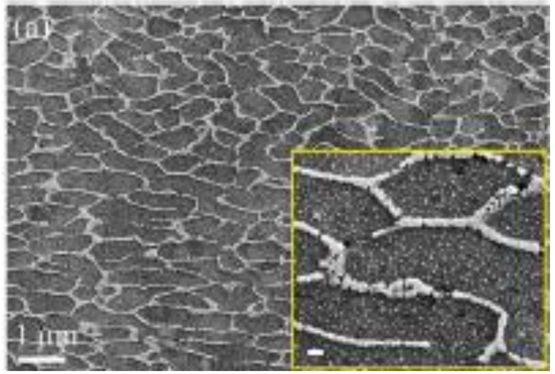
Common Goal = investigate static rupture and delaying it

Two complementary studies to investigate damage mechanism in SLM **as built samples**

Zhao et al. Materials Science & Engineering A 2019

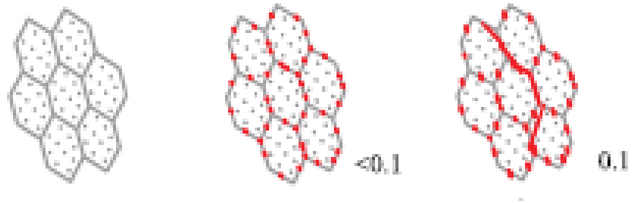
minimum HAZ effect: process param. (thin HAZ)

+ tensile load // HAZ



eutectic network
with Si precipitates

Si rich network
→ voids
nucleation
and crack
formation
Not in HAZ



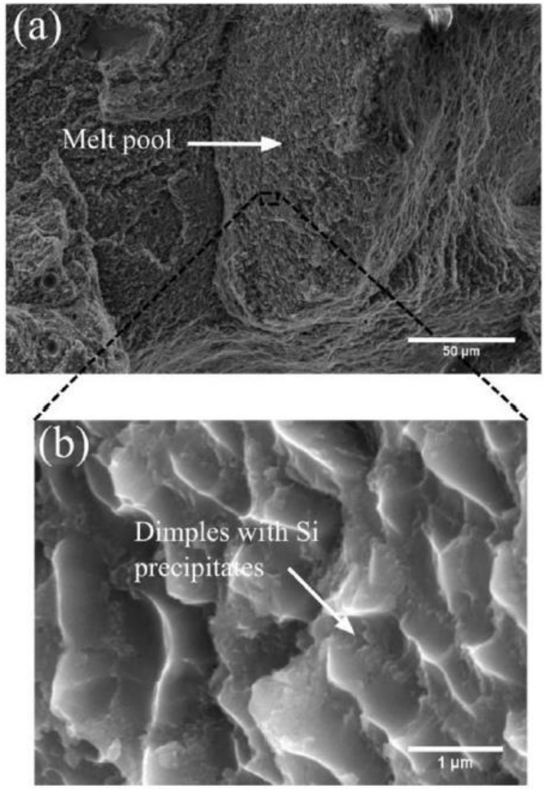
strain strain

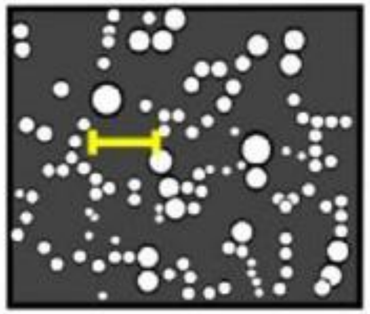
To increase
elongation but
dcreasing elastic
stress
→Globularization Post
treatments (Tp° or
FSP) delay crack

J. Delahaye et al. Acta Materialia 2019

maximum HAZ effect: process param. (thick HAZ)

+ tensile load ⊥ HAZ





HAZ

Damage nucleate around Si
precipitates in HAZ
Crack formation in HAZ

Tang parameters (small HAZ)
→ 12,5 % elongation
Delahaye param (HAZ ↑)
→ 4,5%

What is the goal with AlSi10Mg?

→ **Interest to further investigate thermal history impact**

Finite element to get representative T(t)

Phase Field approach

to better understand Si diffusion in typical positions MPF, MPC, HAZ…

Characterize by indentation mechanical behavior of different cells and Si rich eutectic network

Links to fracture behavior

Contents

Evolution of the microstructure prediction

Challenges about Additive Manufacturing

About Ti6Al4V and phase prediction

What is the goal with AlSi10Mg?

Why is AISI M4 case so challenging and interesting?

Material High Speed Steel AISI M4

- Fe-Cr-C-X alloys with X: carbide-forming element (i.e. V, Nb, Mo or W)
- Hard carbides ⇒ High hardness and wear resistance
- Applications: high speed machining, cutting tools, hot **rolling mill rolls, molds…**

C	Cr	Mo	V	W	Ni	Si	Fe
1.35	4.30	4.64	4.10	5.60	0.34	0.9	0.33

Finite Element Model - Identification of input data

Material data

conduction, heat capacity, latent heat
measured on samples extracted
from the clad & the substrate
(DSC, Laser flash, dilatometry, quench dilatometer)

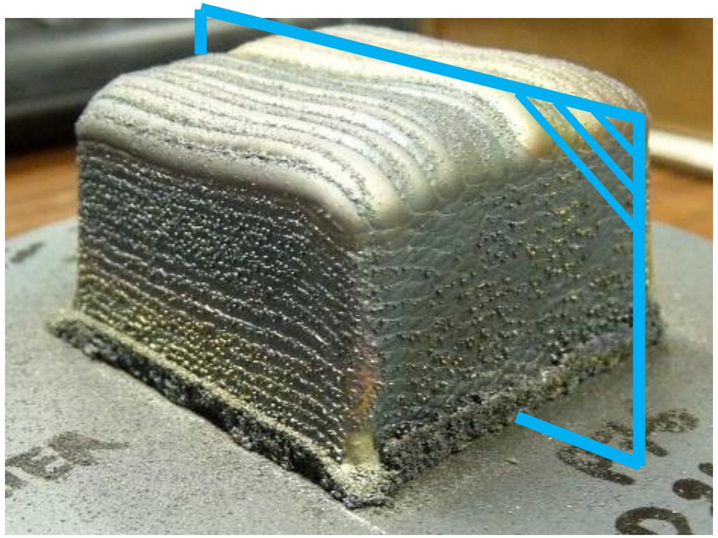
Boundary conditions

Convection, Radiation, laser absorption fitted by inverse modelling
target BOTH
Measured Temperature history + Melt pool depth

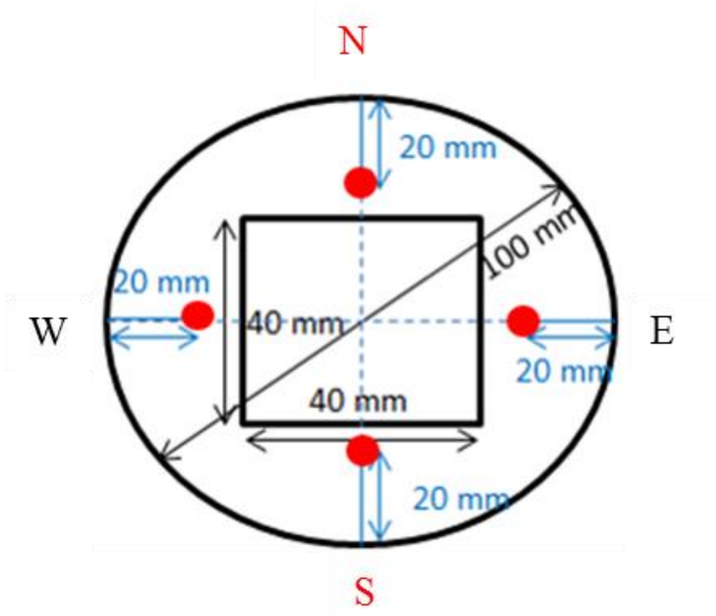
Laser path (velocity, idle time, tracks scheme)
Real one in 3D, simplified but per layer in 2D simulations

Bulk samples

	Bulk Sample
Laser beam speed (mm/s)	6.67
Laser power (W)	1100
Pre-heating (°C)	300
Mass flow (mg/s)	76
Number of tracks per layer	27
Total number of layers	36



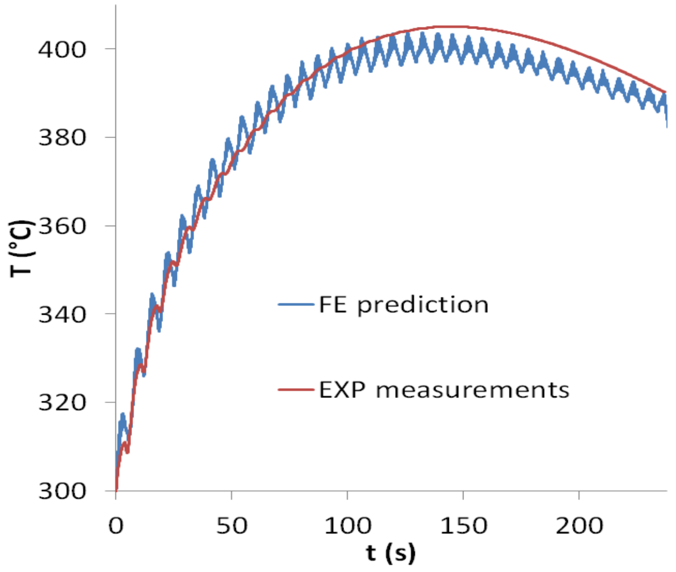
40 x 40 x 27.5 mm **(972 tracks)**



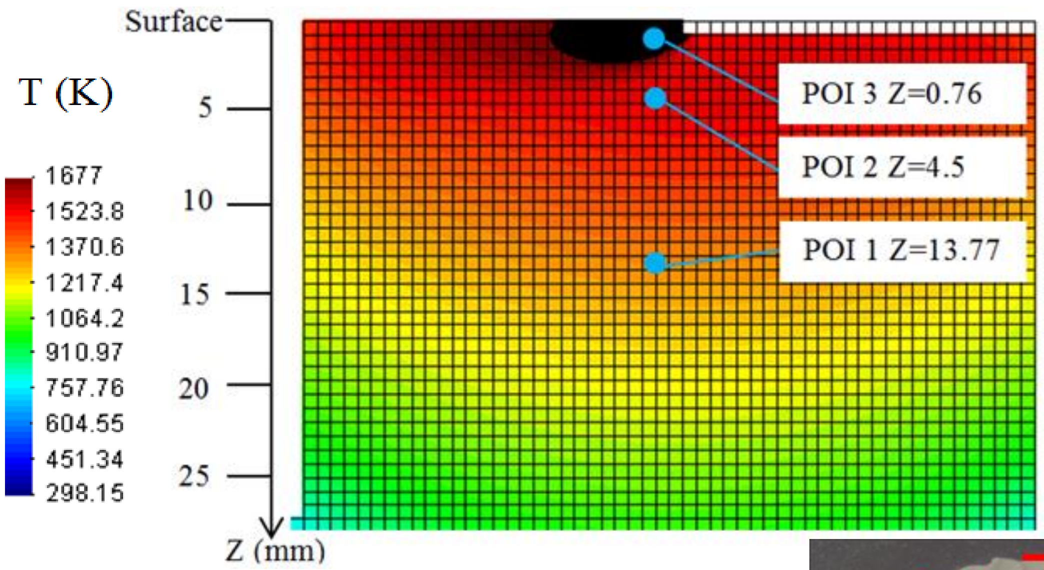
4 Thermocouples
Thermal measurement in the substrate

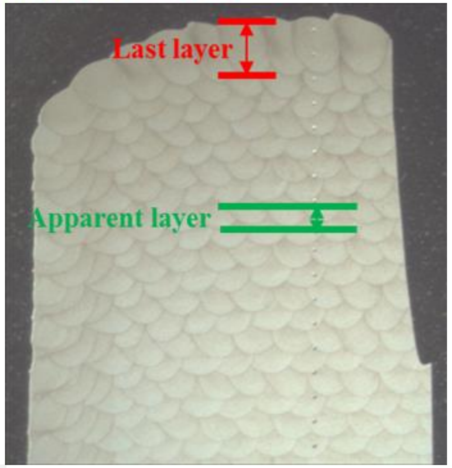
"2D FE " - bulk samples

Tp° in the substrate



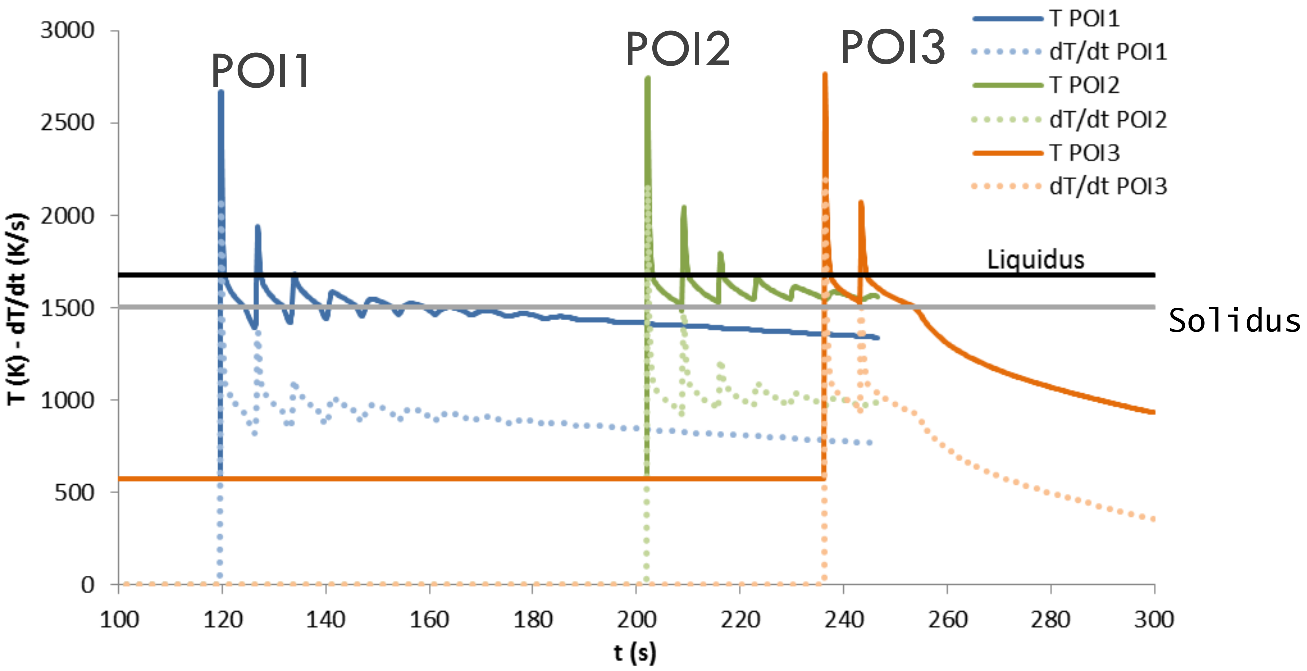
Predicted Tp° in the clad

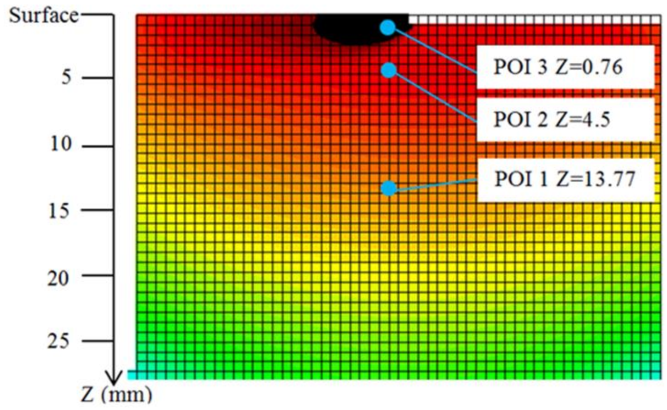




Melt pool depth

Key data for identifying single set of data by inverse simulations (convection, radiation, absorption coefficient)

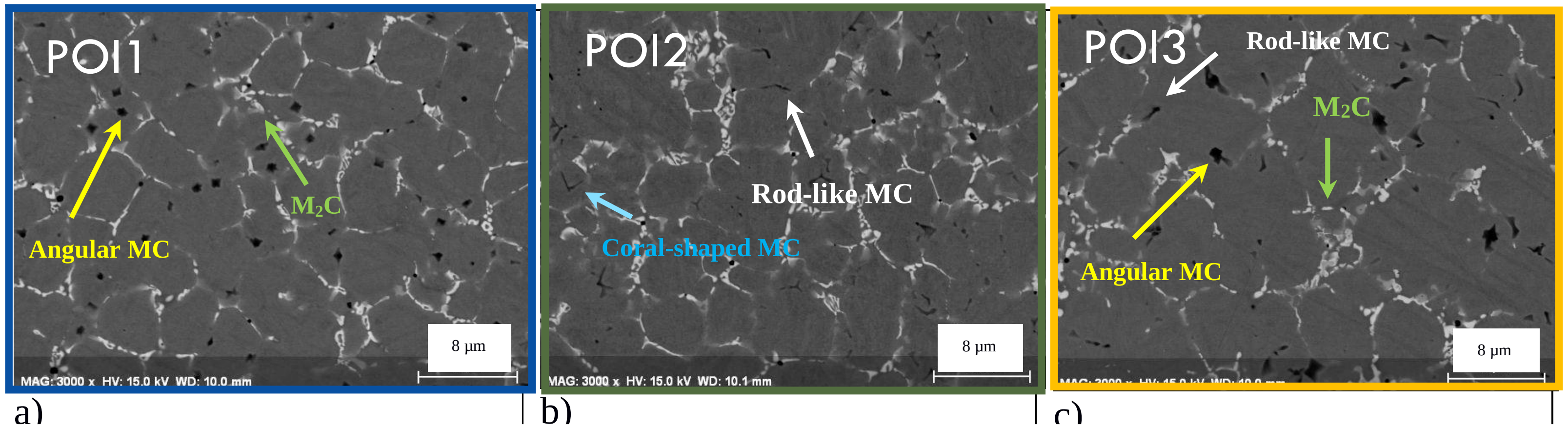




-Number of full partial remelting

-Tp° Level between solidus & liquidus

- Superheating temperature



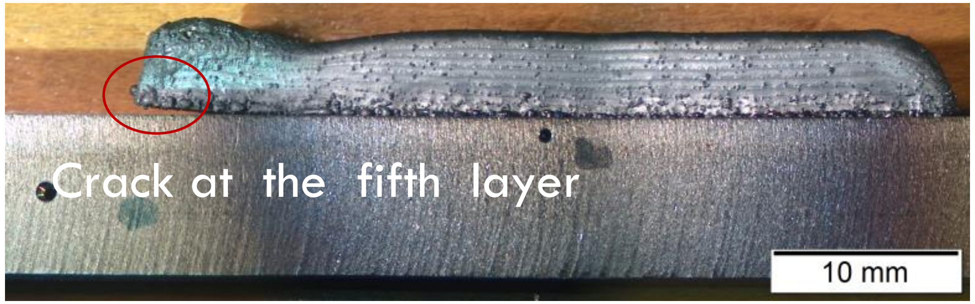
Jardin R.T., et al. (2019) Materials Letters.

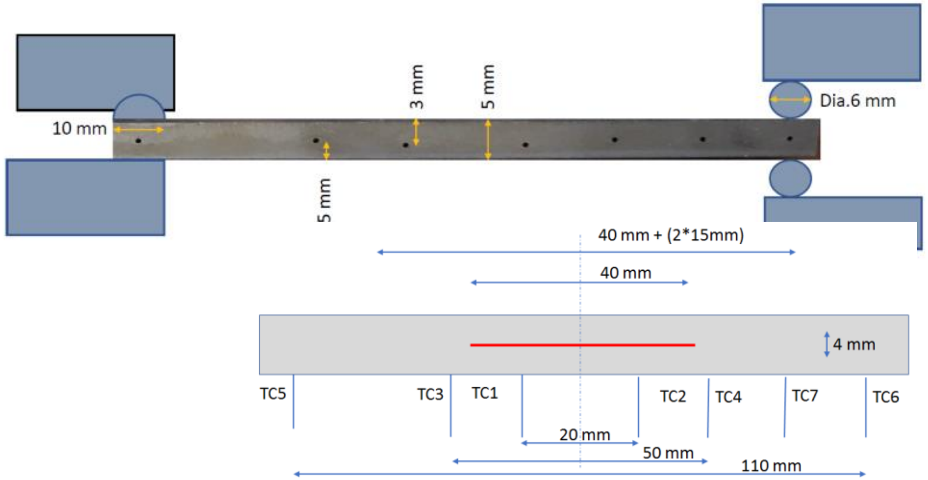
star-like MC and lamellar eutectic M2C intercellular carbides

coral-shaped intracellular MC, intercellular eutectic M2C and refined cells due to multiple melting

coarse angular MC and eutectic M2C within intercellular zones

Thin wall experiments (1) Preheating =150˚C

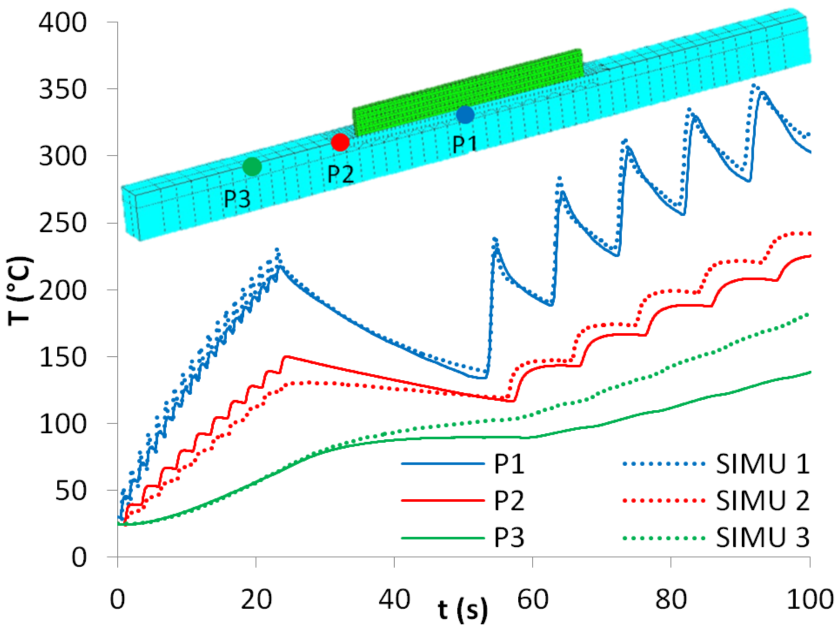




	Substrate pre-heating	Clad deposition
Length of centered laser pass for pre-heating (mm)	40	40
Laser beam speed (mm/s)	41.7	8.3
Laser power (W)	260	(Constant)500
Temperature at thermocouple TC1 at preheating end and at cladding start in °C	217	134
Number of laser passes	20	10

With a thiner substrate: there too much bending → risk for laser position
With thicker substrate crack situation worst

3D FE thin wall simulations



Measured thermophysical parameters Stress strain curves at 3 tp° and strain rate
on samples extracted from DED samples

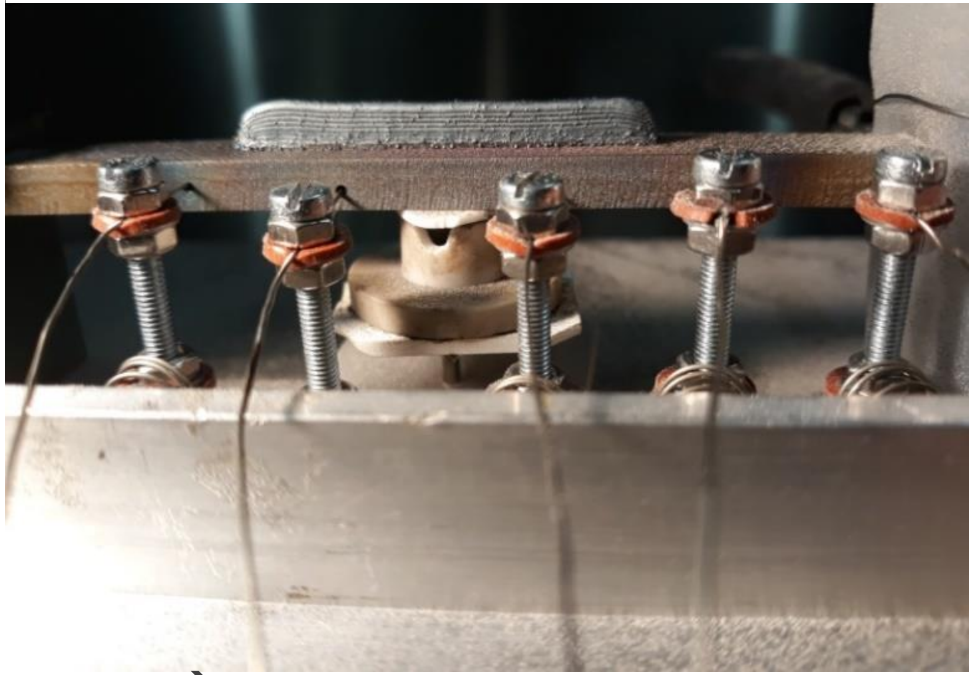
2D Substrate 42crMo4 ≠ than for bulk sample
→Impossible to recover temperature measurements with previous values of conductivity and thermal capacity.

→New measurements
(Previous block for bulk sample in martensite state, current bars in Pearlitic state)

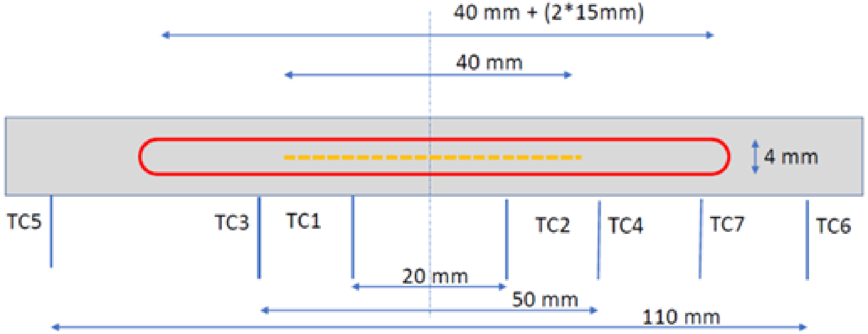
target measured Tp° history

Simulations untill 5th layer
Convection f(T) constant value not OK

Thin wall experiments (2) Preheating = 300˚C



→No more crack
→Nearly constant height



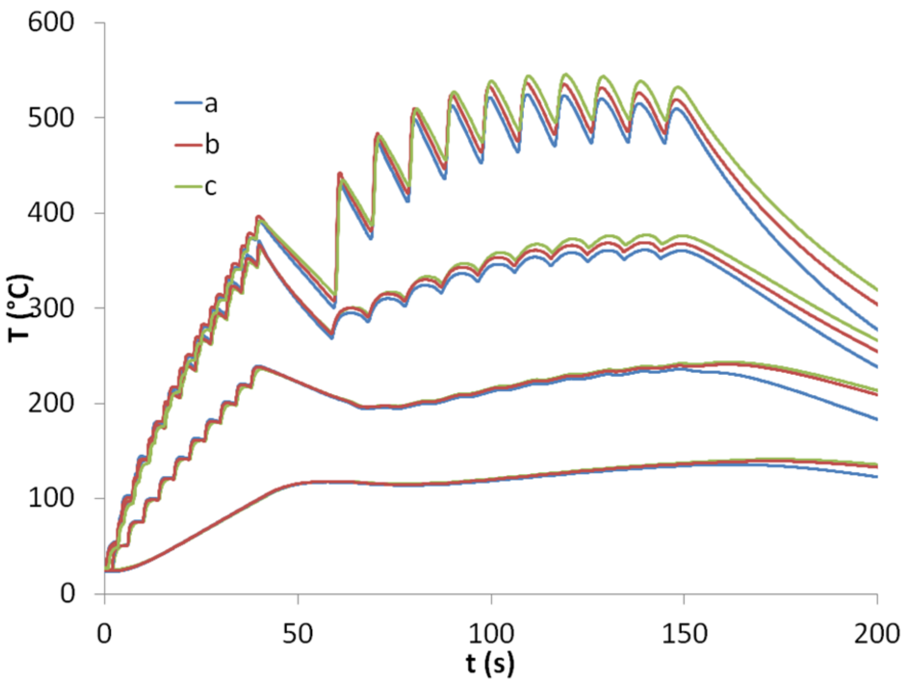
	Substrate pre-heating	Clad deposition
Length of centered laser pass for pre-heating (mm)	70	40
Laser beam speed (mm/s)	41.7	8.3
Laser power (W)	260	600+500=> 400
Temperature at thermocouple P1 at preheating end and at cladding start in °C	400	310
Number of laser passes	20	10

Pre heating at 300˚C

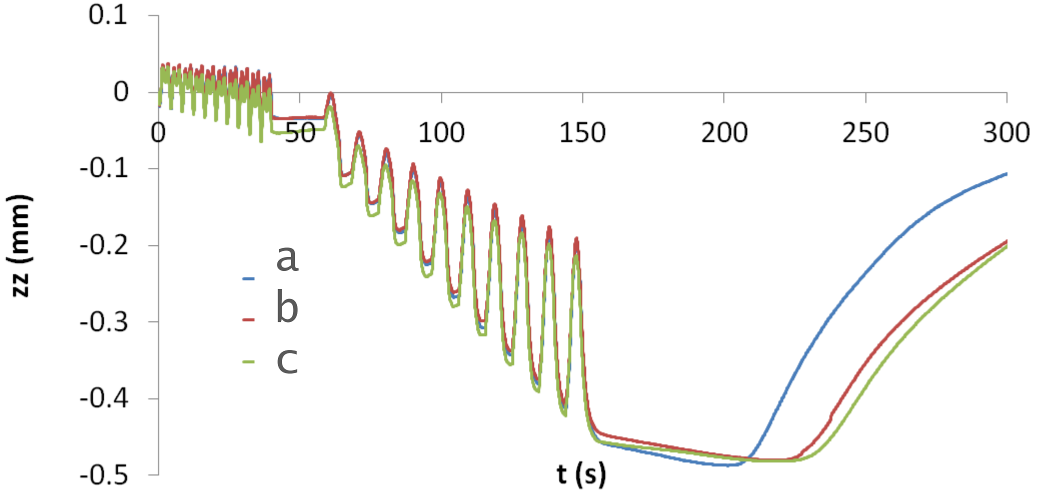
Thin wall experiments (2)

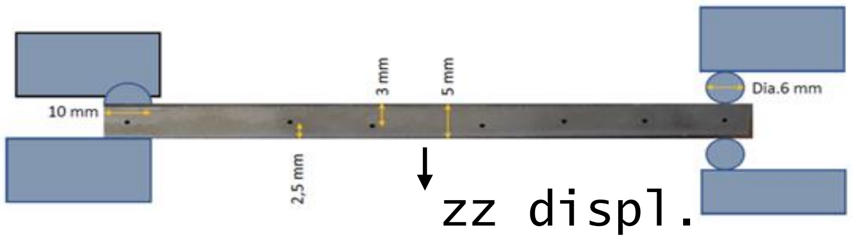
3 Experiments with similar conditions 10 layers without crack

Temperature history



Vertical displacement at the middle

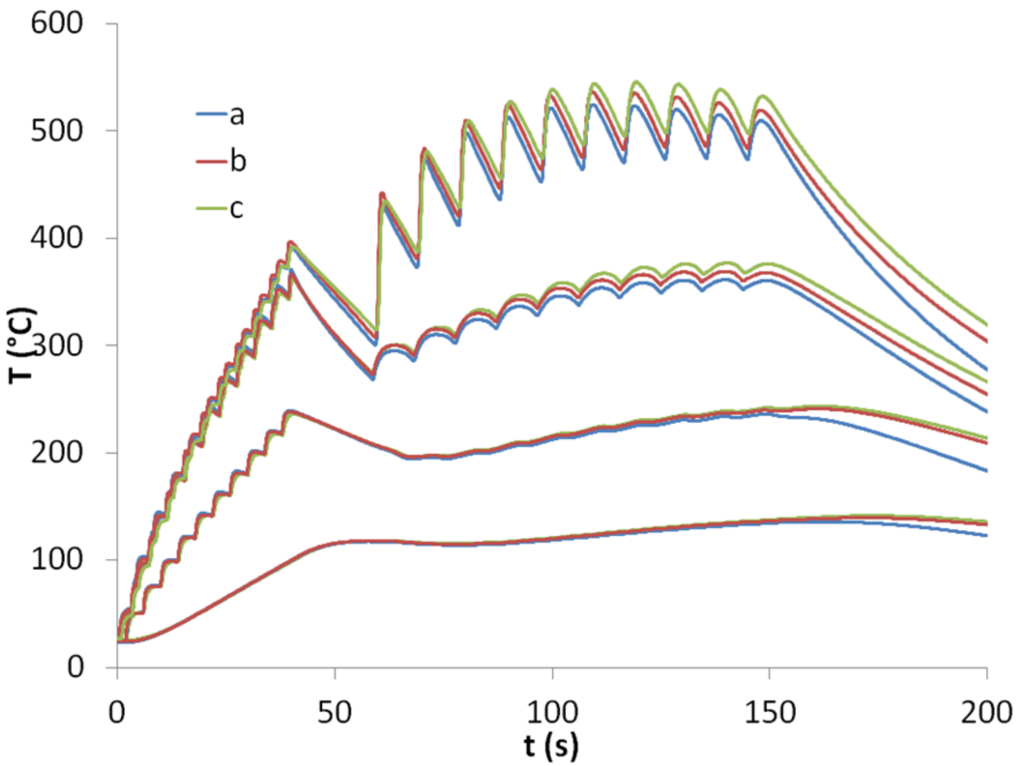


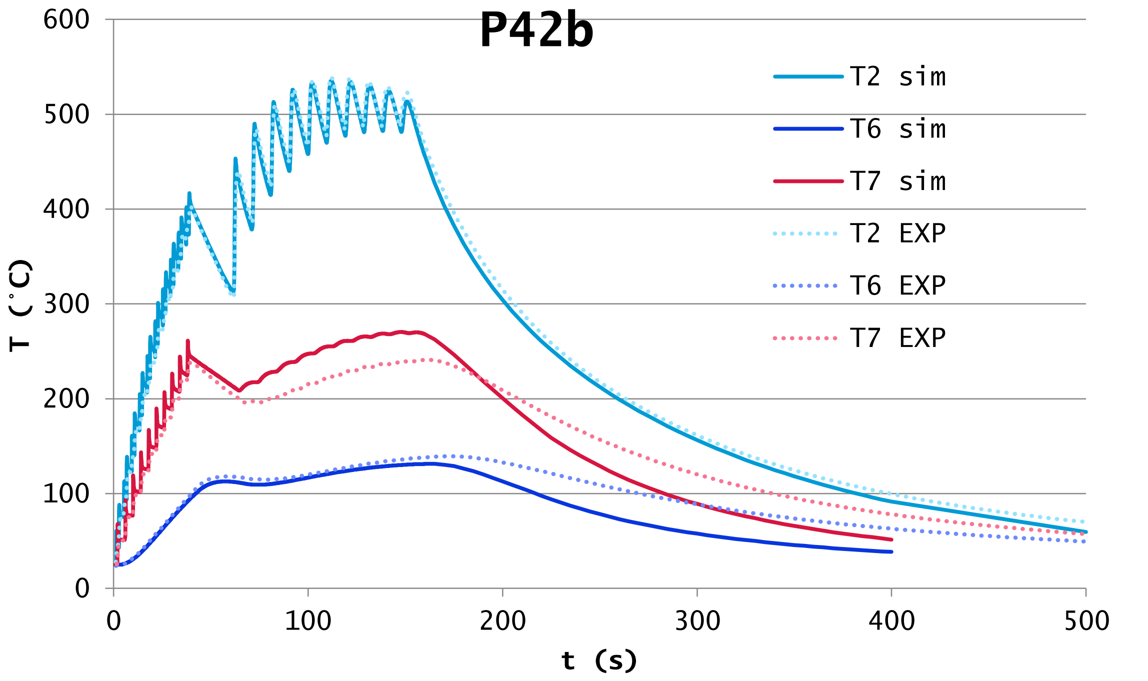


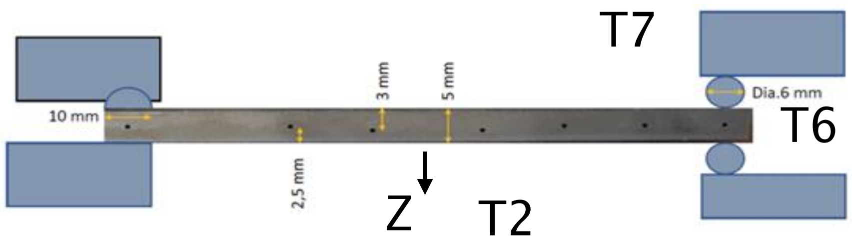
“3D” thin wall thermal simulations

3 Experiments with similar conditions 10 layers without crack

Measured Temperature history

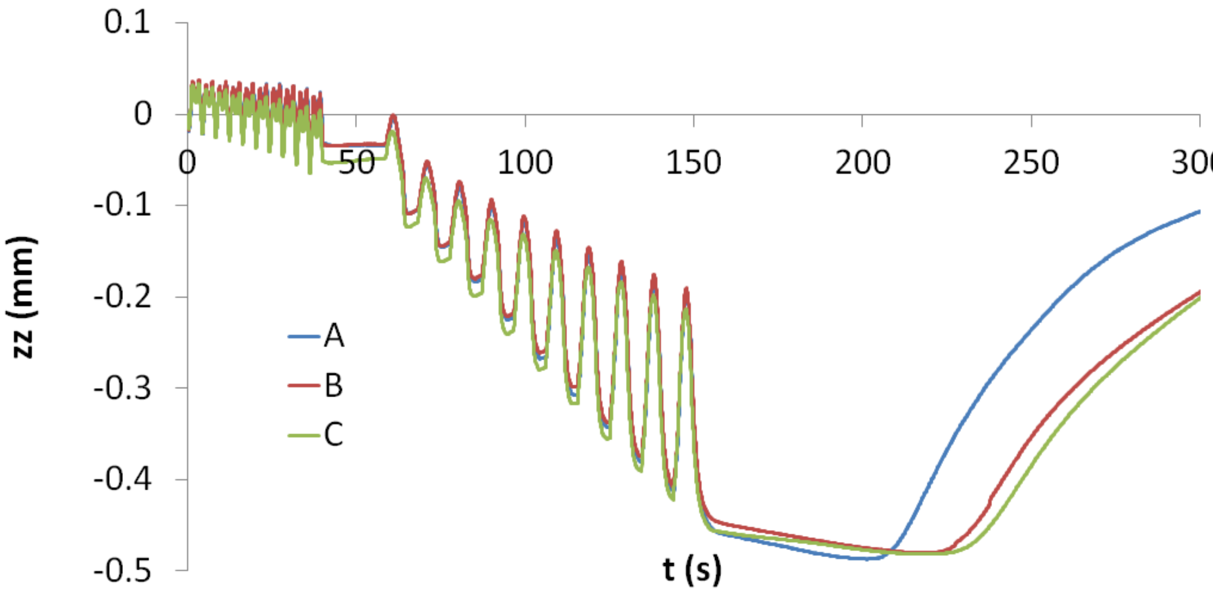


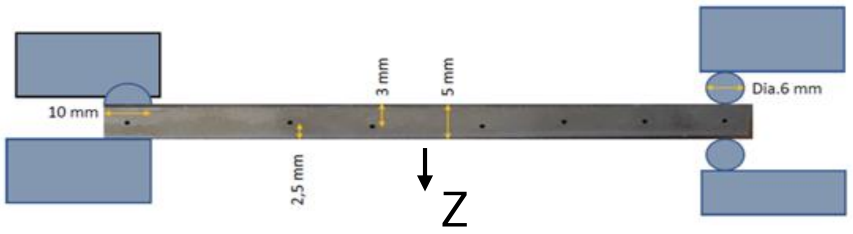




3D FE thin wall thermal simulations

Vertical displacement at the middle





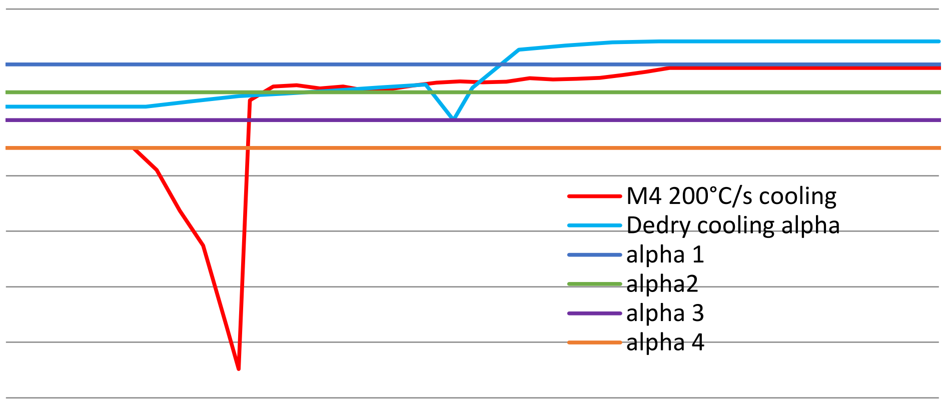
Pre heating curves demonstrated high sensitivity to the right boundary condition TP<500°C so no phase transformation

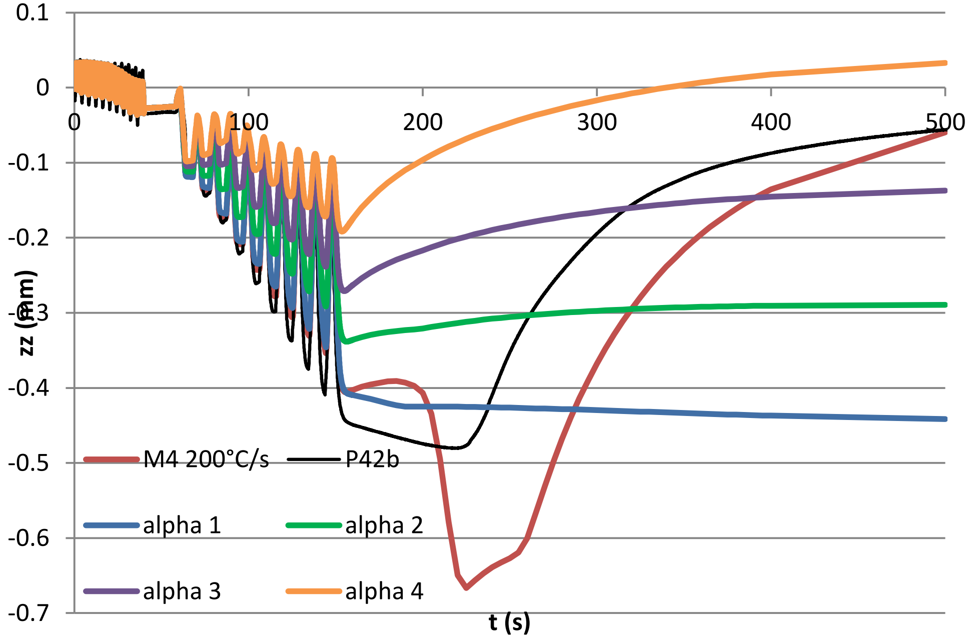
Cladding process:
Low sensitivity to Young modulus
Low sensitivity to hardening curve
Low sensitivity to elastic limit

High sensitivity to different dilatation coefficient of the substrate and the clad (but clad measurement based on bulk simples with different microstructure→ wrong values)

“3D” thin wall simulations

Idea of dilatation coefficients





High sensitivity to different dilatation coefficients of the substrate and the clad

clad property measured on material from bulk samples (→different microstructures, carbides)

-literature on close composition at higher cooling rate
-extrapolation… as first transformation modifies composition

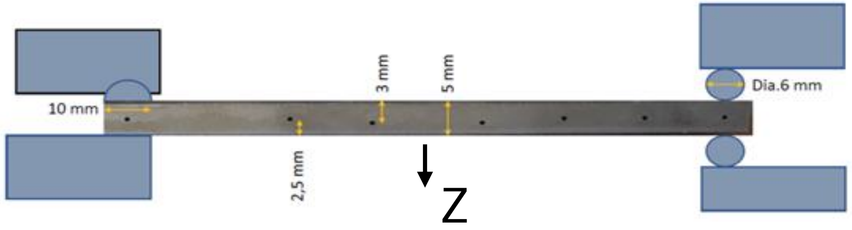
… a nightmare…

3D FE thin wall thermal simulations

Next steps

Shift martensitic transformation to end thermal validation

Work on the stress validation



Why is AISI M4 case
so challenging?

Phase transformation define the behavior

More fundamental knowledge should be known before trying to model the mechanical behavior

Why is AISI M4 case
so interesting?

Good properties + goal for model coupling approaches

Thank you for attendance

Anne Marie Habraken

anne.habraken@uliege.be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