Thermo-Mechanical laser cladding simulations of M4 High Speed Steel

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Material High Speed Steel 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, cylinders for hot rolling mills, molds...

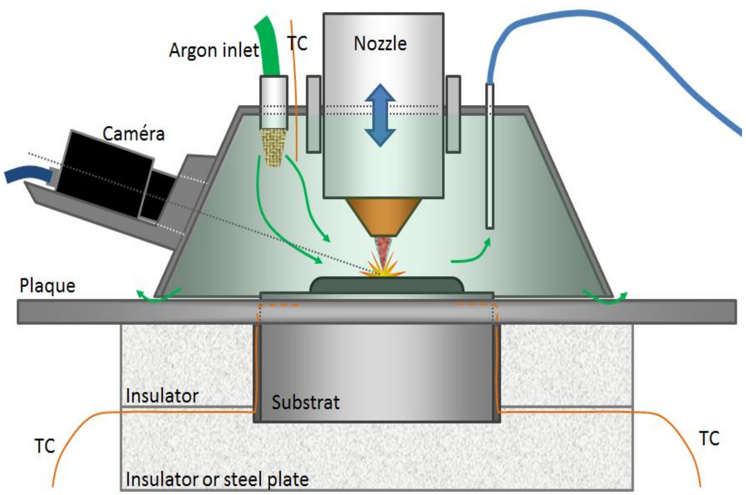
Towards a thermo- mechanical validated model

For High Speed Steel (M4 grade) wt%

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

Particle size [50 to 150 µm]

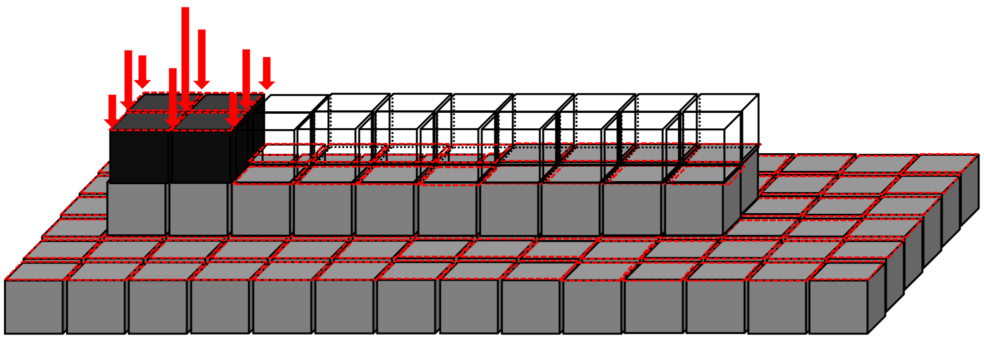
Direct Energy Deposition DED process



Content

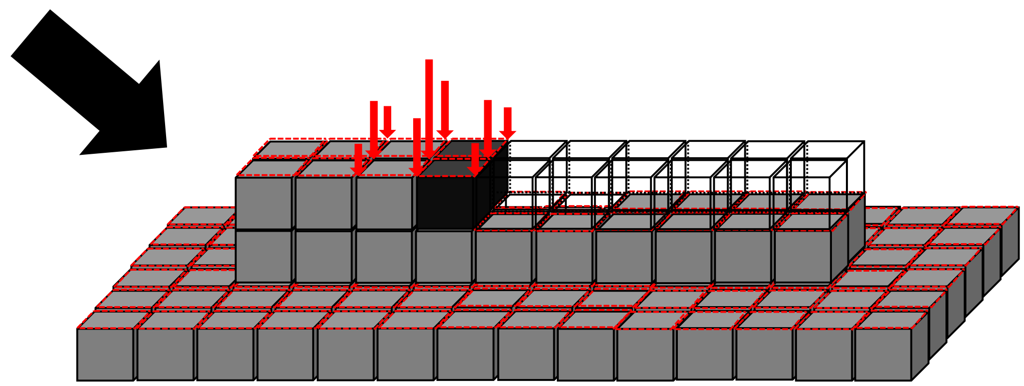
- FE code Lagamine
- Bulk experiments
- 2D thermal simulations
- Thin wall experiments
- 3D thermo-mechanical simulations
- Conclusion

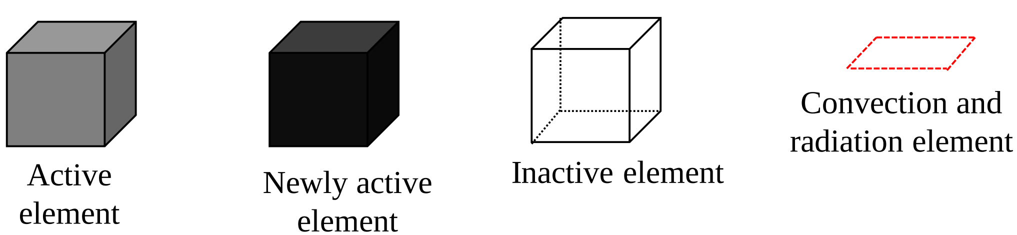
Element birth technique



For a thin wall 3D

Bulk Sample 2D

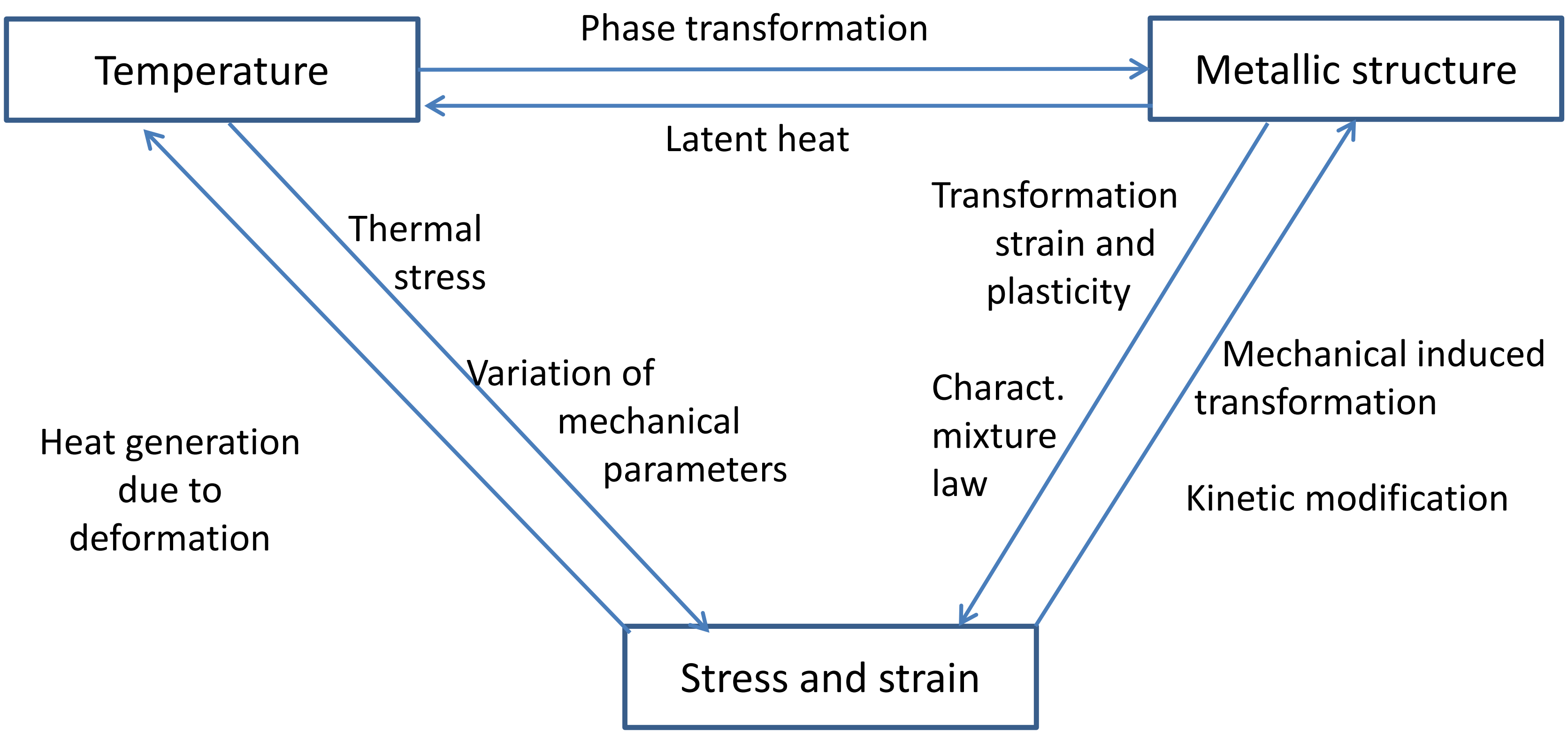




convection-radiation elem. on vertical planes of the clad not drawn

Lagamine FE code
Coupled thermo metallurgic mechanical

Coupled thermo mechanical metallurgical analysis during the cooling process of steel pieces
(A.M.Habraken, M. Bourdouxhe, Eur.J. Mec A/Solids 11 (1992)



Mechanical equations

$$\underline{\underline{\dot{\varepsilon}}} = \underline{\underline{\dot{\varepsilon}}}^{e} + \underline{\underline{\dot{\varepsilon}}}^{p} + \underline{\underline{\dot{\varepsilon}}}^{th} + \underline{\underline{\dot{\varepsilon}}}^{tr} + \underline{\underline{\dot{\varepsilon}}}^{pt}$$

– Elastic strain rate $\underline{\underline{\dot{\varepsilon}}}^{e}$

– Plastic strain rate $\underline{\underline{\dot{\varepsilon}}}^{p}$

– Thermal dilatation rate $\underline{\underline{\dot{\varepsilon}}}^{th}$

– Transformation dilatation rate $\underline{\underline{\dot{\varepsilon}}}^{tr}$

– Transformation plasticity strain rate $\underline{\underline{\dot{\varepsilon}}}^{pt}$

Prediction of temperature, stress, strain + y_i volume phase fraction
Martensite: Koistingen- Marburger
Diffusion transformation: Johnson-Mehl-Avrami → **Difficulty = input data**

Transformations described by TTT + additive principle → FE code able to predict CCT
Non equilibrium state → Threshold temperature, kinetic of transfo f(tp° rate)
Advanced work in TA6V (Master thesis Elena Esteva 2018) not ready for M4

Thermal equations

Heat transfer per conduction

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q_{\text{int}}=\rho c_p\frac{\partial T}{\partial t}$$

Conductivity

Volume energy

Density

Heat Capacity

Heat transfer per convection and radiation

$$-K.(\nabla T.n)=-h(T-T_0)-\varepsilon\sigma(T^4-T_0^4)$$

Convection Coef.

Emissivity

Stefan-Boltzmann Constant

Melting latent Heat

$$C_p{}^{*}=\frac{L_f}{T_{em}-T_{sm}}+C_p$$

Enthalpic formulation

Enthalpy

$$H=\int\rho\cdot c(T)\mathrm{d}T$$

Mechanical equations

– Hooke's law

$$\underline{\underline{\sigma}} = \frac{E(T,y)}{1+\nu(T,y)}\left(\underline{\underline{\varepsilon}}^{e} + \frac{\nu(T,y)}{1-2\nu(T,y)}\mathrm{Tr}(\underline{\underline{\varepsilon}}^{e})\underline{\underline{I}}\right)$$

– Plastic criterion: von Mises

$$f = \frac{3}{2}\underline{\underline{\tilde{\sigma}}} : \underline{\underline{\tilde{\sigma}}} - R^{2}$$

– Hardening law: isotropic (multilinear curve)

$$R = \sigma_{y}(T,y) + E^{p}(T,y)\varepsilon_{eq}^{p} \text{ avec } \varepsilon_{eq}^{p} = \sqrt{\frac{2}{3}\underline{\underline{\varepsilon}}^{p} : \underline{\underline{\varepsilon}}^{p}}$$

– Flow rule: associated plasticity

$$\underline{\underline{\dot{\varepsilon}}}^{p} = \dot{\lambda}\frac{\partial f}{\partial \underline{\underline{\sigma}}}$$

Currently no viscous approach,
Compression tests
at 3 temperatures
3 strain rates
→ NO need

Easy ?

Param. Identification ??

INPUT DATA

Thermo physical parameters
α, ρ, λ, C_p for each phase f(T)

Metallurgical parameters
TTT diagrams
Transformation strain
Plasticity transf strain,
Shift of transformation
Coef of Koist Marburger
Latent heat of transformation

Mechanical parameters
(E, ν, E_t, σ_y for each phase f(T))

FE code

Lagamine

OUTPUT DATA

Stresses
(σ_x , σ_y ,σ_z , σ_{xy})

Strains
(ε_{th}, ε_p, ε_{ph}, ε_{ptr})

Phase rates
(%Fe, %Pe, %Ma)

Analysis of results

VALIDATION ??

M4 Methodology Summary

M4 Microstructure = post-treatment of thermal history
not computed in a a single coupled FE simulation
In FE code : single phase approach
latent heat for phase transformation f(T)
a single dilatation coefficient f(T)

1. Thermal simulations (bulk samples: 2D FE model OK)
Validation by T and microstructure

2. Thermomechanical simulations
(thin wall samples: need 3D FE model)
Validation by T, microstructure and displacement

Validated 2D thermal simulations

In put

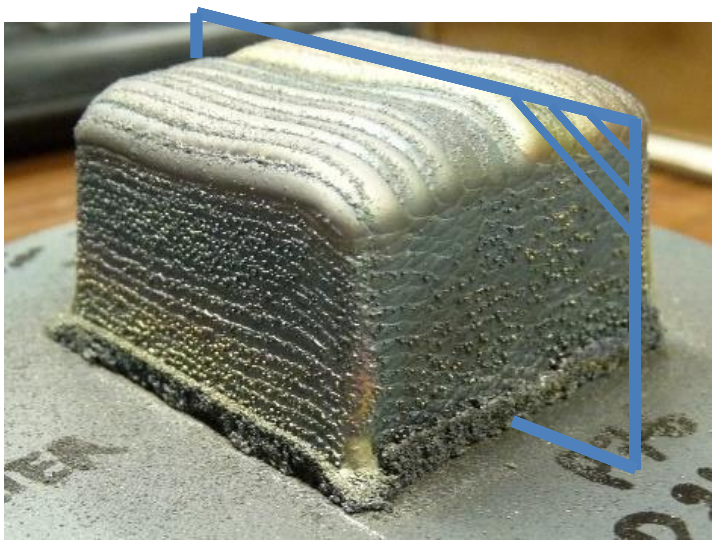
conduction, heat capacity, latent heat
measured on samples extracted
from the clad & the substrate
(DSC, Laser flash, dilatometry)

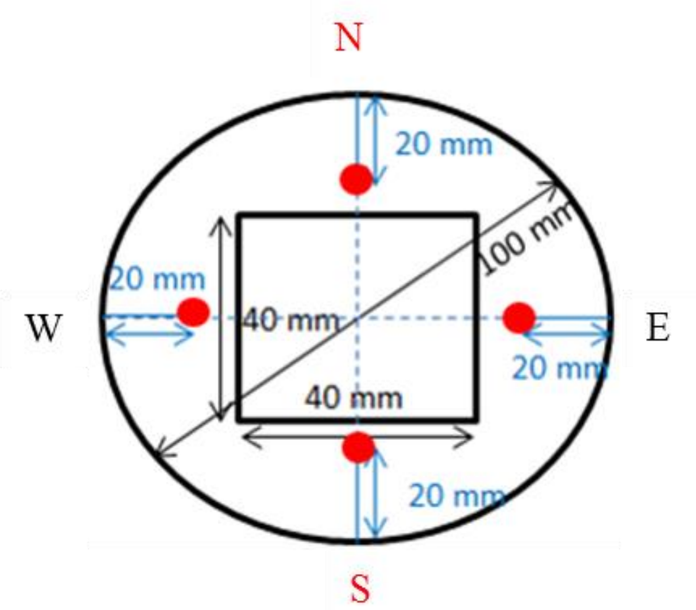
Convection, Radiation, laser absorption
fitted by inverse modelling

Target **BOTH**
Temperature + Melt pool depth measured

"2D" 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



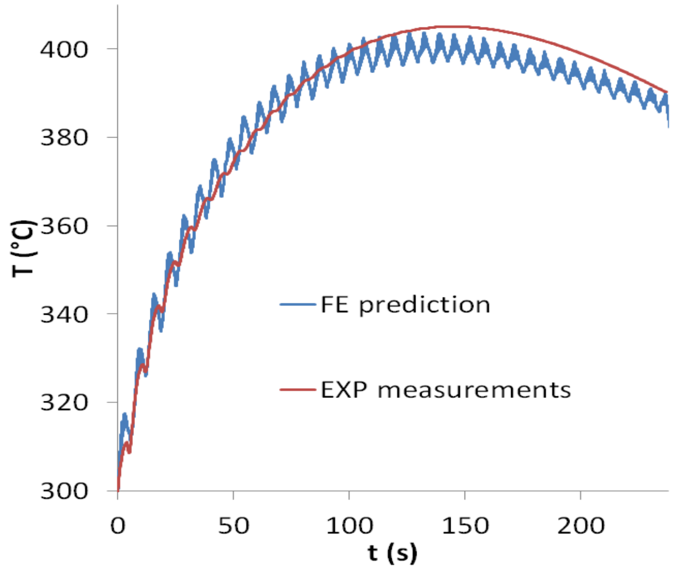


4 Thermocouples
Thermal measurement in the substrate

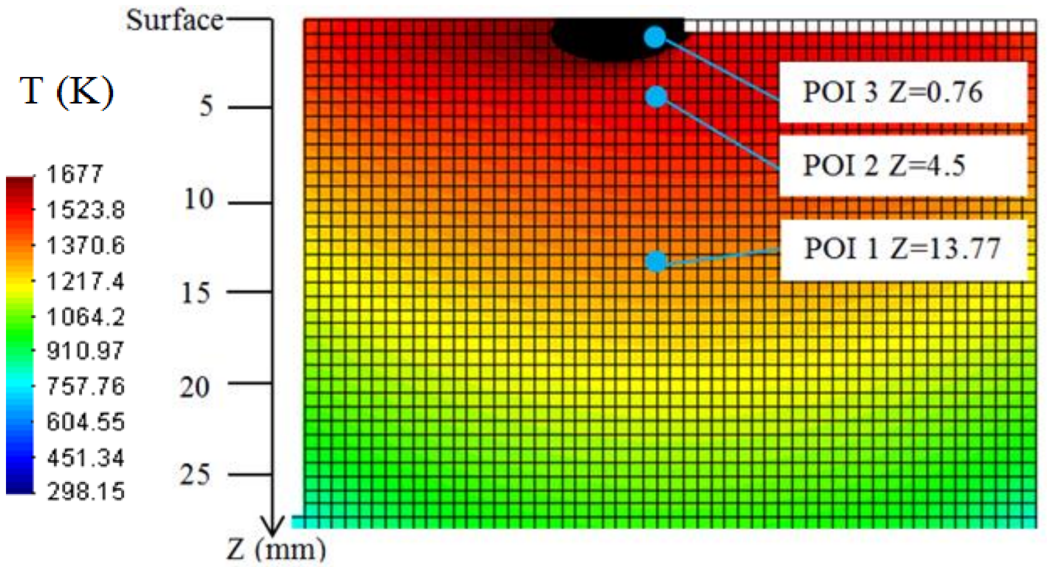
40 x 40 x 27.5 mm **(972 tracks)**

"2D" bulk samples

Tp° in the substrate

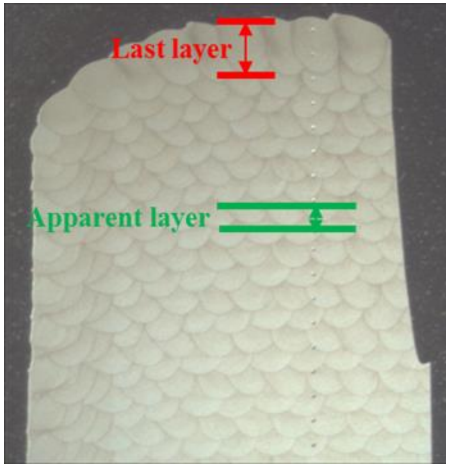


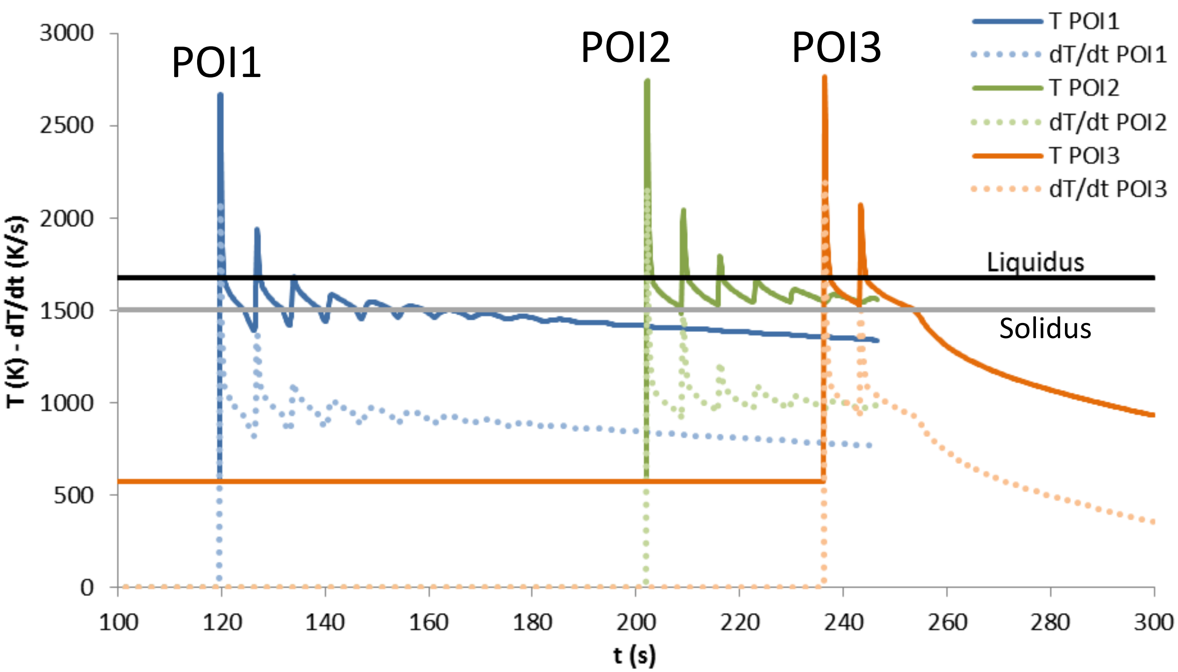
Predicted Tp° in the clad

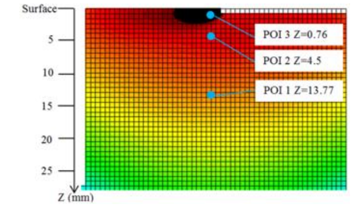


Melt pool depth

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





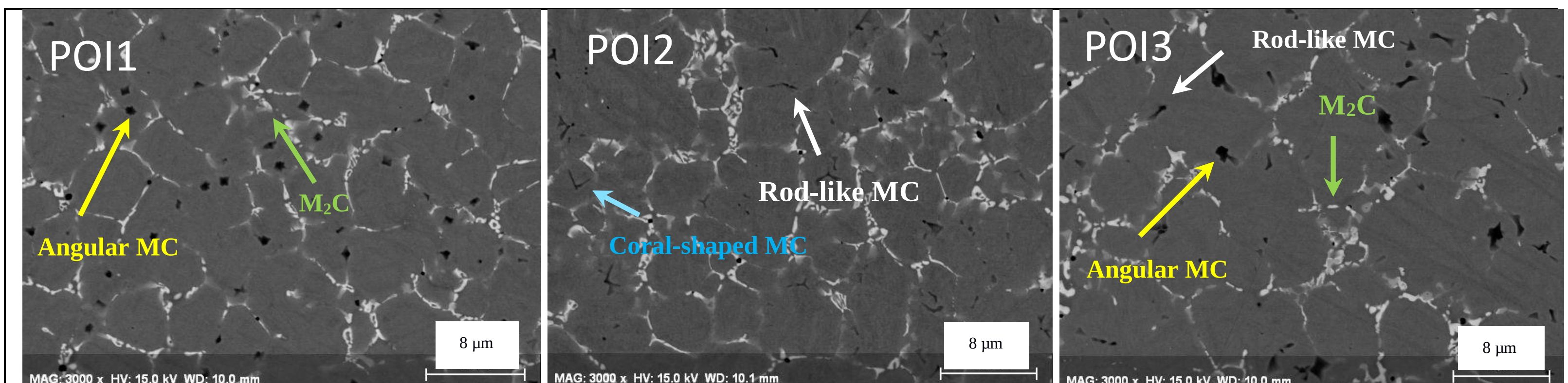


-Number of full partial remelting

-Tp° Level between solidus and liquidus

- Superheating temperature

Jardin R.T., et al. (2019) Materials Letters. 236:42-45

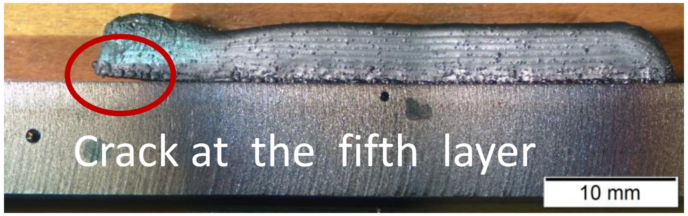


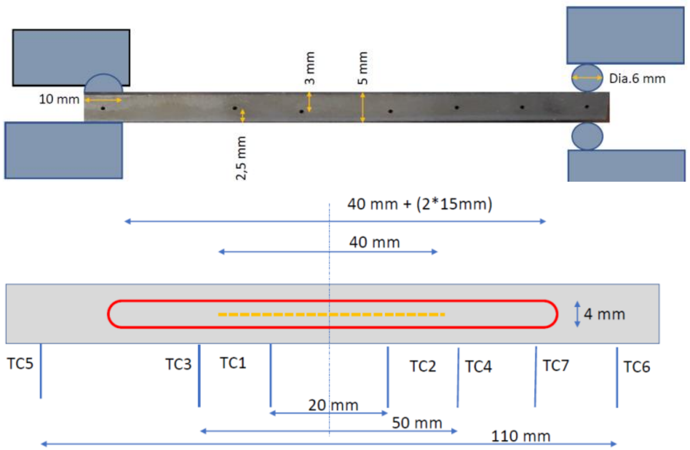
a) star-like MC and lamellar eutectic M_2C intercellular carbides

b) coral-shaped intracellular MC, intercellular eutectic M_2C and refined cells due to multiple melting

c) coarse angular MC and eutectic M_2C within intercellular zones

“3D” thin wall experiments



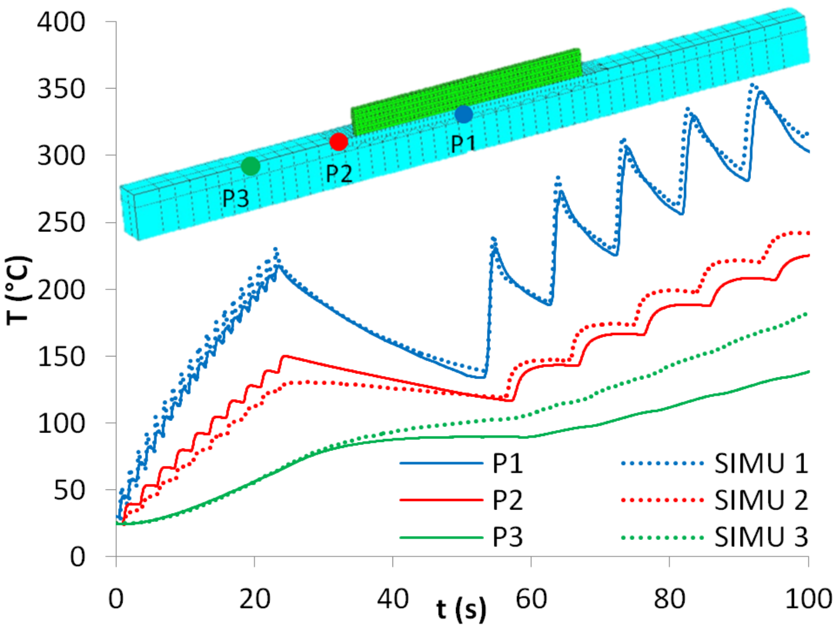


Preheating reached = 150°C

	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 P1 at preheating end and at cladding start in °C	217	134
Number of laser passes	20	10

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

“3D” thermal analysis - thin walls



Simulations until 5^{th} layer
Convection needs to be function of T
Constant value not OK

Previous measured thermophysical parameters for the clad

Substrate 42crMo4
different origin than for bulk sample

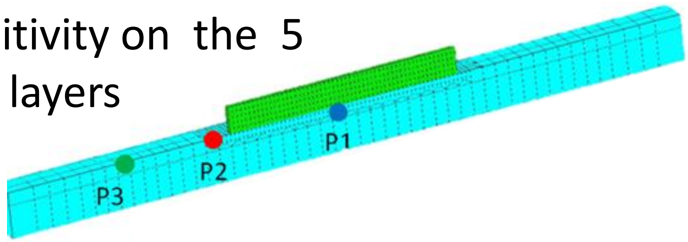
→ Impossible to recover temperature measurements with previous values of conductivity and thermal capacity.

→ New measurements indeed showed different results for conductivity and heat capacity

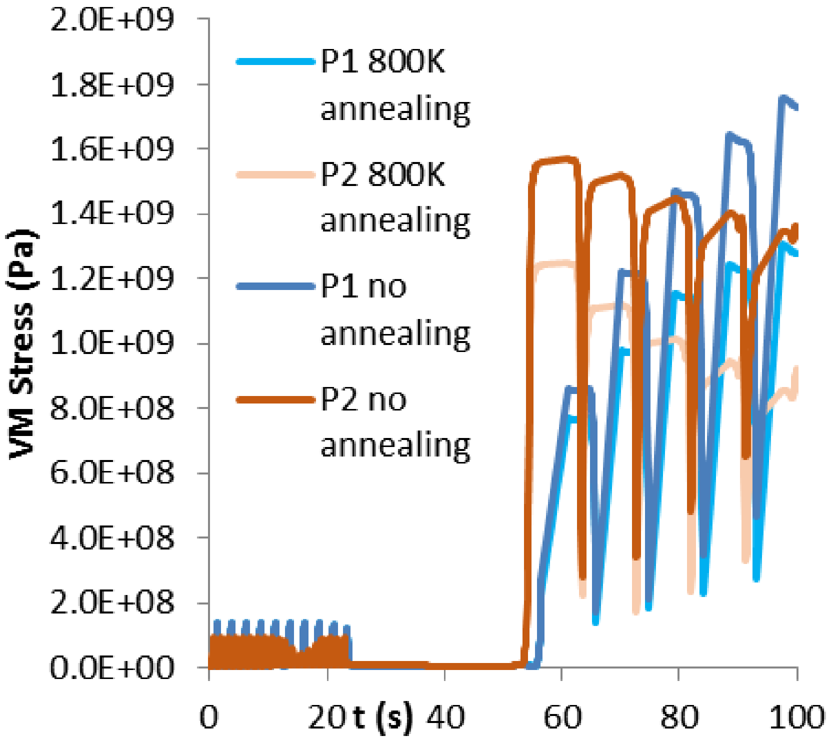
(Previous block for bulk sample in martensite state, current bars in Pearlitic state)

“3D” thermo-mechanical data analysis - thin walls

Sensitivity on the 5 first layers

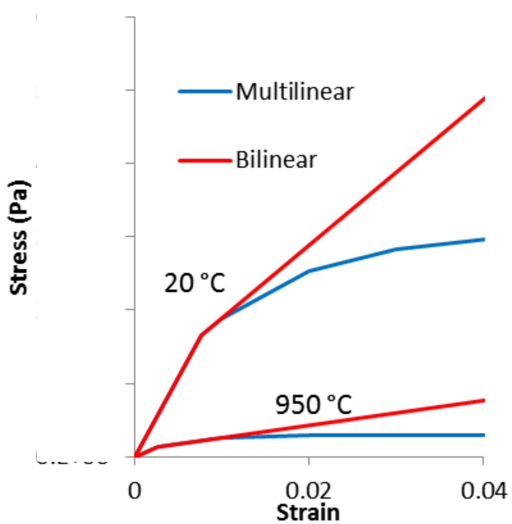


Numerical annealing temperature:
plastic strain if forgotten if tp° decreases below this annealing tp°

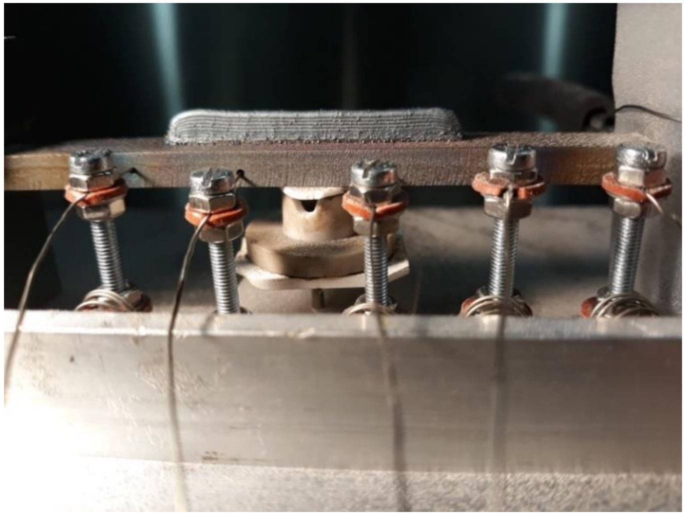


Results for bilinear stress-strain curves

Far Less sensitive for multi linerar curves



“3D” thin wall experiments



No more crack
Nearly constant height

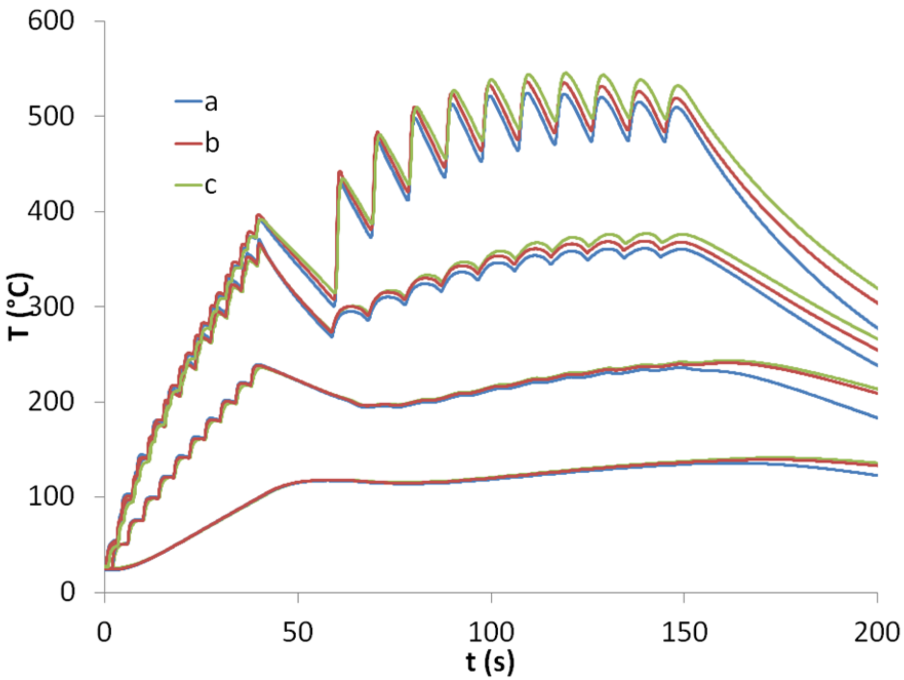
	Substrate pre-heating	Clad deposition
Length of centered laser pass for pre-heating (mm)	70	40
Laser beam speed (mm/s)	41.7	8.3
Laser power (W)	260	600+500=> 400
Temperature at thermocouple P1 at preheating end and at cladding start in °C	400	310
Number of laser passes	20	10

Pre heating at 300°C

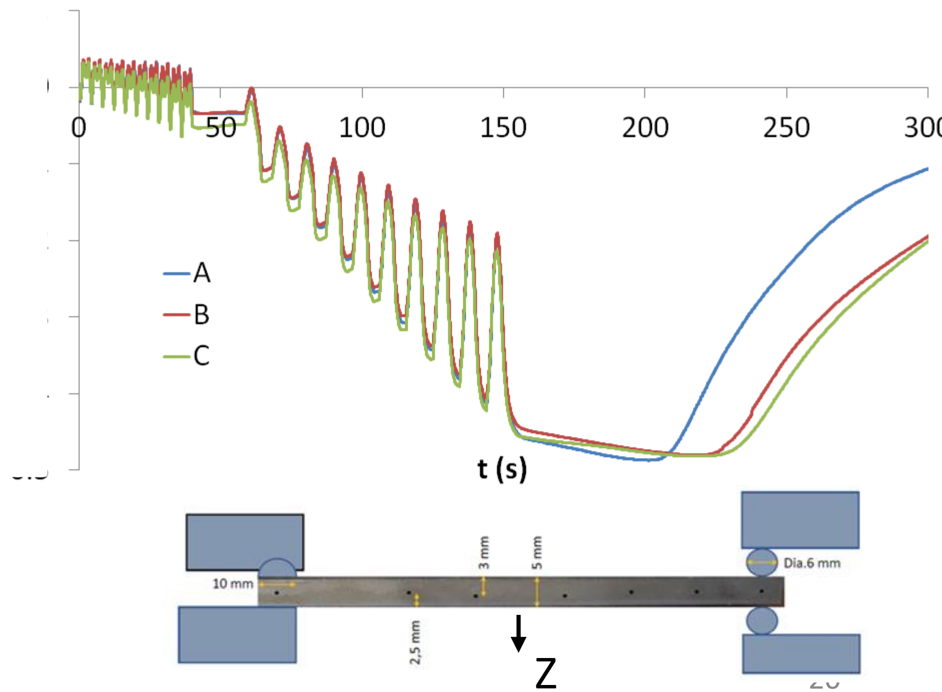
“3D” thin wall experiments

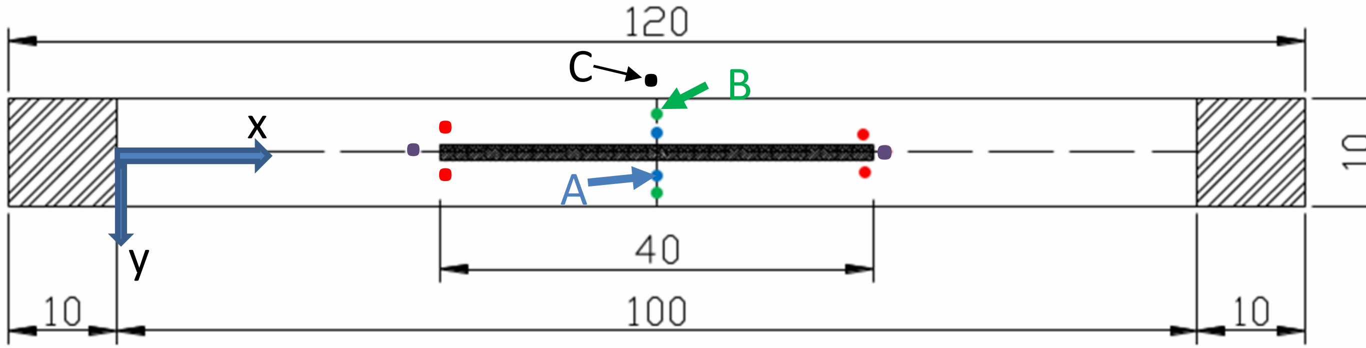
3 Experiments with similar conditions

Temperature history



Vertical displacement at the middle





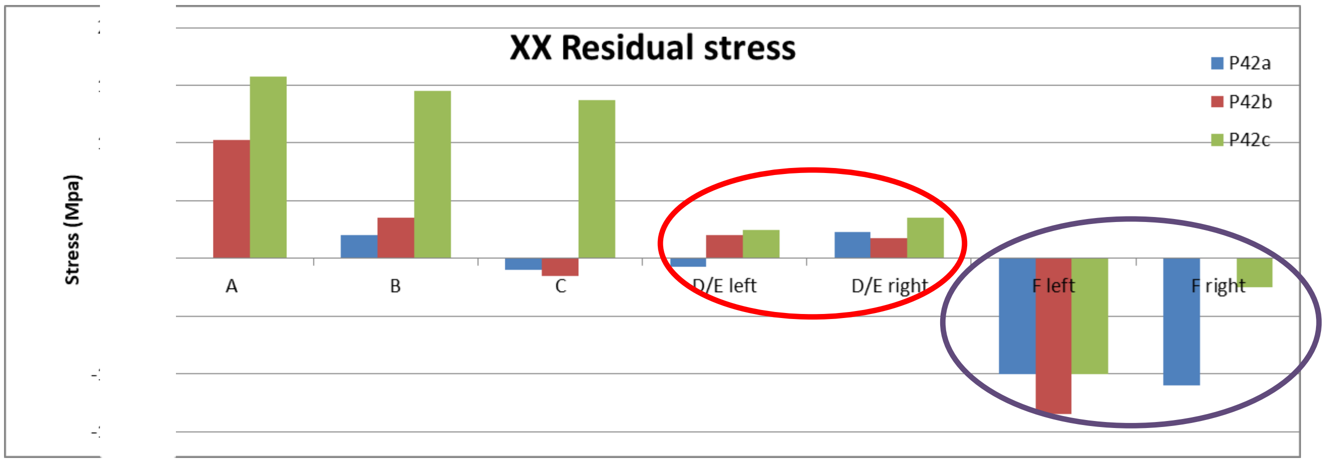
In the middle of the sample

A= 2,5 mmm

B= 3.5

C= 4.5

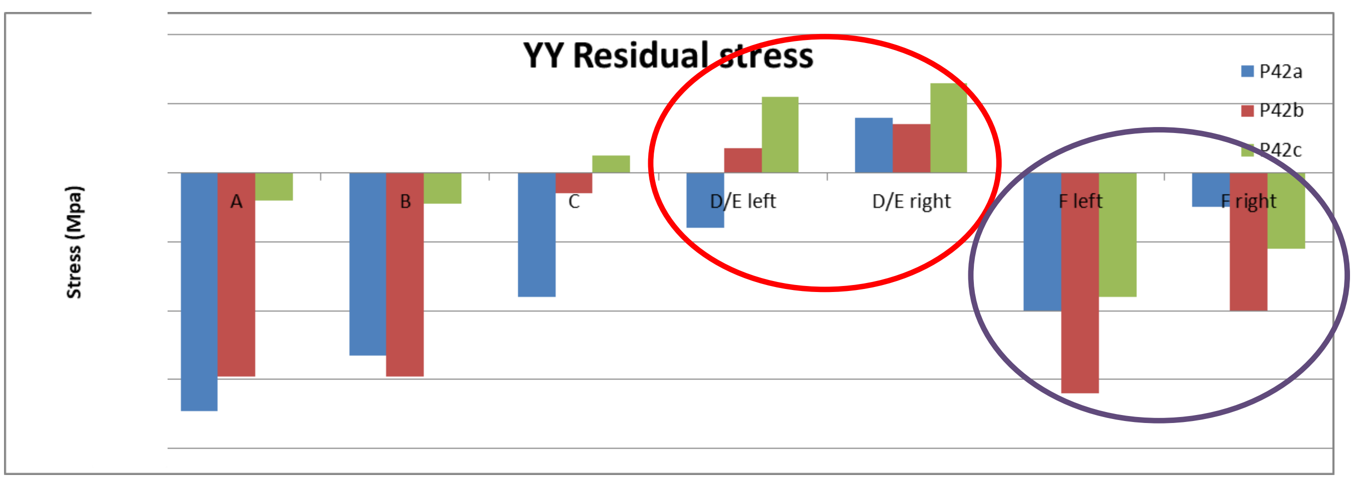
Average good reproducibility



At the edge 2.5 mm

D E left or right

F Left or right

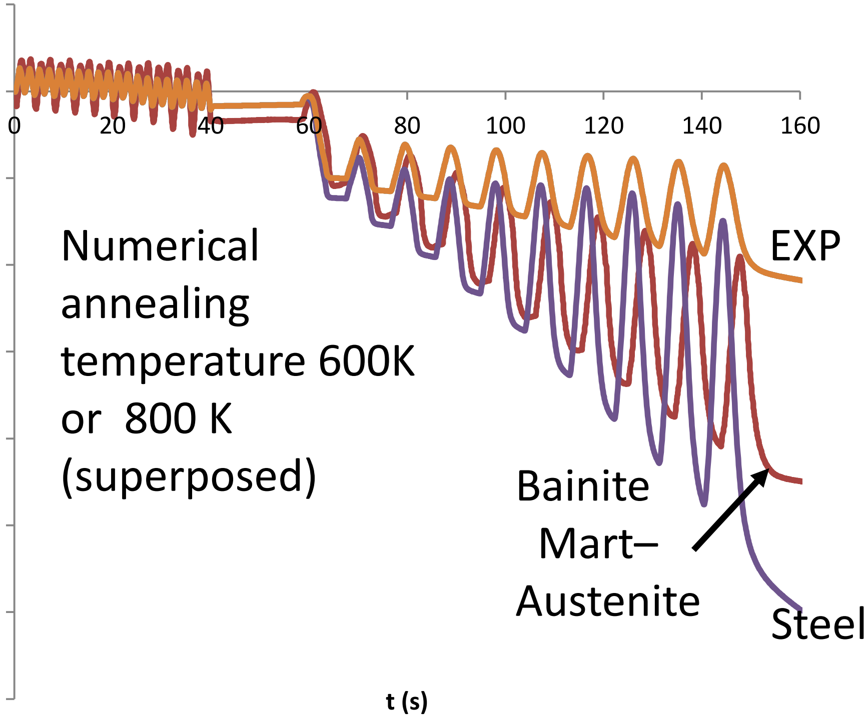


Thermal history

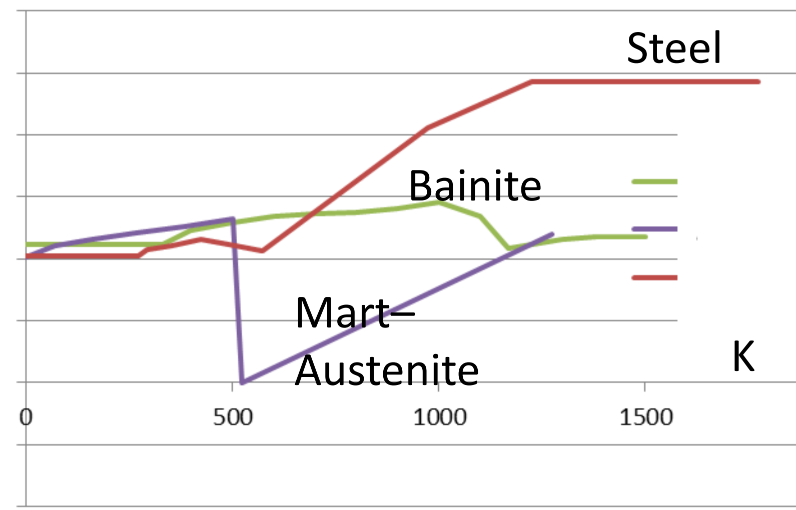
Sample a always a little cooler.

Samples b, c close

"3D" thermo-mechanical data analysis - thin walls - validation?



Dilatation coefficient



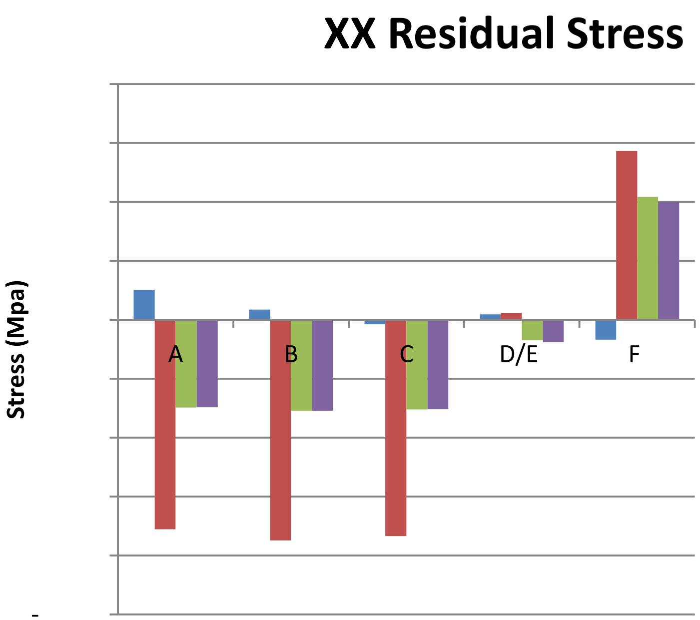
No effect of annealing temperature

Detailed dilatation coef of the clad: Bainite // Mart-Aust → similar value

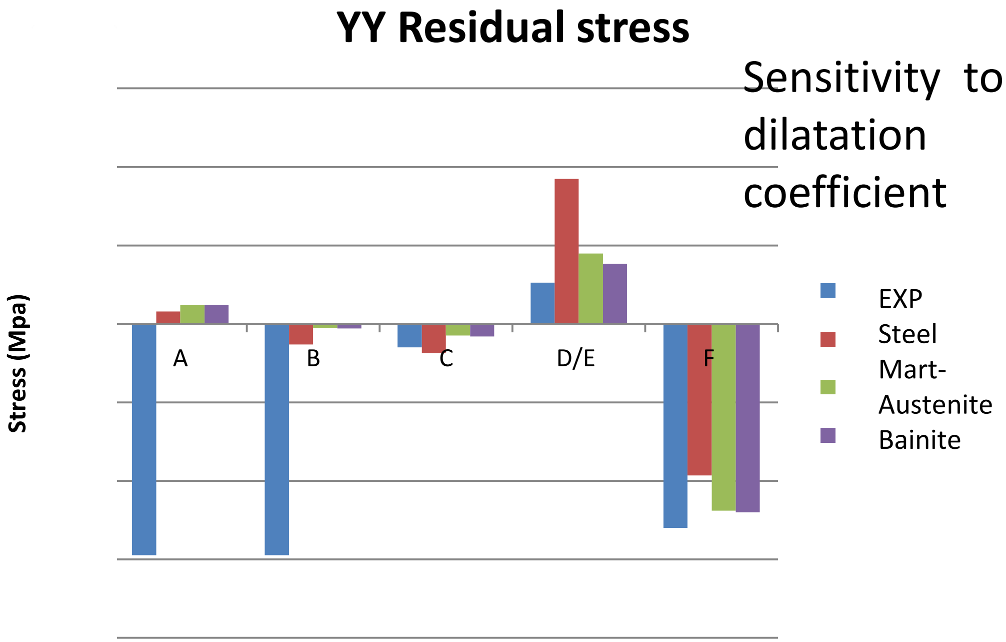
closer to experiment than "steel data'" but still far from validation

→ To be checked dilatation of substrate…

"3D" thermo-mechanical data analysis - thin walls - validation?



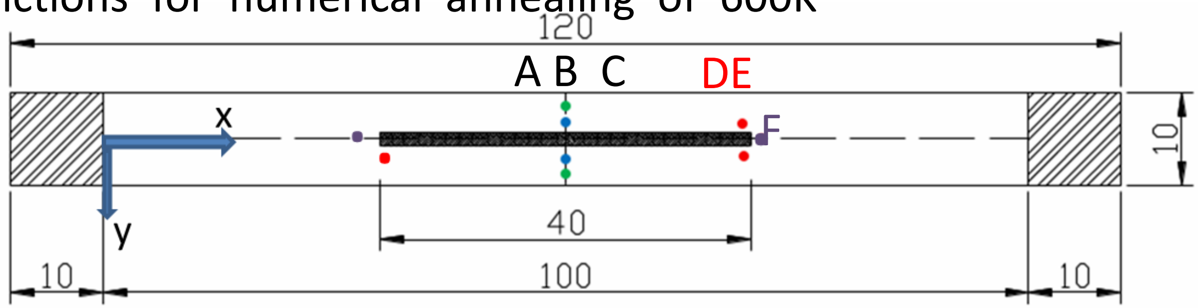
No consistency with experiment b



Sensitivity to dilatation coefficient

More consistency with experiment b

Predictions for numerical annealing of 600K



Iso value and gradients should be studied

Effect of substrate dilatation coefficient should be checked

Conclusions - Perspectives

FE thermo-mechanical model available,
without activation of the phenomenological phase transformation model
Trials to model solid latent heat and dilatation effect at correct time

Annealing temperature effect depends on the shape of hardening curves
No effect on prediction of residual stress or displacement for the correct stress-strain curves

Validation by temperature, melt pool size, displacement, residual stress, microstructure
not yet reached…

X Ray measurements provide quite scattered data
Complex microstructure justifies scattering + Laser cladding experiment repeatability

Additional way :
Different experimental conditions
crack and no cracks cases + hot rupture value: another FE validation method