Numerical Analysis of Thermal Stress in Laser Cladding Technology of M4 High Speed Steel

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NUMIFORM Portsmouth
USA June 23-29, 2019

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...



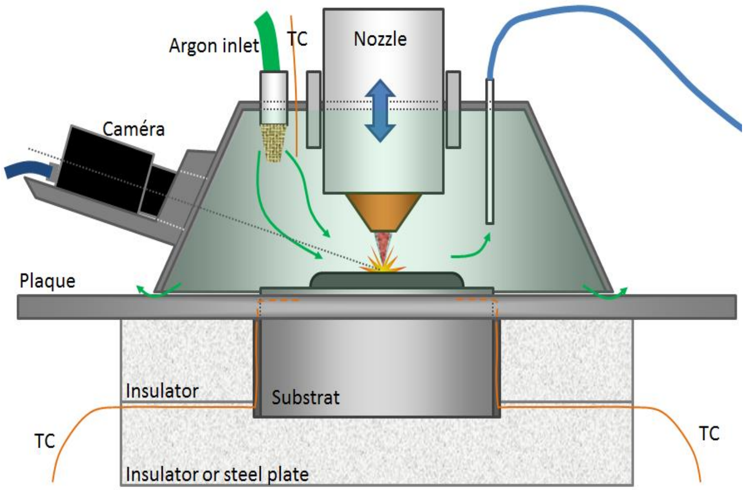
Towards a thermo- mechanical validated model

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

- In house FE code « Lagamine »

- Bulk experiments

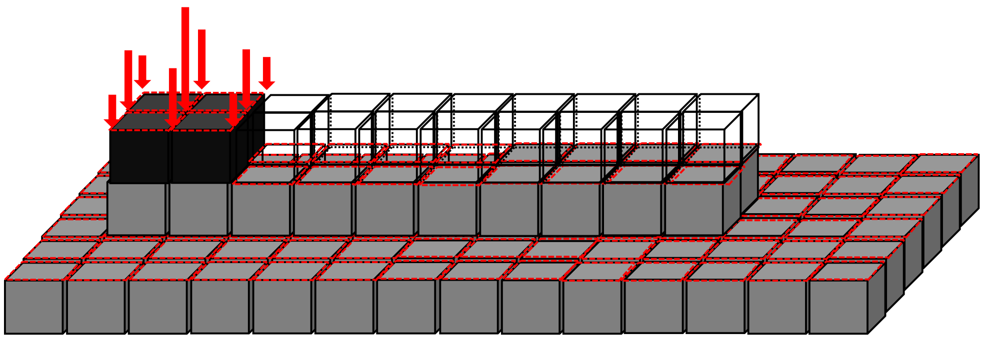
2D thermal simulations

- Thin wall experiments

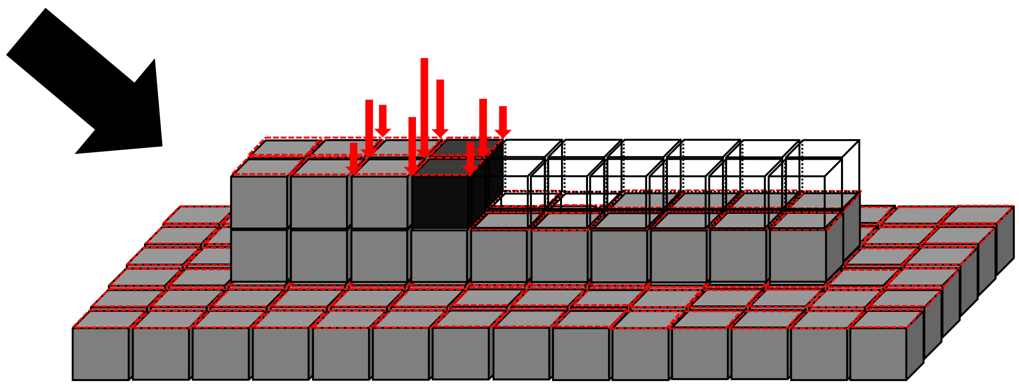
3D thermo-mechanical simulations

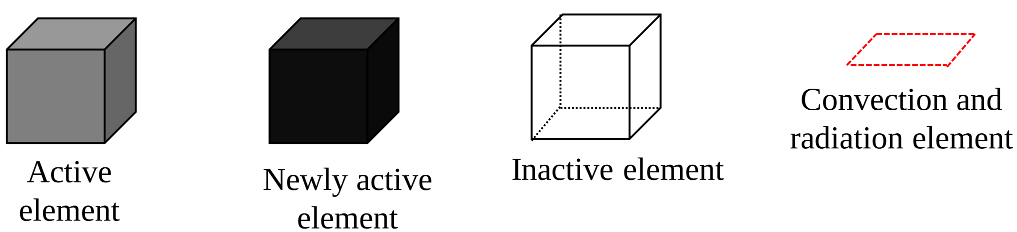
- Conclusions - Perspectives

Element birth technique



For a thin wall 3D
Bulk Sample 2D





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

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

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

– Plastic criterion: von Mises and associated plasticity

$$f = \frac{3}{2}\underline{\underline{\tilde{\sigma}}} : \underline{\underline{\tilde{\sigma}}} - R^{2} \qquad \dot{\underline{\underline{\varepsilon}}}^{p} = \dot{\lambda}\frac{\partial f}{\partial \underline{\underline{\sigma}}}$$

– Hardening law: isotropic (multilinear curve)

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

Compression tests at 3 temperatures and 3 different strain rates
→ NO need viscous approach

Model identification phase

In put material data

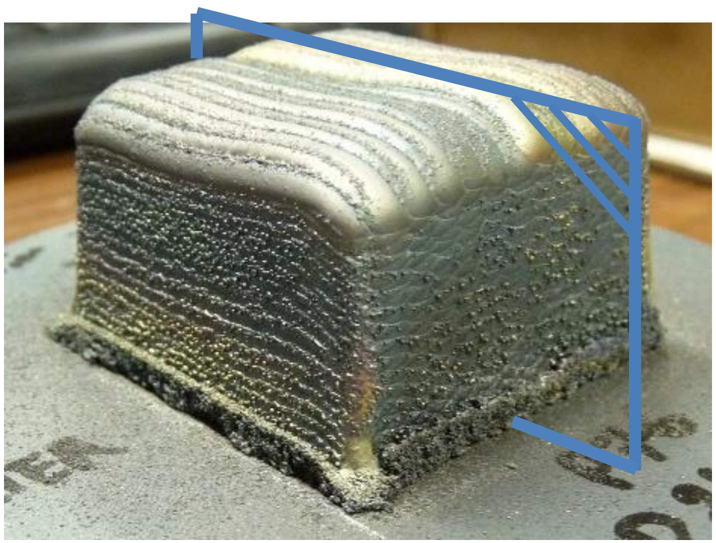
conduction, heat capacity, latent heat
measured on samples extracted
from the clad & the substrate
(DSC, Laser flash, dilatometry)

Convection, Radiation, laser absorption
fitted by inverse modelling

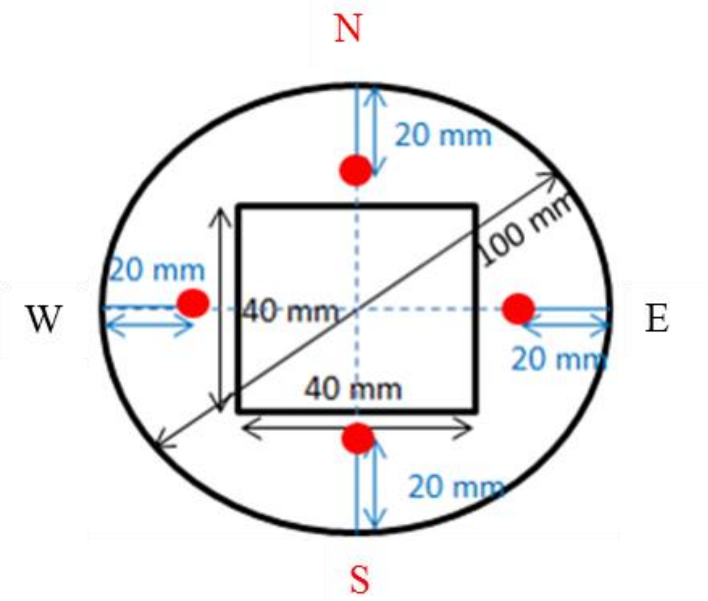
Target **BOTH**
Temperature + Melt pool depth measured

"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



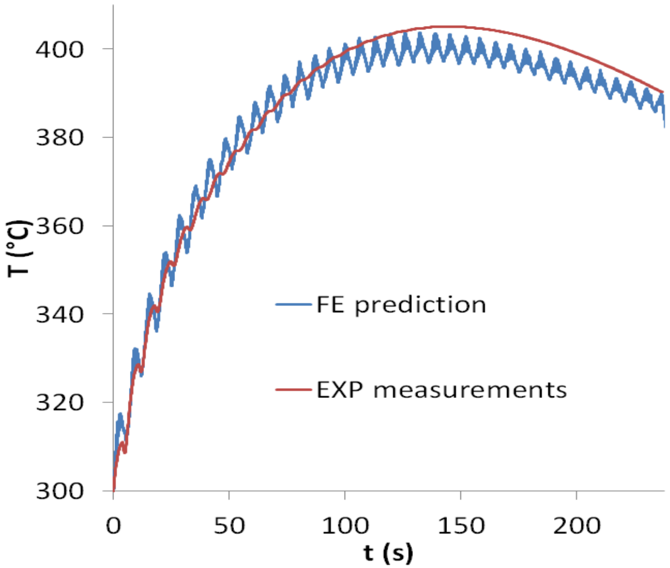
40 x 40 x 27.5 mm **(972 tracks)**



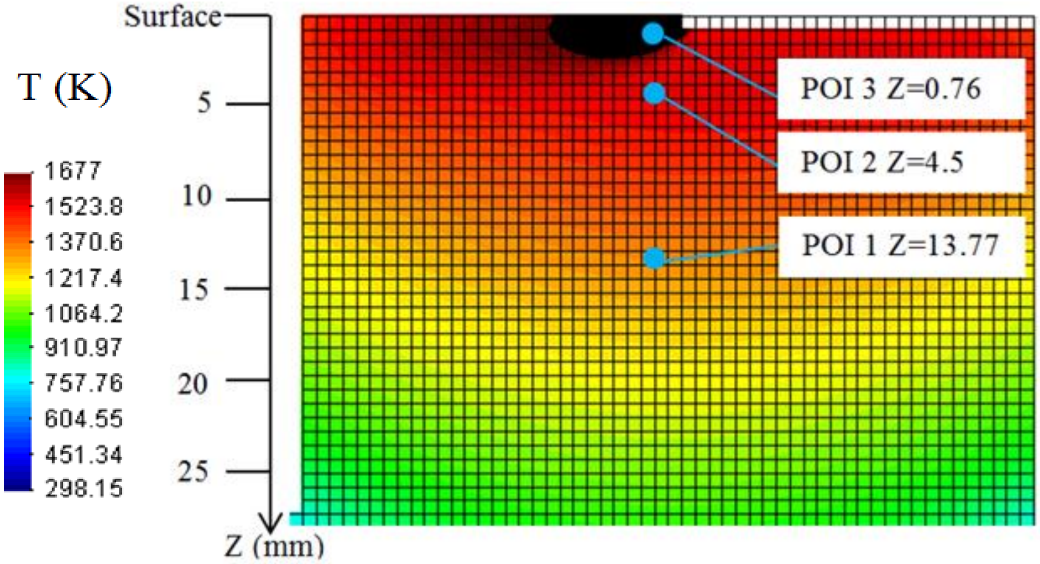
4 Thermocouples
Thermal measurement in the substrate

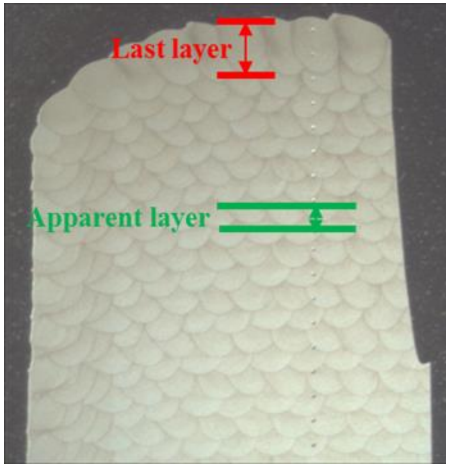
“2D” bulk samples

Tp° in the substrate



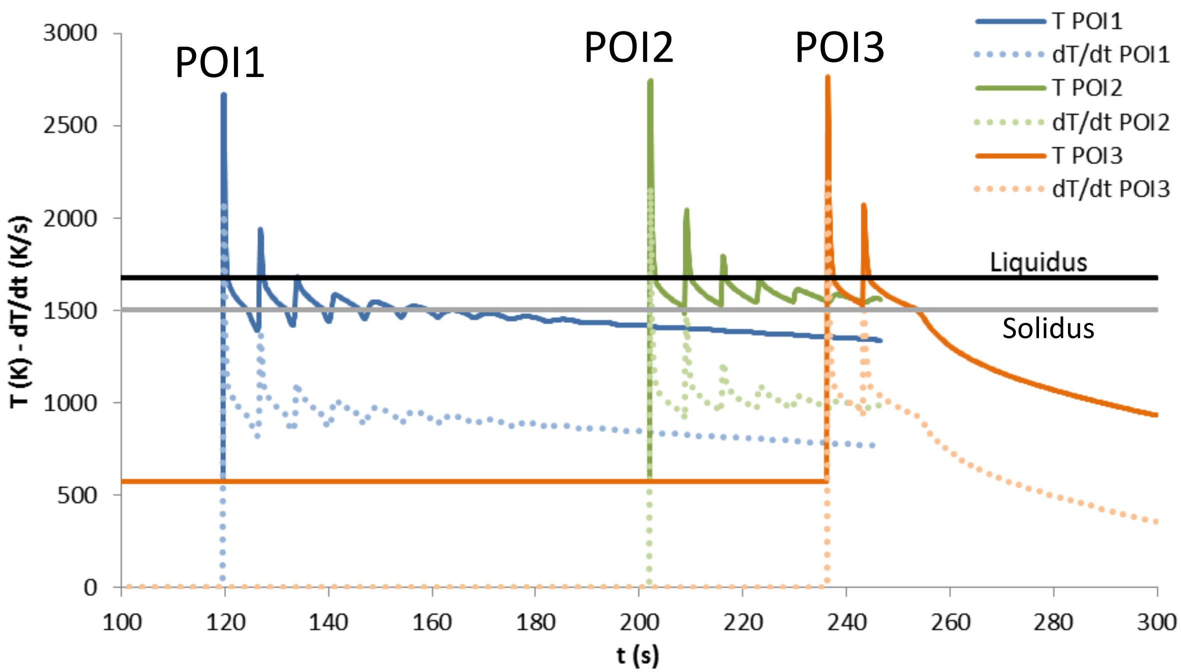
Predicted Tp° in the clad

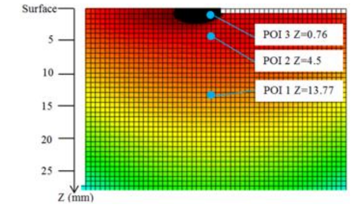




Melt pool depth

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



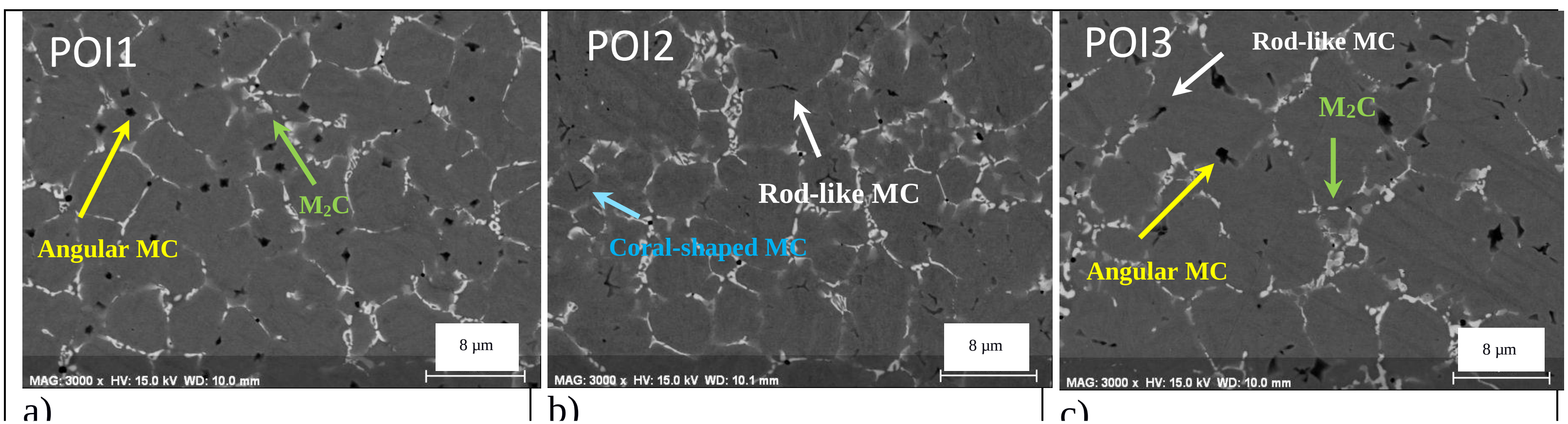


-Number of full partial remelting

-Tp° Level between solidus and liquidus

- Superheating temperature

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

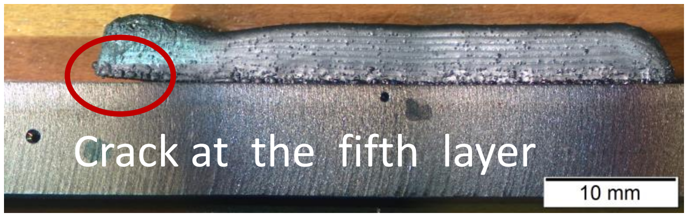


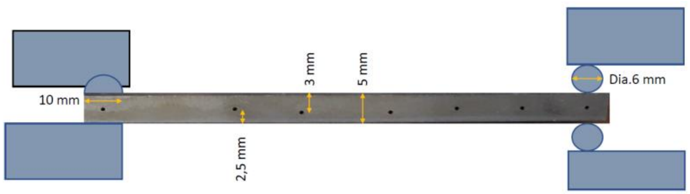
star-like MC and lamellar eutectic M_2C intercellular carbides

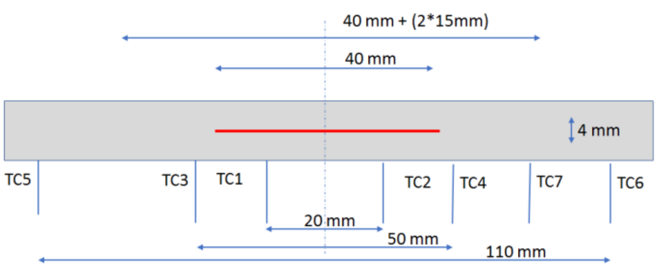
coral-shaped intracellular MC, intercellular eutectic M_2C and refined cells due to multiple melting

coarse angular MC and eutectic M_2C within intercellular zones

“3D” thin wall experiments (January)





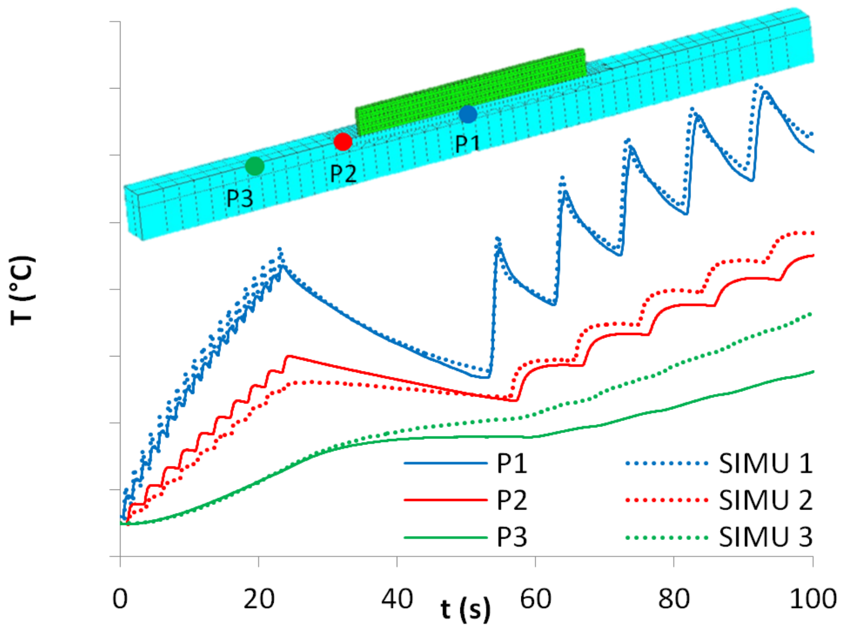


Preheating reached = 150°C

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

“3D” thermal analysis - thin walls



Simulations until 5th 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

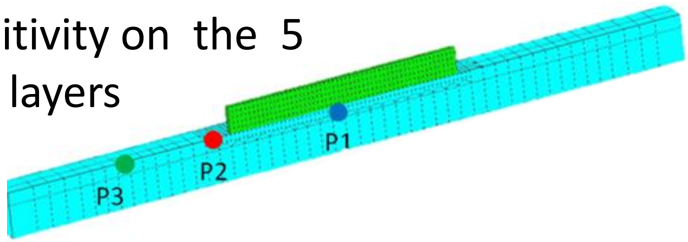
→ Impossible to recover temperature measurements with previous values of conductivity and thermal capacity.

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

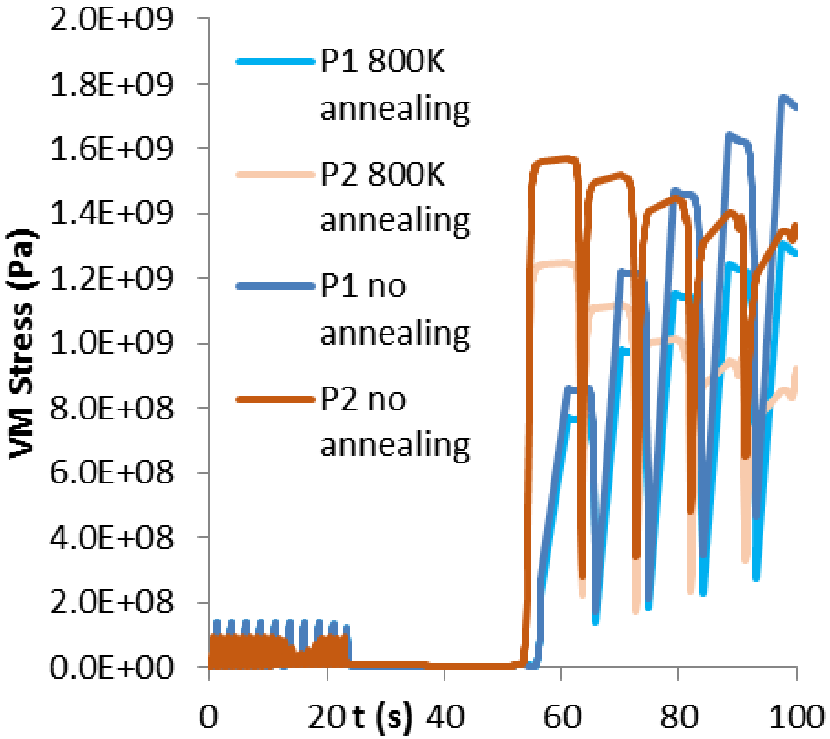
(Previous block for bulk sample in martensite state, current bars in Pearlitic state)

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

Sensitivity on the 5 first layers

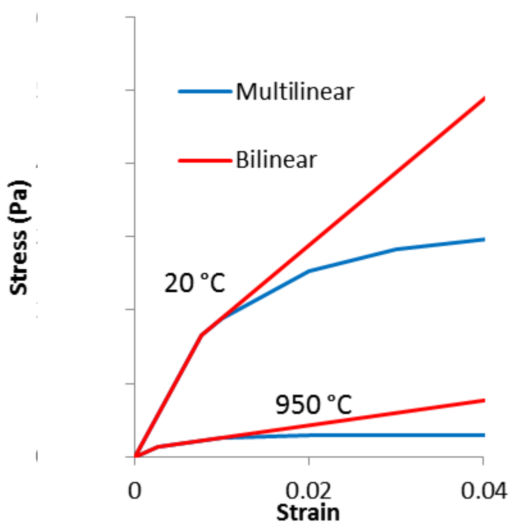


Numerical annealing temperature: plastic strain is forgotten if tp° decreases below this annealing tp°

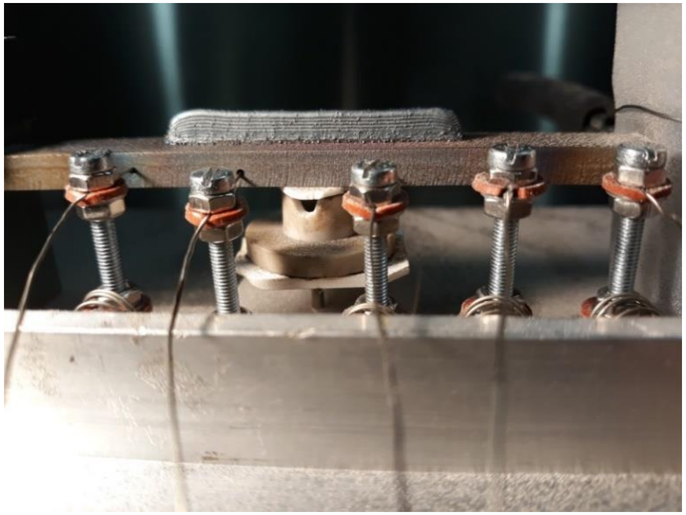


Results for bilinear stress-strain curves

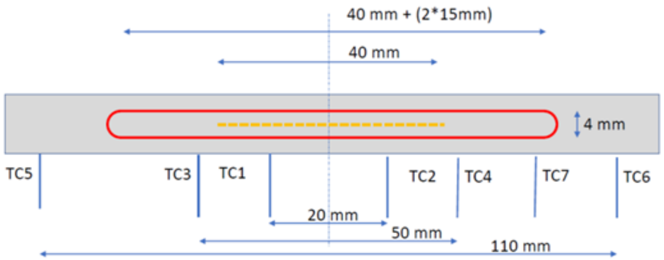
Far Less sensitive for multi linerar curves



“3D” thin wall experiments (March)



No more crack
Nearly constant height



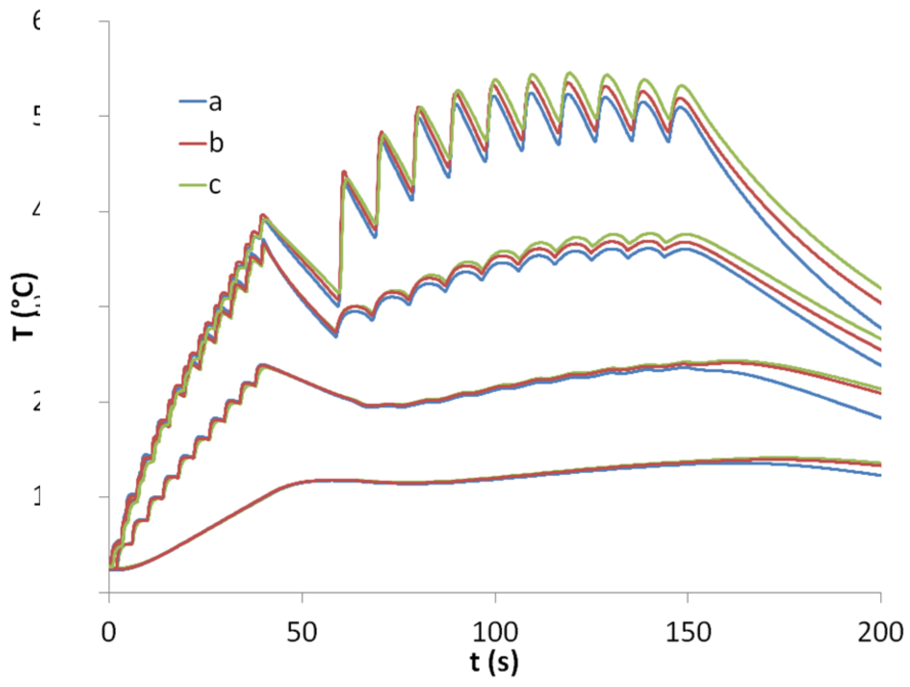
	Substrate pre-heating	Clad deposition
Length of centered laser pass for pre-heating (mm)	70	40
Laser beam speed (mm/s)	41.7	8.3
Laser power (W)	260	600+500=> 400
Temperature at thermocouple P1 at preheating end and at cladding start in °C	400	310
Number of laser passes	20	10

Pre heating at 300°C

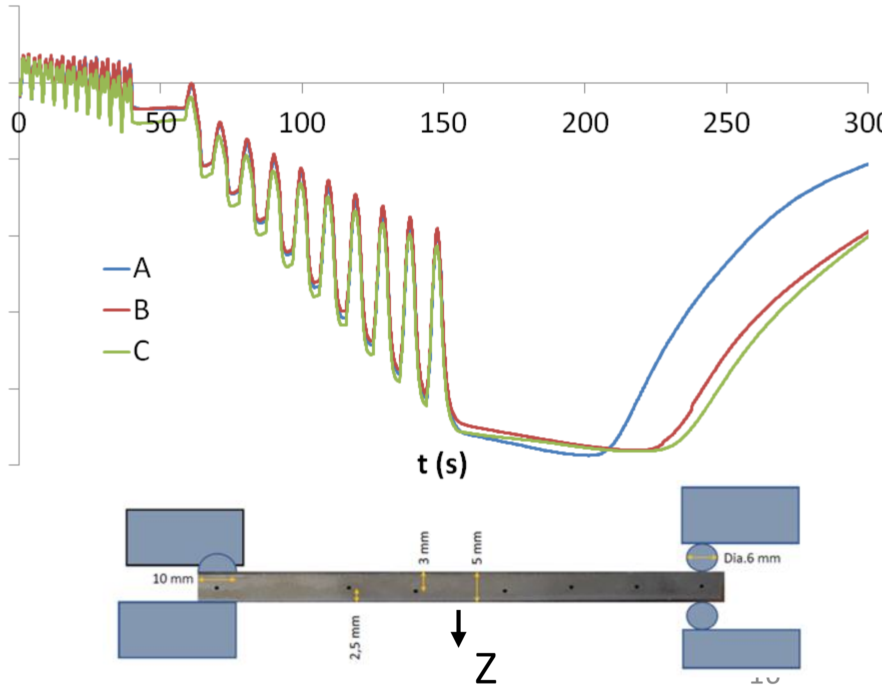
“3D” thin wall experiments

3 Experiments with similar conditions 10 layers without crack

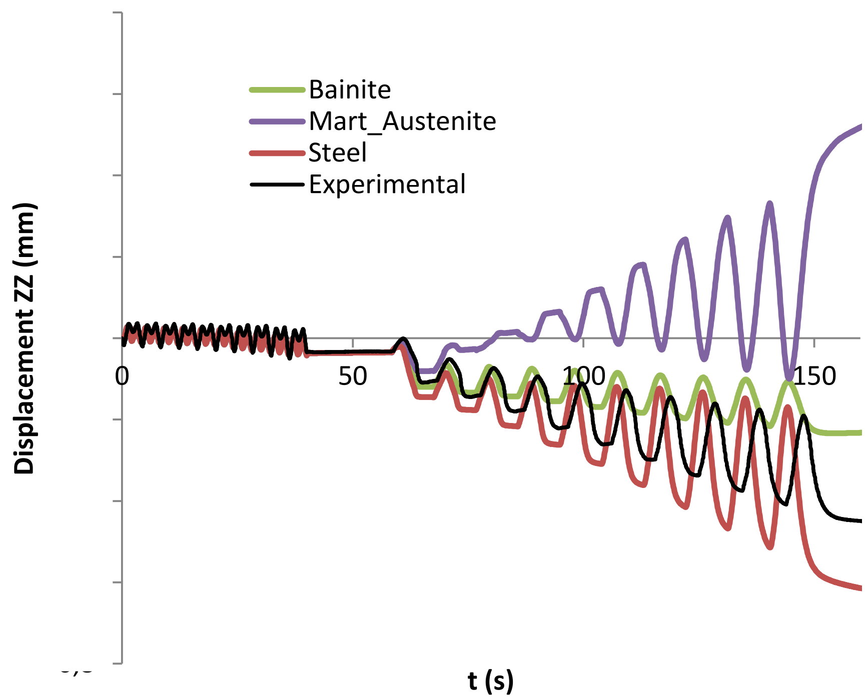
Temperature history



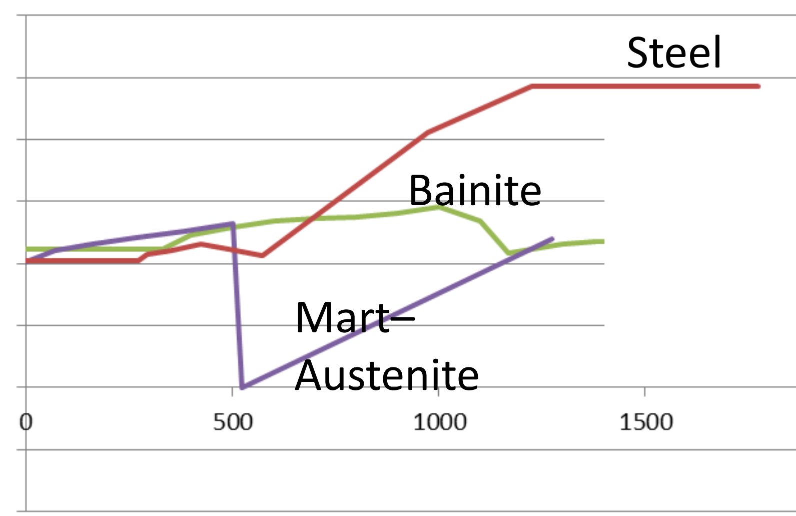
Vertical displacement at the middle



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



Dilatation coefficient of the clad



No effect of annealing temperature

Strong sensitivity to the dilatation coef of the clad

→ Sensitivity to dilatation of substrate, HAZ, have to be done

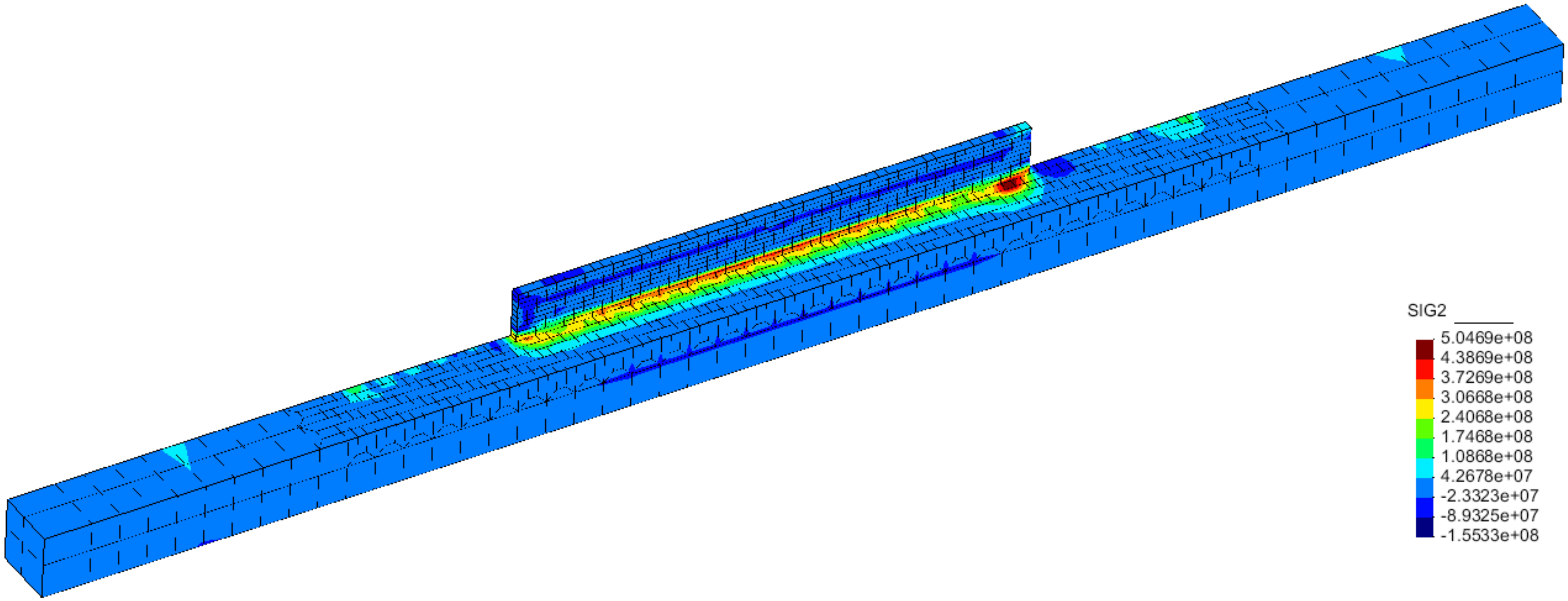
→ Metallography on the thin wall is on going

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

Transversal stress σ_{yy} along thin wall

At the end of cooling

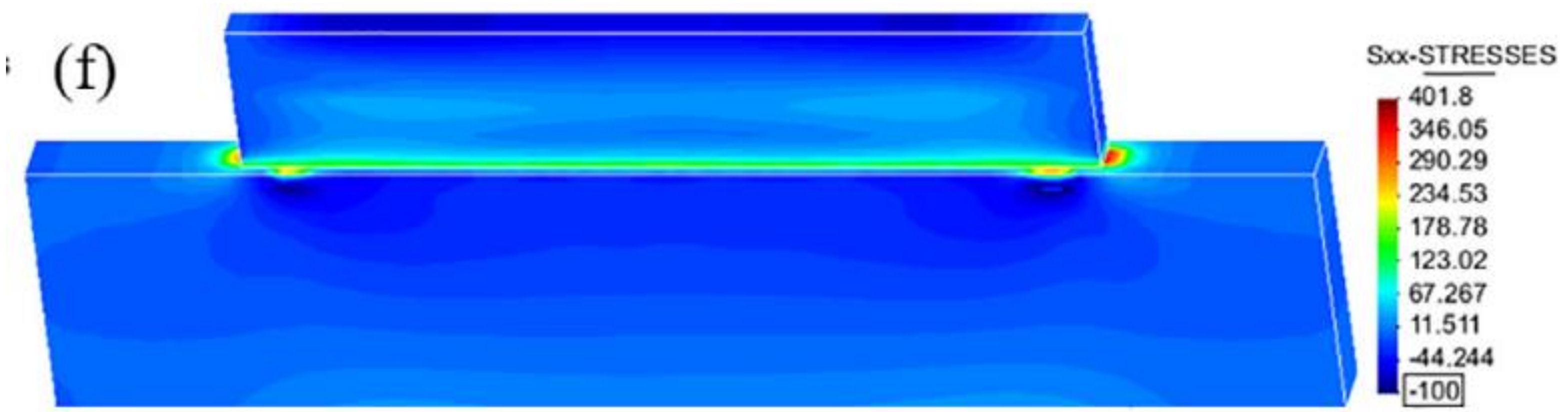
Dilatation Case « steel »



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

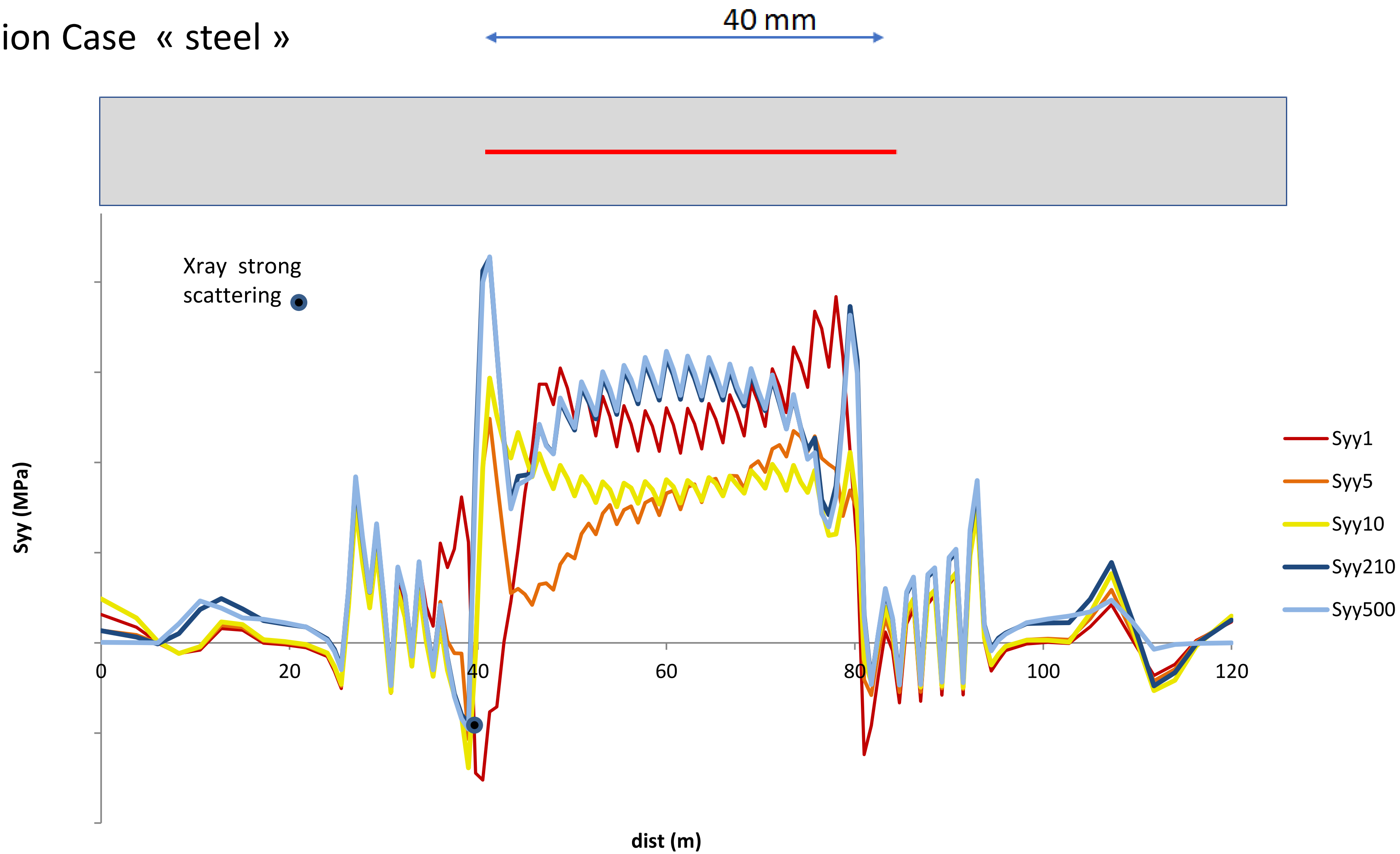
Transversal stress σ_{yy} along thin wall from literature

X. Lu,et al. , *In situ measurements and thermo-mechanical simulation of Ti – 6Al – 4V laser solid forming processes*, Int. J. Mech. Sci. 153–154 (2019) 119–130..



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

Dilatation Case « steel »



Conclusions

FE thermo-mechanical model available,
Solid latent heat and dilatation of a single phase
No activation of phenomenological solid phase transformation model

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

Validation by temperature, melt pool size, displacement, residual stress, microstructure of thin wall still ongoing …

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

Perspectives

Systematic sensitivity approach (clad and substrate properties)
→ Identify what should be improved to reach validation

Use of different experimental conditions
crack and no cracks cases + hot tensile rupture value
for further FE validation method

Thank you

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