The European Network on Neutron Techniques Standardization for Structural Integrity

ÉTUDE - CONSEIL - CALCUL

Numerical activities for the NeT Task Groups

23/11/22

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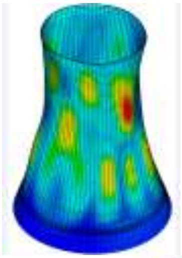
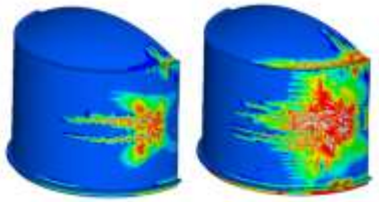
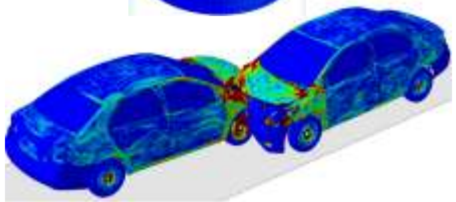
Numerical activities for the NeT Task Groups

EC2 presentation

- **Consultancy company, created in 1998 in collaboration with INSA Lyon laboratories, aiming at responding to the requirements of industrial or academic partners in applied research fields.**
- **Thermal and mechanical numerical modeling (static / dynamic / linear and non-linear) and scientific software development**
- **Fields of expertise : Shell Buckling, Numerical Welding Simulation, Civil Engineering, Dynamic calculations…**

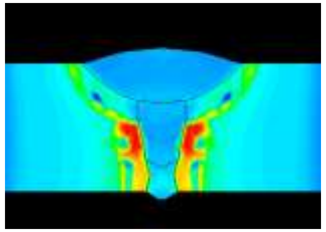


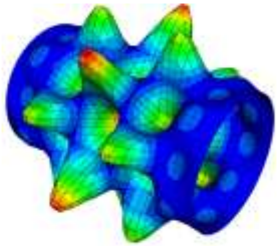


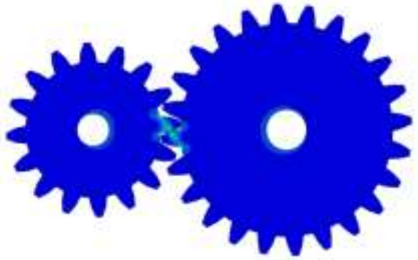


FE Codes : Abaqus, ANSYS, Code_Aster

Customers : Energy, Naval, industry…



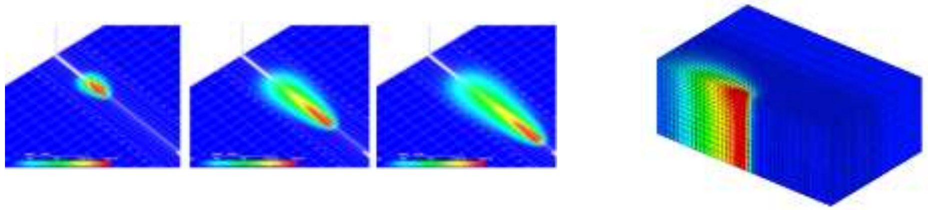


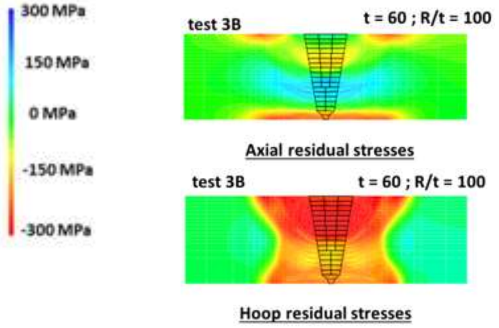


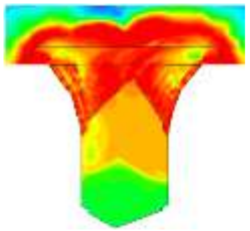
Numerical activities for the NeT Task Groups

EC2 activities in the field of Weld Numerical Simulation

- **Thermal-metallurgical-mechanical simulations**
- **Residual stresses and distortion calculation**
- **Post-weld heat treatment simulation**
- **Post-weld Fracture mechanics/Flaw analysis**
- **Additive manufacturing simulation**







EC2 shows interest in NET TG work

- **Access to a great amount of experimental data, especially material data and residual stresses measurements**
- **Benefit from Feedback from Experts network / both on simulation & measurements**
- **State-of-the art update + networking**
- **Many Benchmarks to validate the simulations → enhancement and validation of modelling strategies :**
  - **develop and validate simplified methods**
  - **Perform parametric studies so as to identify important aspects in simulations**

→ Global Enhancement of EC2 skills in the field of numerical simulation of welding

Numerical activities for the NeT Task Groups

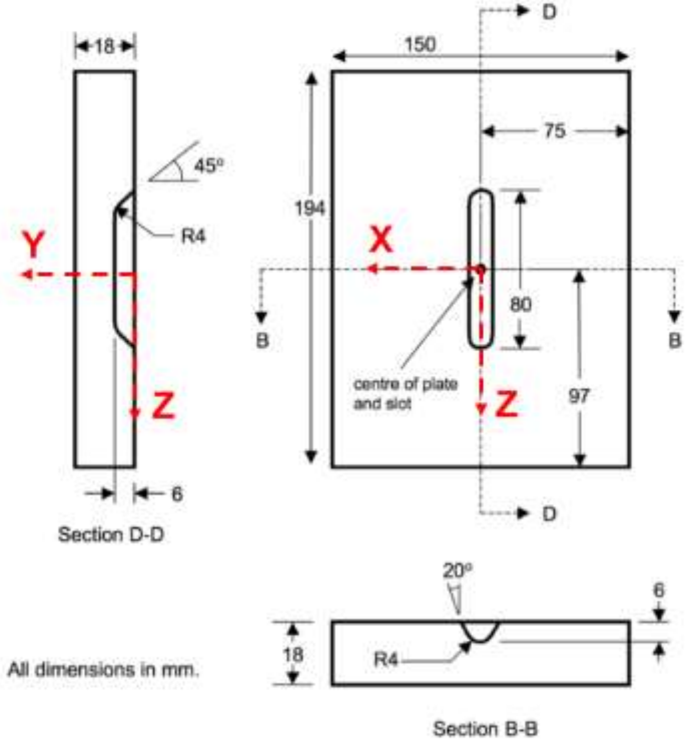
EC2 participation to NET Task Groups

- **NET TG4 : 316L plate with a three pass “slot” weld**
- **NET TG6 : Alloy 600 with a three pass “slot” weld made with Alloy 82 consumables**
- **NET TG8 : 18MnD5 with a five pass “slot” weld made with Alloy 52 consumables (welding repair issues)**
- **NET TG9 : Additive manufacturing TG**

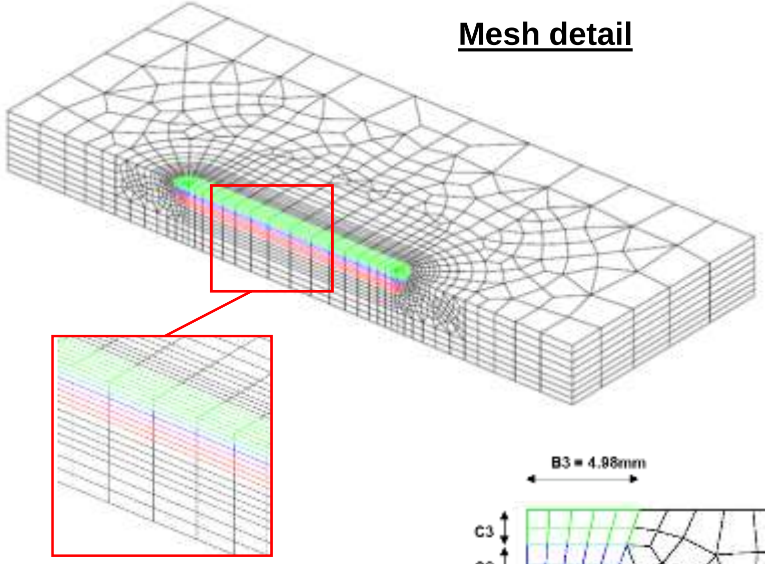
Main scope of the simulations conducted on the NET TG

- **Identify “Best estimate” simulation, accuracy and limitation**
- **Parametric studies to identify predominant parameters of phenomena**
- **Develop enhanced models and methodologies**
- **FE Code benchmarking (Abaqus / Code_Aster)**

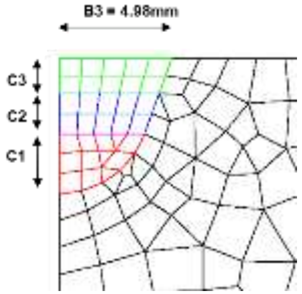
NET TG 4 :



Mesh detail



Groove detail – 3 weld passes



Detail of the groove geometry

EC2 simulation

- **Half Plate modeled**
- **Full 3D thermal and mechanical model**
- **Residual stresses computation**
- **Comparison of various EP & VP constitutive equations for 316L material**

L. DEPRADEUX, R. COQUARD, "Influence of viscoplasticity, hardening, and annealing effects during the welding of a three-pass slot weld (NET-TG4 Round Robin)", int. Journal of pres. Vessel & Piping 164 (2018) 39-54

NET TG 4 experiment :

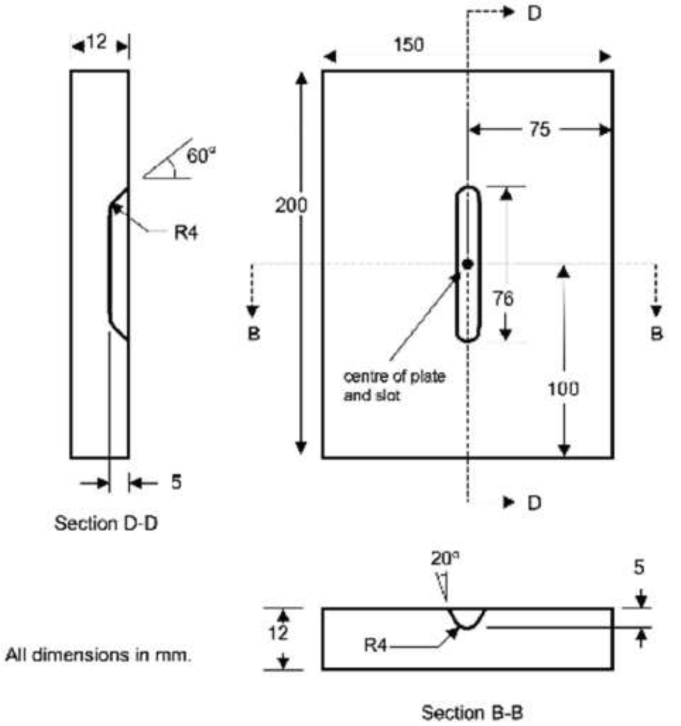
- **Plate 194 × 150 × 18**
- **Slot 80 mm long ; 6 mm deep**
- **316L austenitic steel**
- **GTAW – 3 weld passes**
- **E ~ 10 to 15 kJ/cm ; V = 1.27mm/s**

Measurements : (NET Partners)

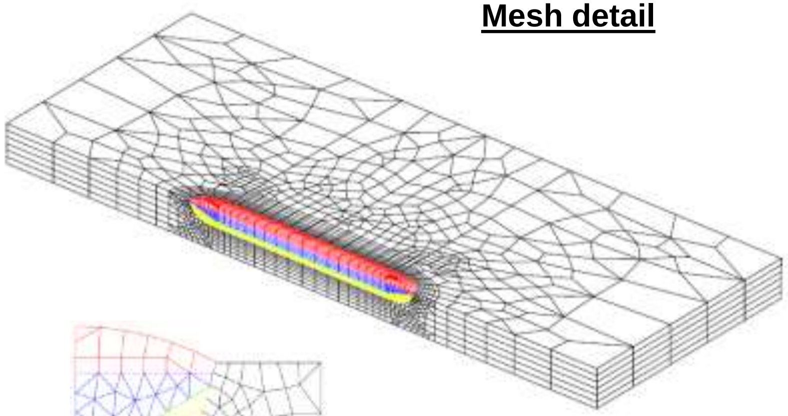
- **Temperature (thermocouples)**
- **Macrography / Hardness / metallurgy**
- **Residual stresses**
- **Distortion**

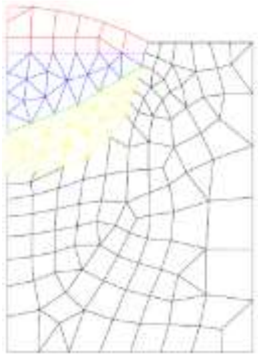
316L austenitic steel (Base & Weld)

NET TG 6 :



Mesh detail





Detail of the groove geometry

EC2 simulation

- **Half Plate modeled**
- **Full 3D thermal and mechanical model**
- **Residual stresses computation**
- **Comparison of 2 EP constitutive equations for Alloy 600 & 182**

NET TG6 experiment :

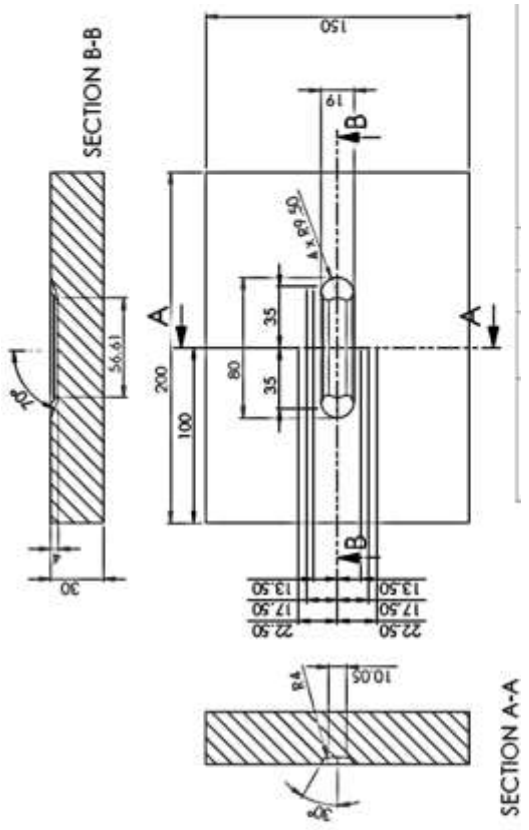
- **Plate 200 × 150 × 12**
- **Slot 76 mm long ; 5 mm deep**
- **Base metal Alloy 600**
- **GTAW – 3 weld passes**
- **Weld metal alloy 182**
- **E ~ 20 kJ/cm ; V = 1.166mm/s**

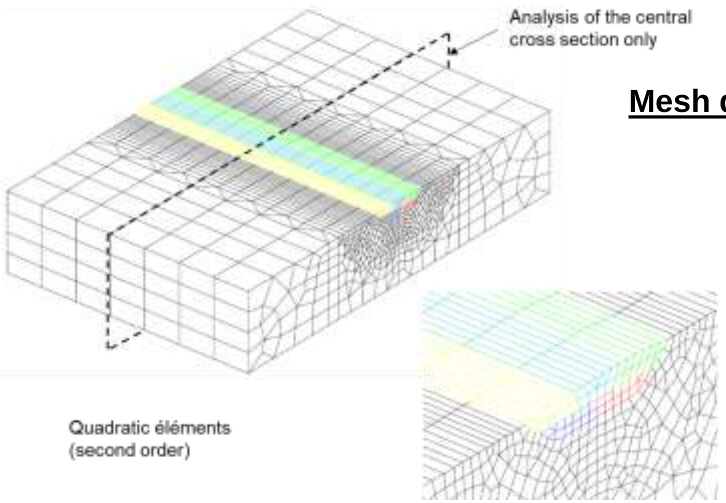
Measurements : (NET Partners)

- **Temperature (thermocouples)**
- **Macrography / Hardness / metallurgy**
- **Residual stresses**
- **Distortion**

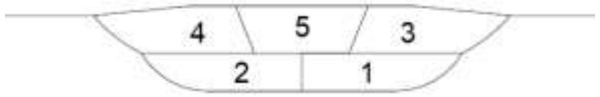
Alloy 600 (base)
Alloy 182 (Weld)

NET TG 8 :





Mesh detail



EC2 simulation

- **Half Plate modeled**
- **“2,5D” thermal and mechanical model (w moving heat source)**
- **Residual stresses computation**

“2,5D” simul. :

- Intermediate between 2D and full 3D computation
- Less severe restraint in the weld direction
- “arbitrary” length in the weld direction
- Only the center section is analyzed

18MnD5 (base)
Alloy 52 (weld)

NET TG8 experiment :

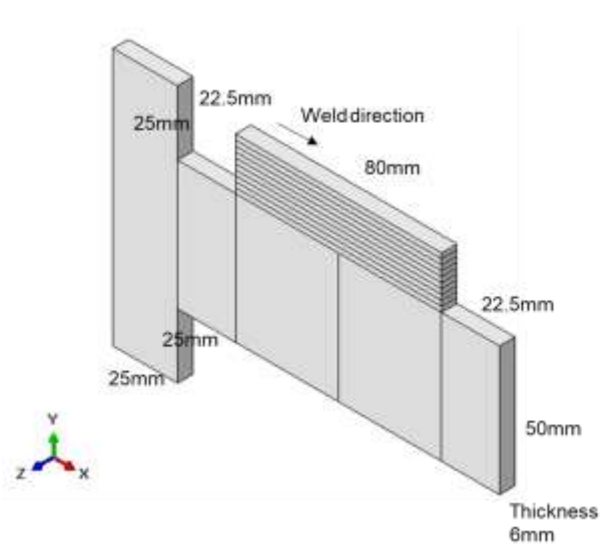
- **Plate 18MND5**
- **Weld Inco 52**
- **5 Weld passes**
- **Post-Weld heat treatment**

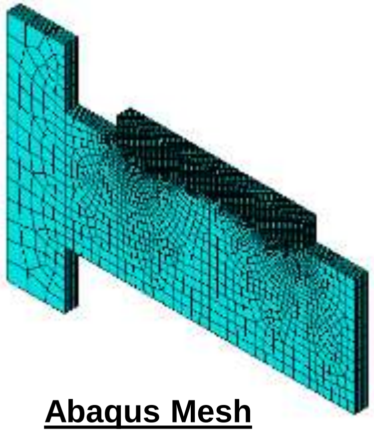
Measurements : (NET Partners, ongoing)

- **Temperature (thermocouples)**
- **Macrography / Hardness / metallurgy**
- **Residual stresses**
- **Distortion**

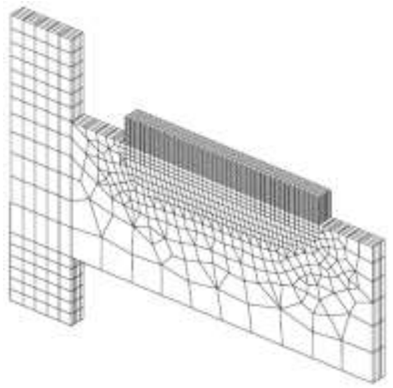
Numerical activities for the NeT Task Groups

NET TG(9) / additive manufacturing :





Abaqus Mesh



Code_Aster Mesh

EC2 simulation

- Half Plate modeled
- “2,5D” thermal and mechanical model (w moving heat source)
- Residual stresses computation
- Support Plate distortion

- Material : 316L (substate & deposited Wall)
- 5 to 10 layers
- 1st layer : I=108 A ; U = 13.2 A (averaged)
- Other layers : I=99 A ; U = 13 A (averaged)
- Welding speed = 0.42m/min = 7mm/Sec

- Travel time 11.43 sec (for 80mm)
- Time between layer hyp. 36,5 sec
- Total pass time=48sec.
- Filler wire 1.2mm

Measurements : (NET Partners)

- Temperature (thermocouples)
- Residual stresses
- Distortion

316L austenitic steel (Base & Weld)

Numerical activities for the NeT Task Groups

General strategy / Main features of the simulation (all TGs) :

- **Code_Aster (mainly) and/or Abaqus simul. (NET TG9)**
- **Uncoupled thermo-(metallurgical)-mecanical simul.**
- **Full 3D simulation or "2,5D" simulation with moving heat source (avoid severe restraint in the weld direction due to 2D-cross section assumption)**

"Classical" Weld numerical simulation hypothesis

- **No thermo-fluids in the Weld pool → Equivalent mathematical heat source model**
- **Moving heat source (ellipsoidal/triangle) / parameters adjusted from Macros +TCs measurements**
- **EP or EVP mechanical constitutive equ.**
- **Bead by bead deposition**
- **"Birth element" for thermal approach / "Quiet elements" (E~0) for mechanical approach**

Specific Model Development & Enhancement

- **High T° annealing implementation for 316L & Inconel Alloy**
- **Tempering effects for ferritic material**

Numerical activities for the NeT Task Groups

Known Key points of the simulation (all TGs)

- Heat source model Calibration → Calibration against TCs measurements and macrography
- Mechanical Constitutive equation & material data → Calibration against data provided within NET

Other points that have revealed critical :

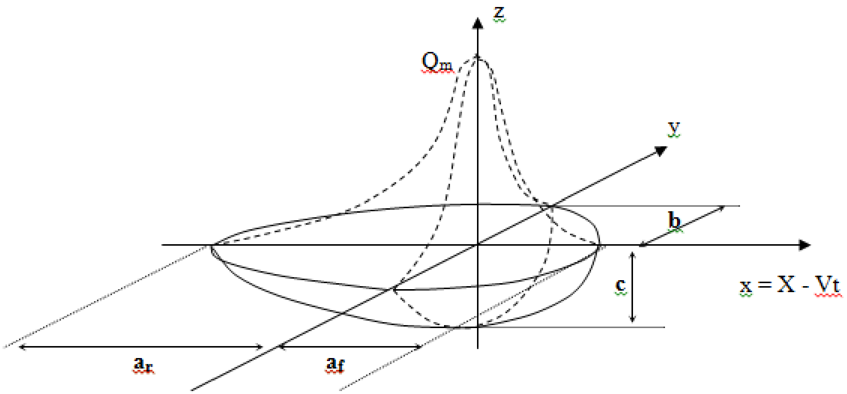
- Mixed hardening characteristics (austenitic steel / Nickel based alloy) → importance of cyclic data
- Handling of progressive annealing at high T° (austenitic steel / Nickel based alloy)
- Phases transformations and mechanical consequences (Ferritic steel / 18MnD5)

Not clearly established (from EC2 point of view) :

- Thermo-fluid phenomena in the weld pool → Weld pool shape prediction ?
- Viscous effects (weak effect on welding RS ? But very important for Heat treatment simulation)
- Tempering effects during welding (Ferritic steel / 18MnD5)
- Material deposition modelling strategy (especially for additive manufacturing)

Numerical activities for the NeT Task Groups

Heat source Model choice & Calibration



J. Goldak ellipsoidal model

$$q(x,y,z) = Q_0 \cdot \frac{6\sqrt{3}\,f_\xi}{a_\xi\, b\, c\, \pi^{3/2}} \exp\left(\frac{-3x^2}{a_\xi^2}\right) \cdot \exp\left(\frac{-3y^2}{b^2}\right) \cdot \exp\left(\frac{-3z^2}{c^2}\right)$$

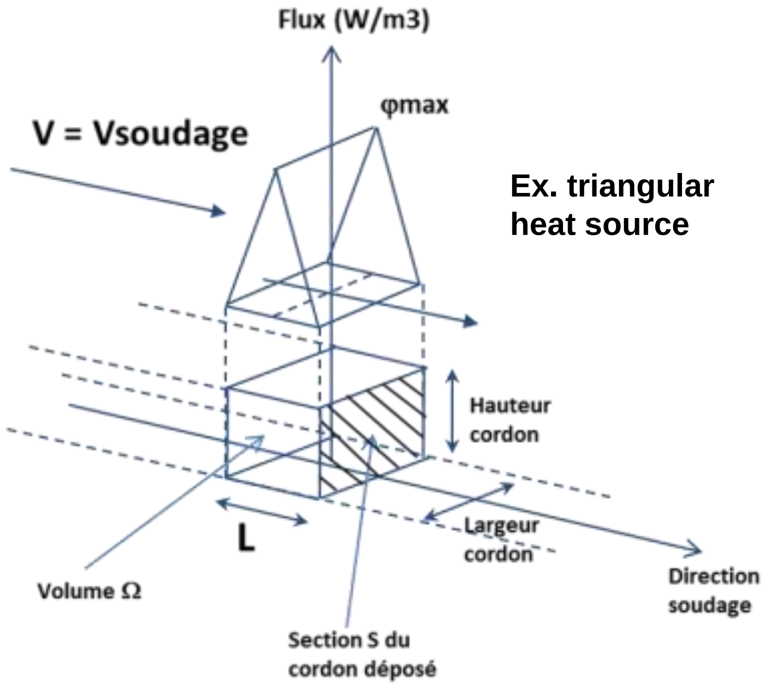
avec $\xi = f$ ou r selon que x est positif ou négatif et $f_f + f_r = 2$

$$f_f = \frac{2a_f}{a_f + a_r} \quad \text{et} \quad f_r = \frac{2a_r}{a_f + a_r}$$

Classical heat source model

- **Power parameter : Q0, V**
- **geometrical param. af, ar, b,c**

→ Reliable but more complex to implement & calibrate



Ex. triangular heat source

Q0=ηUI
η = [0.7 – 0.9]

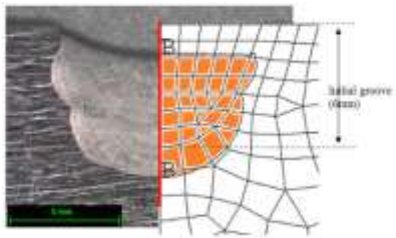
Simplified heat source model(s)

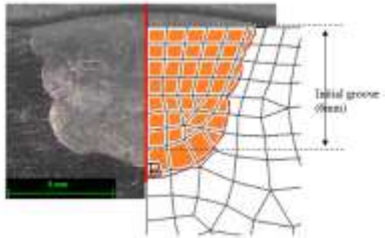
- **Power parameter : Q0, V**
- **geometrical param. S, L**

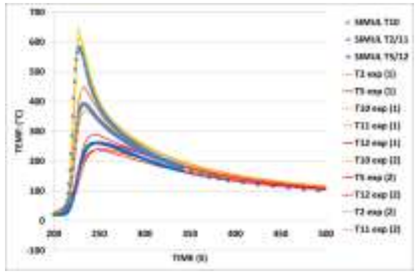
→ Easier to calibrate

→ Generally sufficient

Ex: NET TG 4





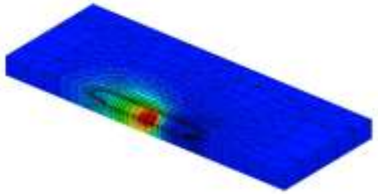


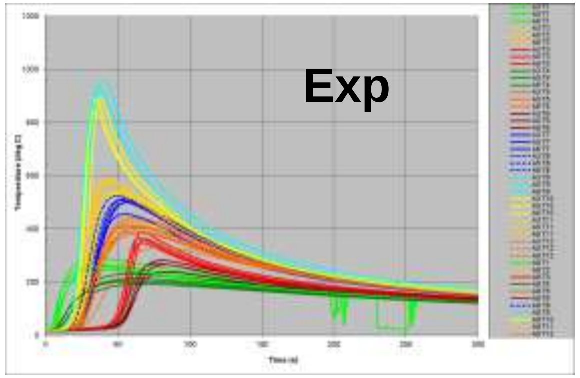
→ **Good agreement between measurment & simul.**

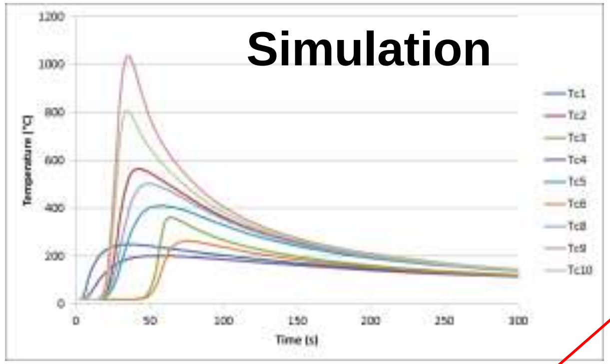
→ **Thermal approach is well validated**

→ **Possible enhancement : weld pool shape prediction (thermofluids effects)**

Ex: NET TG 6

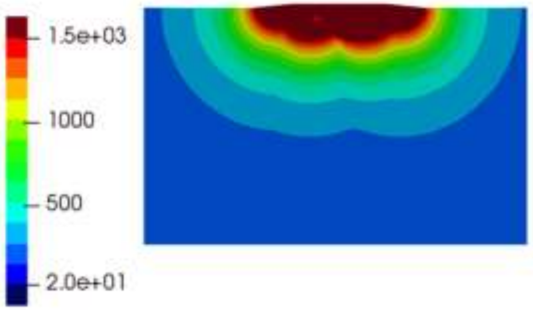


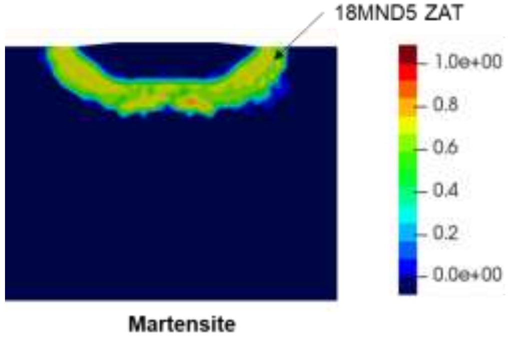


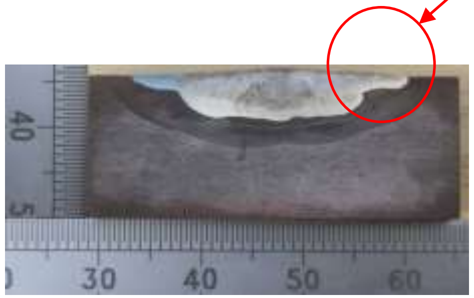


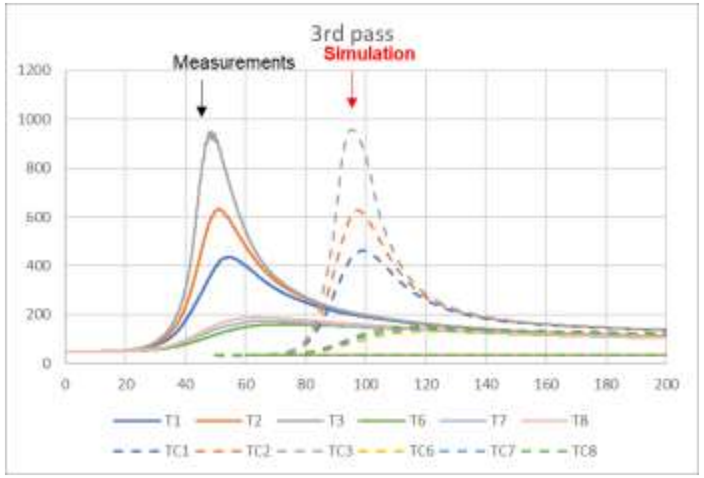
η **= [0.7 – 0.9]**

Ex: NET TG 8



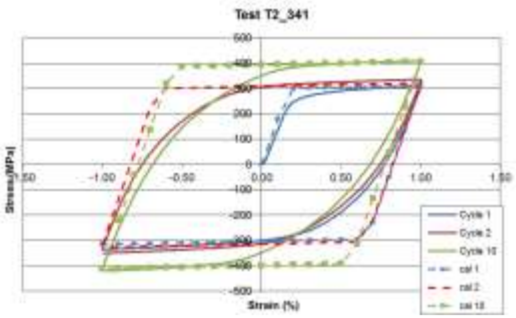


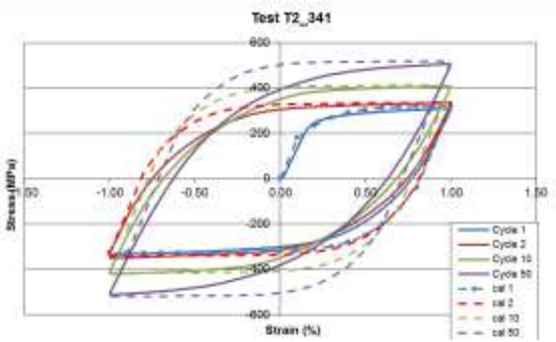




Material model Calibration : austenitic steel & Nickel based alloy

- **316L : EVP isot, Prager, Chaboche**
- **Inco 600 : Prager, Chaboche**
- **Inco 182 : Prager, Chaboche**
- **A508/18MnD5 : EP cine ou isot**





Available Code_Aster models :

Isot/cine/mixt EP Prager model

$$f(\sigma_{ij}) = (\sigma - \chi)^{VM} - R(p) \leq 0$$

$R = R(p) = R(\varepsilon_p^p)$ $\quad \chi = c\ \varepsilon_p^p$

If R=H.p (linear hardening)

- *C = 0 → pure isotropic*
- *C = 2H/3 → pure cinematic*
- *0 < C < 2H/3 → mixed*

EP Chaboche type model

$$F(\sigma, R, X) = (\sigma - X)^{VM} - R(p) \leq 0$$

$$X = \frac{2}{3} C(p).\alpha \qquad \dot{\alpha} = \dot{\varepsilon}^p - \gamma(p).\alpha.\dot{p}$$

$$R(p) = R_\infty + (R_0 - R_\infty) e^{-bp}$$

$$C(p) = C^\infty (1 + (k-1) e^{-wp})$$

$$\gamma_1(p) = \gamma^0 (\alpha_\infty + (1 - \alpha_\infty) e^{-bp})$$

EVP model

$$f(\sigma, r, T) = \sigma^{VM} - R(r,T) - \sigma_s \leq 0$$

$$\dot{\varepsilon}_{ij}^{vp} = \frac{3}{2} \dot{p} \frac{S_{ij}}{\sigma^{VM}} \qquad \dot{p} = \left(\frac{\langle \sigma^{VM} - R(r) - \sigma_s \rangle}{\mu} \right)^n$$

$$\begin{cases} R = R(r).r \\ \dot{r} = \dot{p} - (Cr)^m \end{cases}$$

(viscous annealing)

+ separated annealing :
(internal variables =f(T, t))

Numerical activities for the NeT Task Groups

Material model Calibration : ferritic steel / 18MnD5

EP model with phase transformation :

- **Differential dilatation**

$$\varepsilon^{thm}(Z,T)=Z_\gamma\left[\alpha_\alpha(T-T_{ref})-(1-Z_{ref})\Delta\varepsilon_{\alpha\gamma}^{T_{ref}}\right]+Z_\alpha\left[\alpha_\alpha(T-T_{ref})+Z_{ref}\Delta\varepsilon_{\alpha\gamma}^{T_{ref}}\right]$$

- **Multiphasic plastic behavior**

$$f(\sigma,r,T)=\sigma^{VM}-R(r,T)-\sigma_s\leq 0 \qquad \sigma_y(T,Z_\alpha)=(1-f(Z_\alpha))\sigma_{y\gamma}+f(Z_\alpha)\sigma_{y\alpha}$$

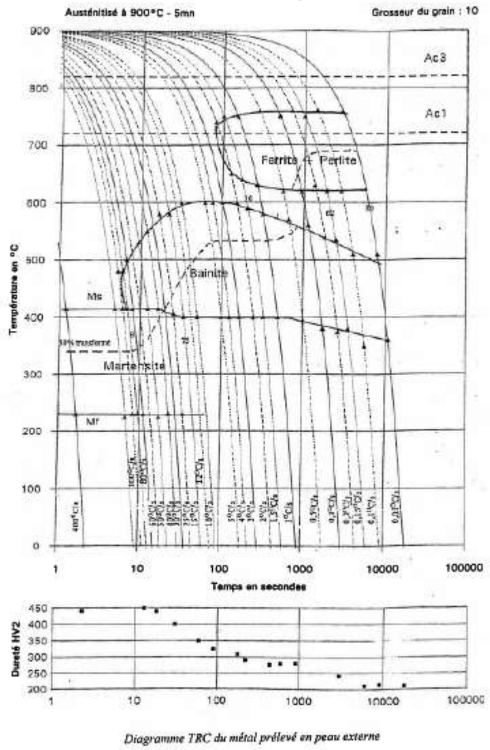
- **Transformed induced plasticity (TRIP)**

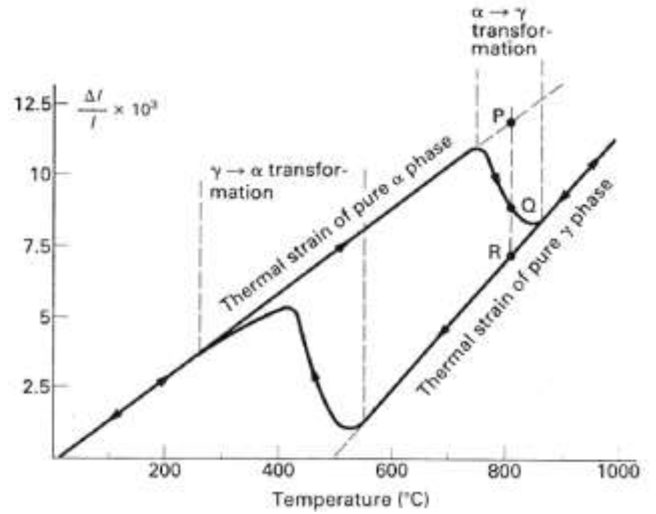
$$\dot{\underline{\varepsilon}}^{pt}=\frac{3}{2}\underline{S}\sum_{i=1}^{i=4}K_iF_i'(Z_\gamma)\dot{Z}_i$$

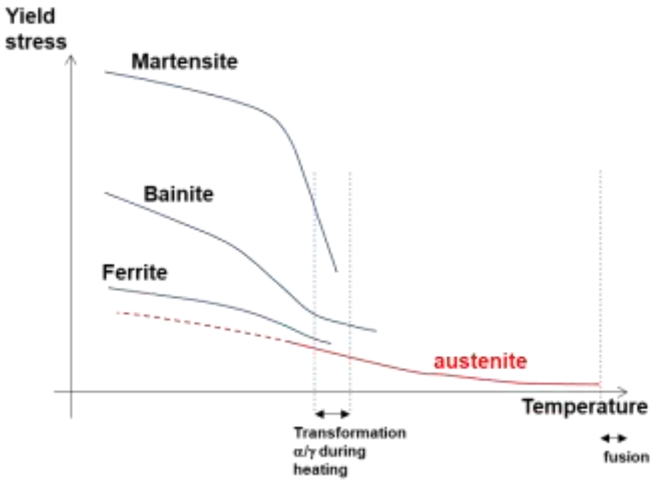
- **Viscous Annealing**

$$\begin{cases} R=R(r).r \\ \dot{r}=\dot{p}-(Cr)^m \end{cases}$$

TRC diagram







→ Generic actual Code_Aster model

→ Purely isotropic or Kinematic hardening model only

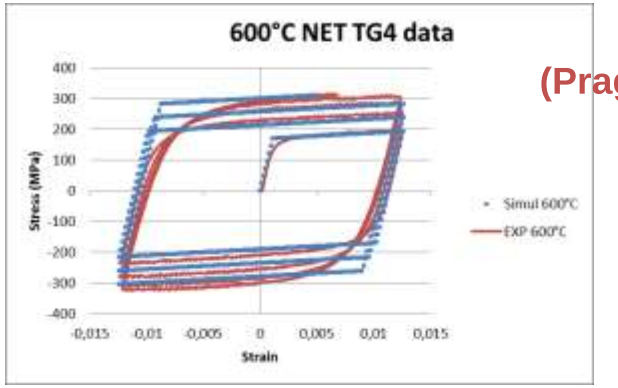
→ Calibration data from literature [Vincent], [Petit], [Martinez]…

Calibration from protocol data

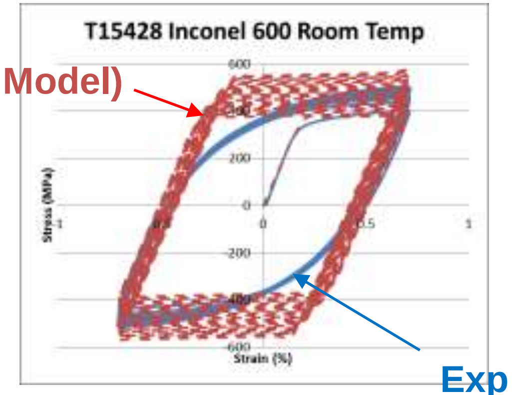
- **Inverse method from cyclic data**
- **"Satoh" tests validation ([Akrivos&al.], [Depradeux], [Vincent])**

316L

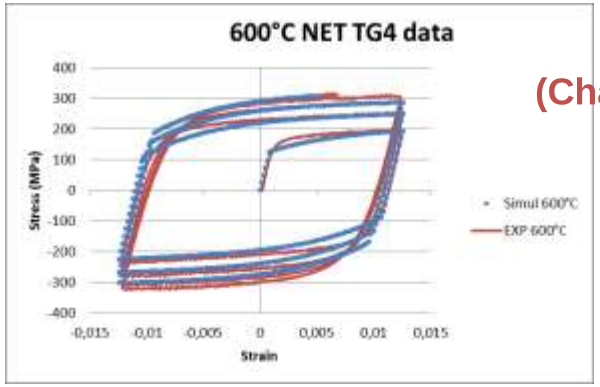
Nickel Base Alloy



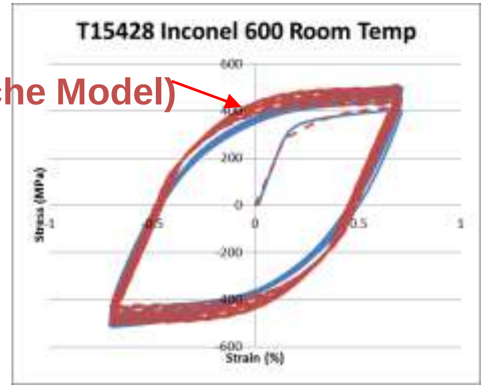
(Prager Model)



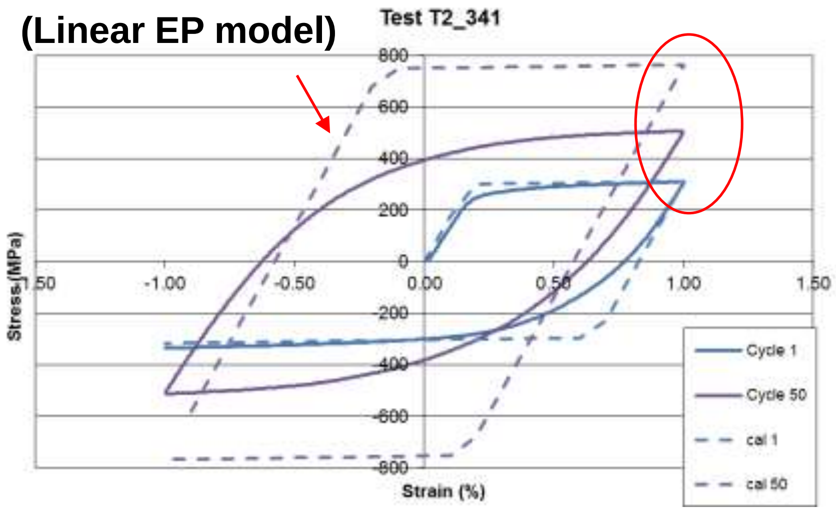
Exp



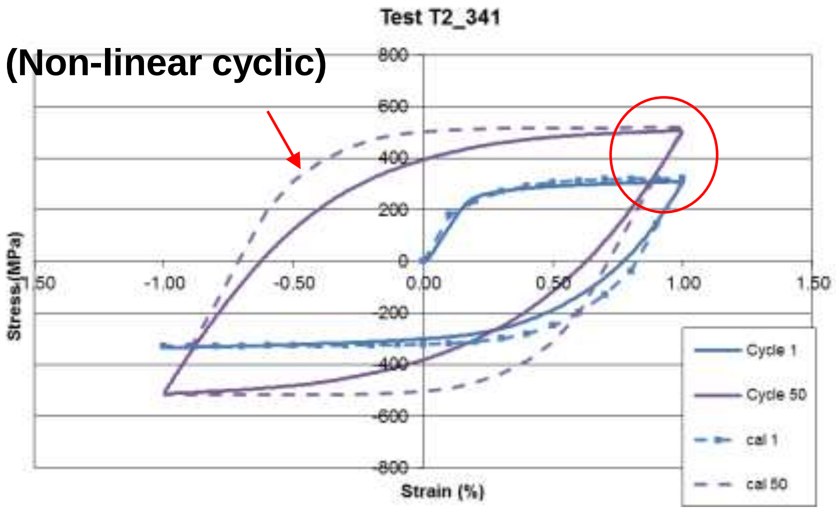
(Chaboche Model)



(Linear EP model)

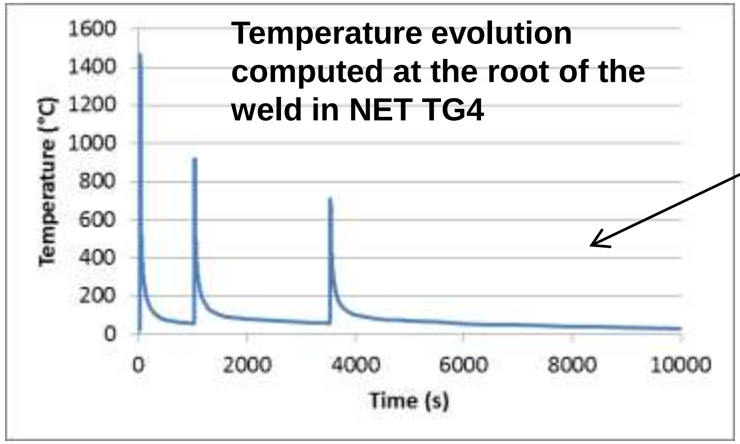


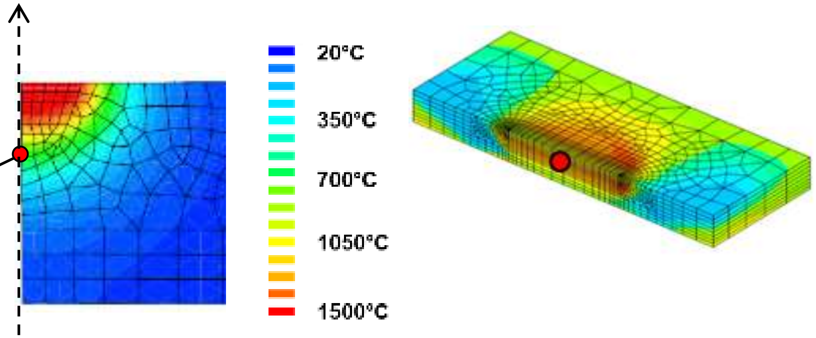
(Non-linear cyclic)



Numerical activities for the NeT Task Groups

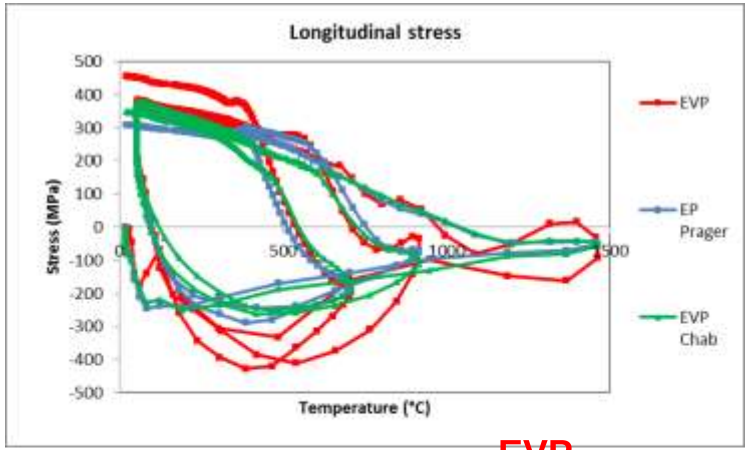
Material model validation : “Satoh tests”

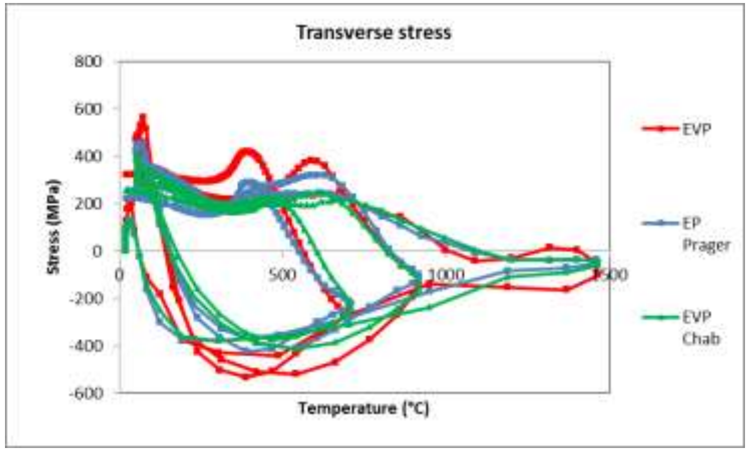




(NET TG 4)

Computed stress evolution with T° during welding : at the center of the plate



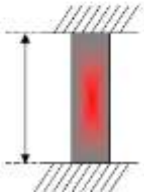


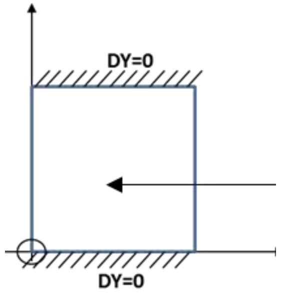
EVP
EP Prager
EVP Chaboche

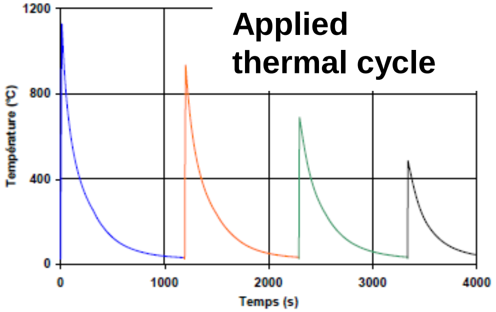
$\sigma = f(T°)$ 316L simul.

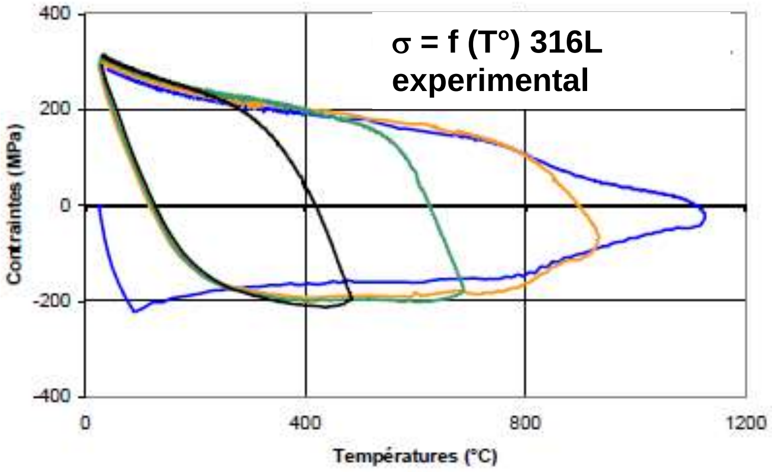
Experimental “Satoh” tests
Restrained dilatometry

$\varepsilon = \varepsilon^{th} + \varepsilon^{e} + \varepsilon^{vp} = 0$



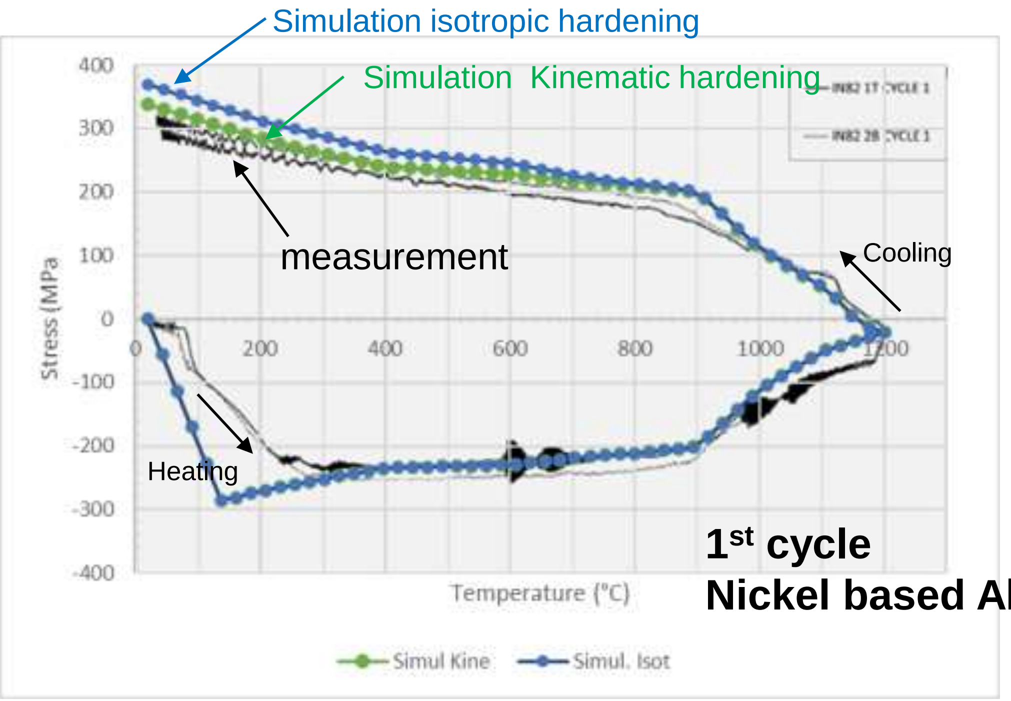




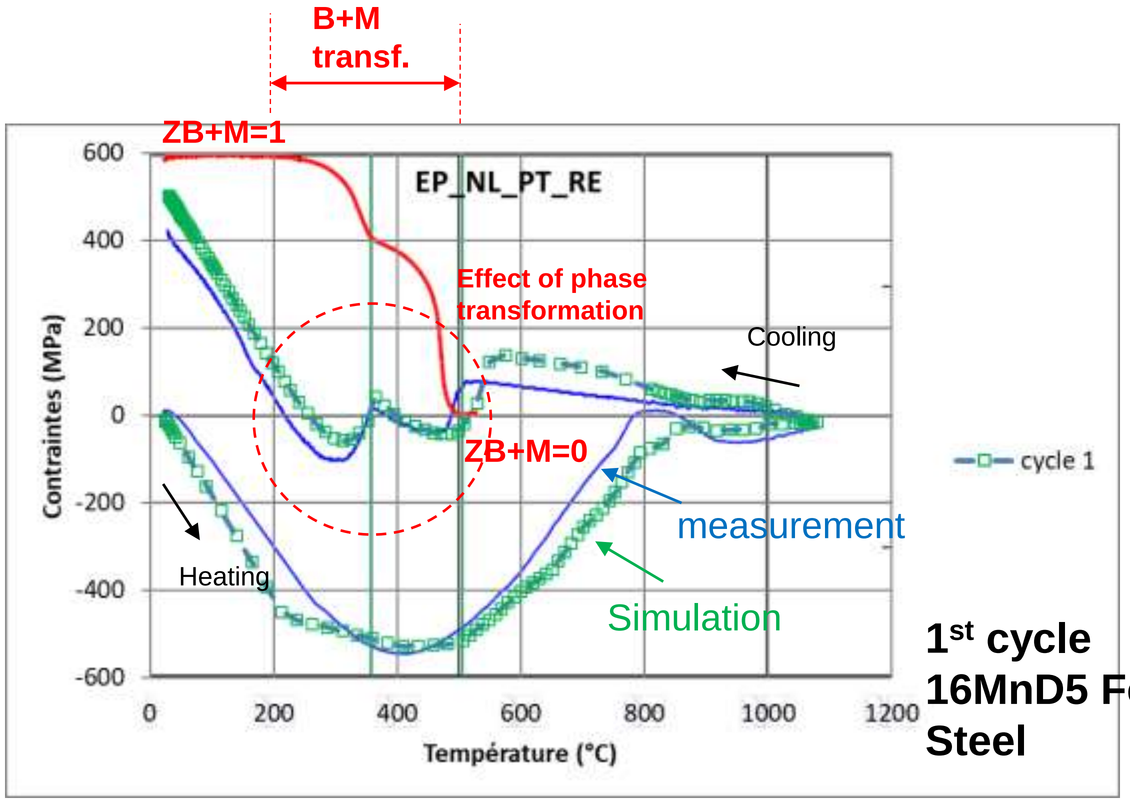


Numerical activities for the NeT Task Groups

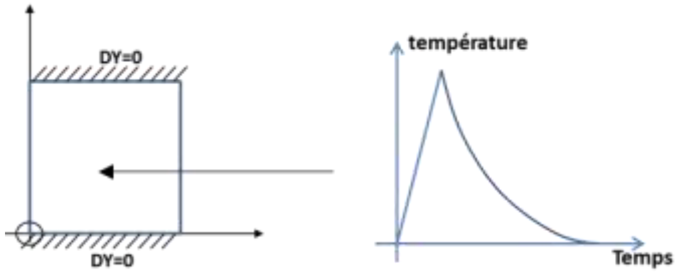
Material model validation : “Satoh tests”



1st cycle
Nickel based Alloy



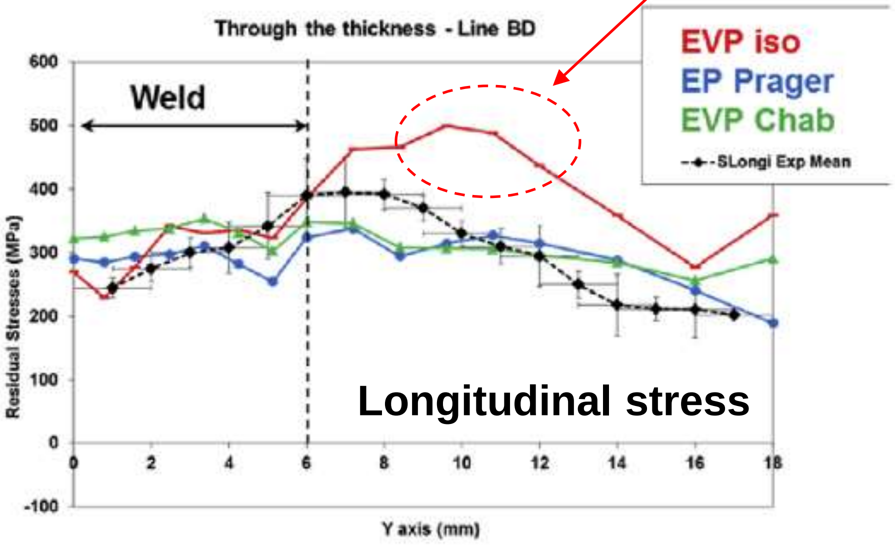
1st cycle
16MnD5 Ferritic Steel

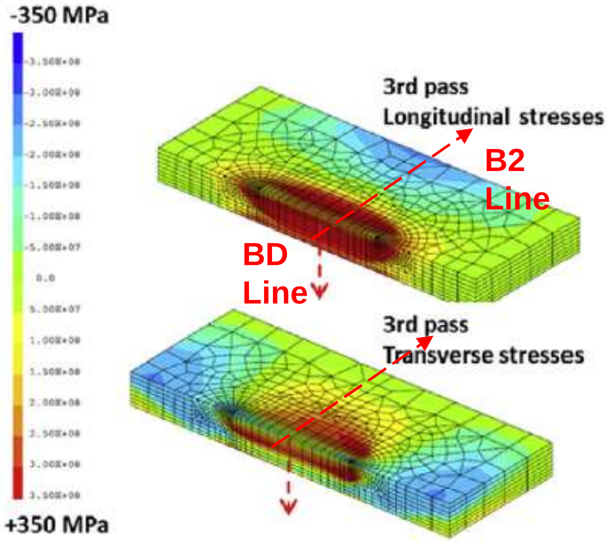


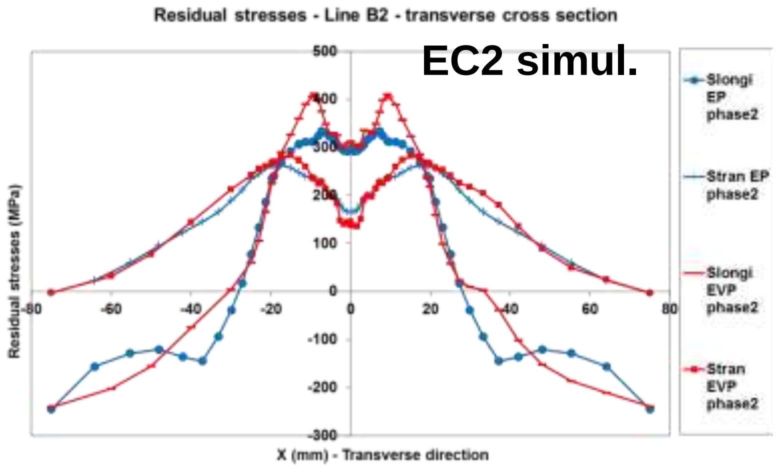
Satoh test

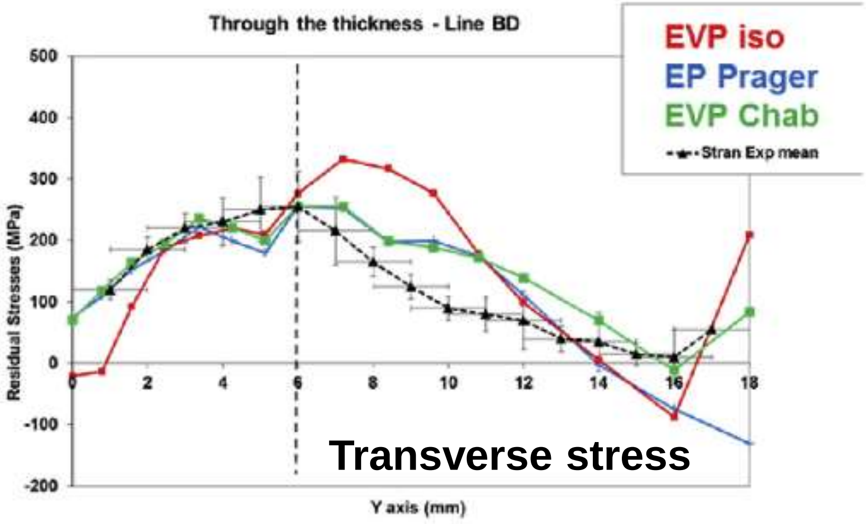
NET TG 4 : Main conclusions

Effect of purely isotropic hardening

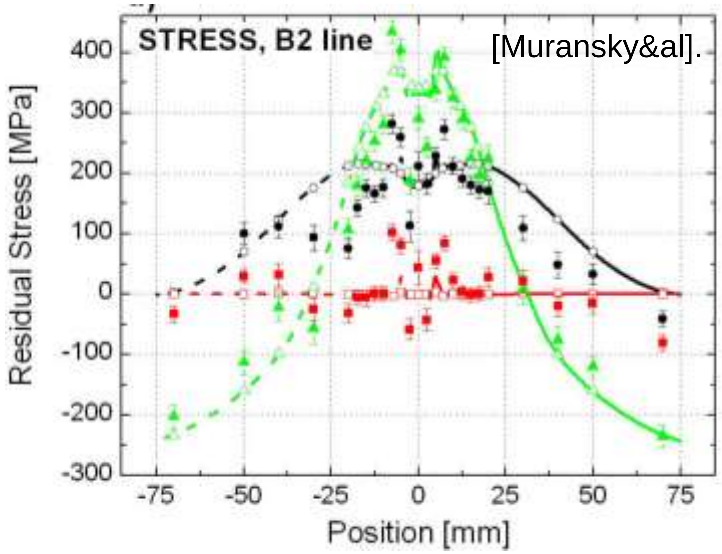






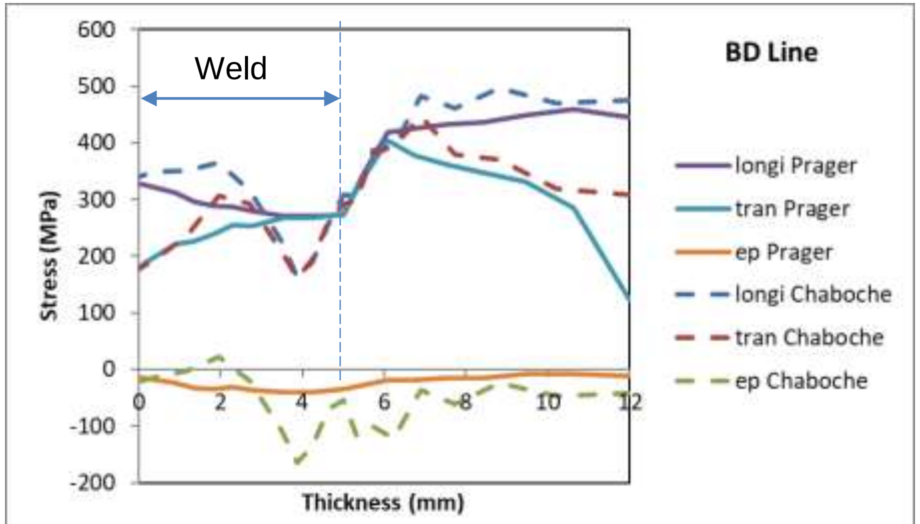


- → **Strong effects of cyclic hardening**
- → **Strong interaction with annealing effects**
- → **VP effects seems weak on RS**

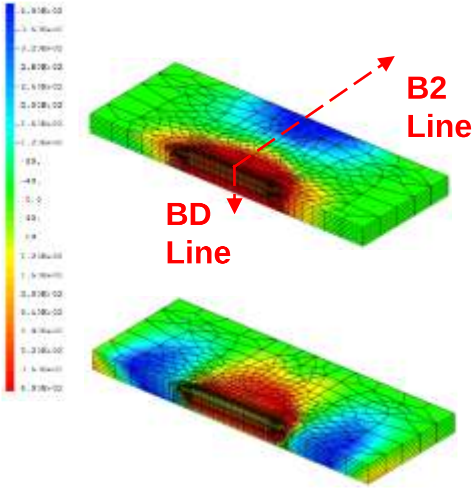


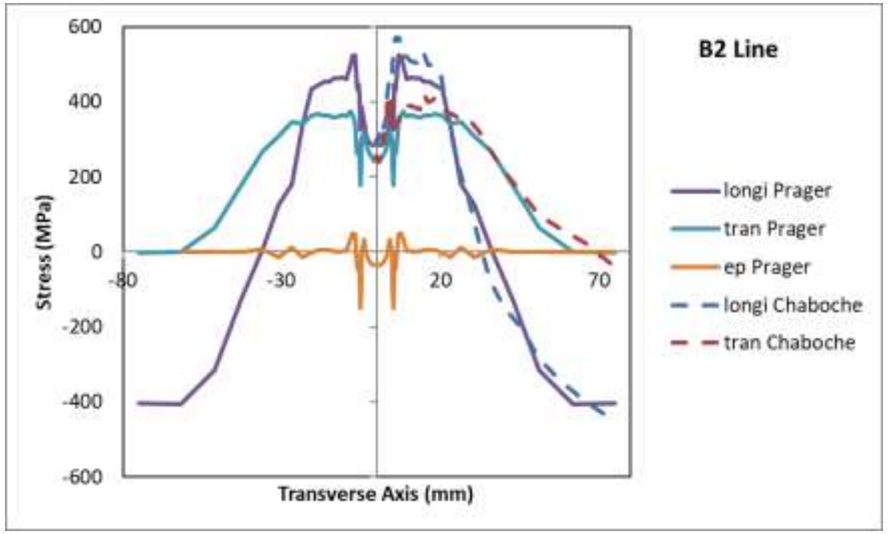
Numerical activities for the NeT Task Groups

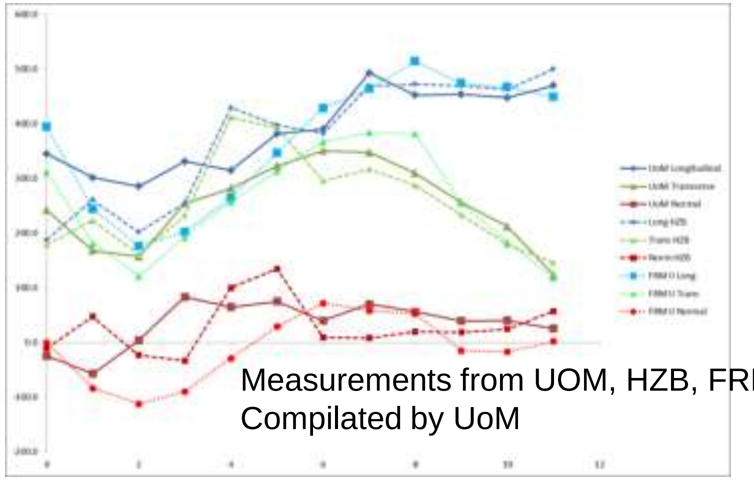
NET TG 6 : Main conclusions



Longitudinal & transverse stresses

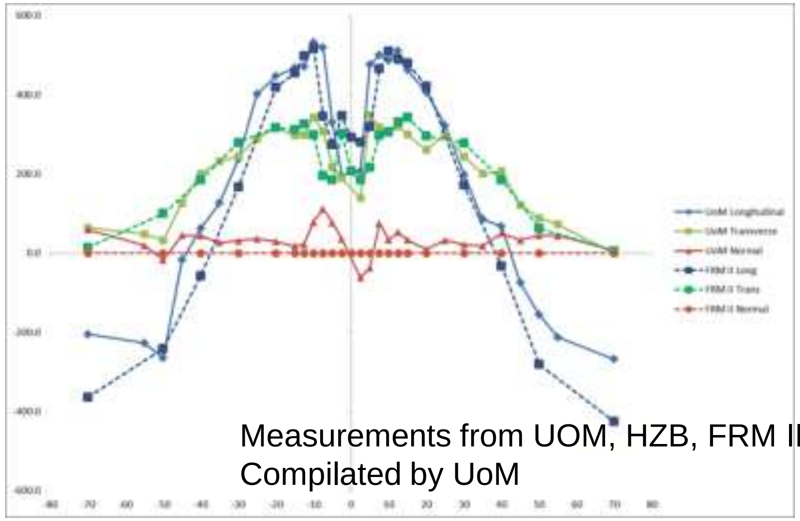






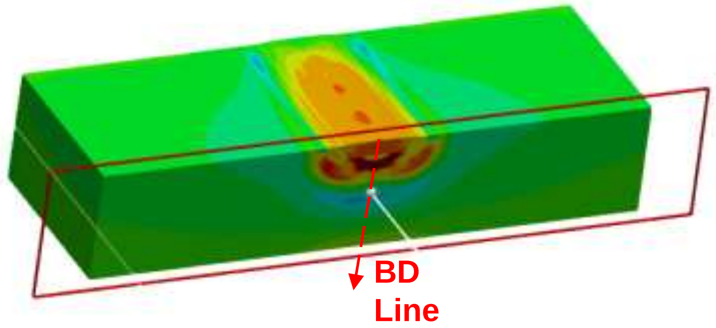
Measurements from UOM, HZB, FRM II
Compilated by UoM

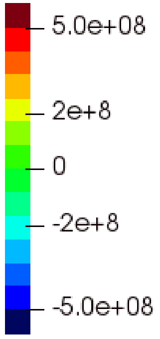
- → **Similar conclusions to NET TG4**
- → **Strong influences of mixed hardening and annealing**
- → **Prager model appears interesting since Chaboche model leads to numerical difficulties**

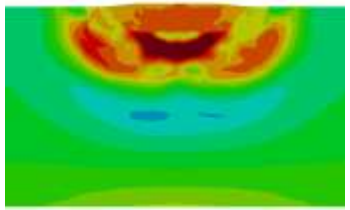


Measurements from UOM, HZB, FRM II
Compilated by UoM

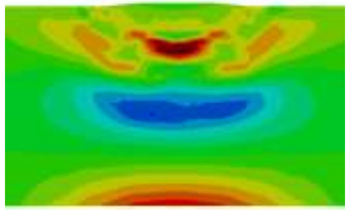
NET TG 8 : Main conclusions



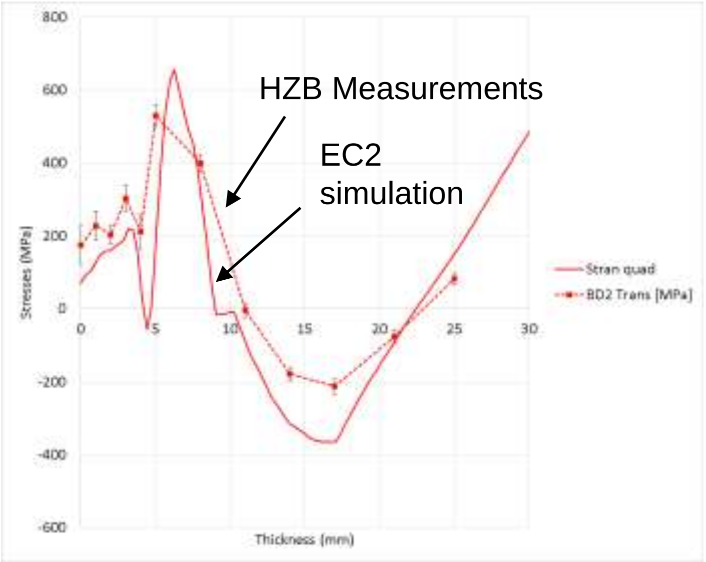


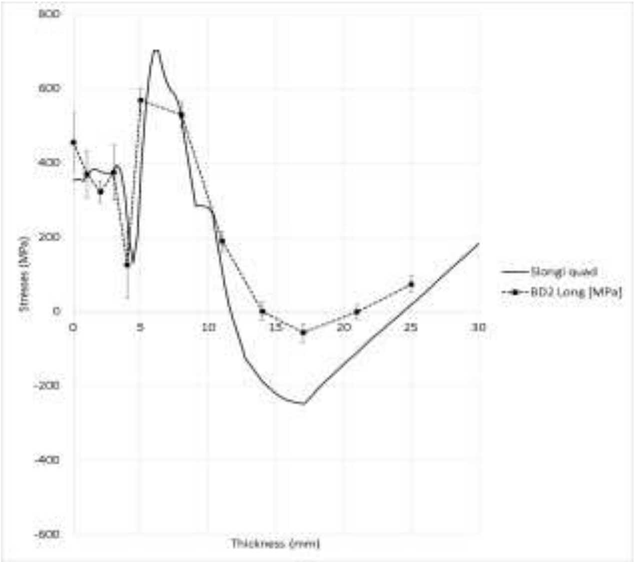


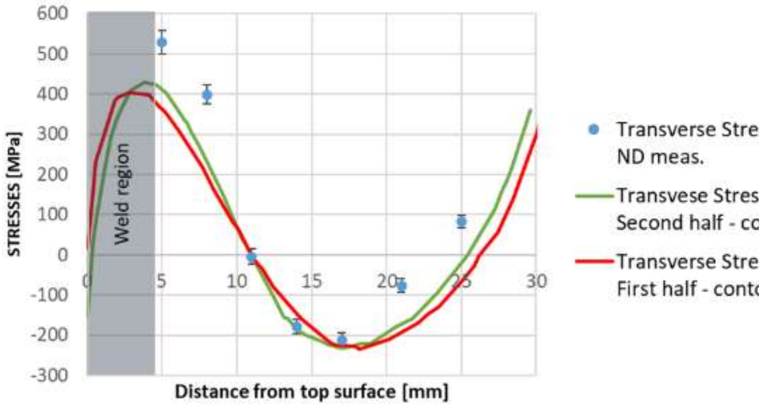
Longitudinal stresses

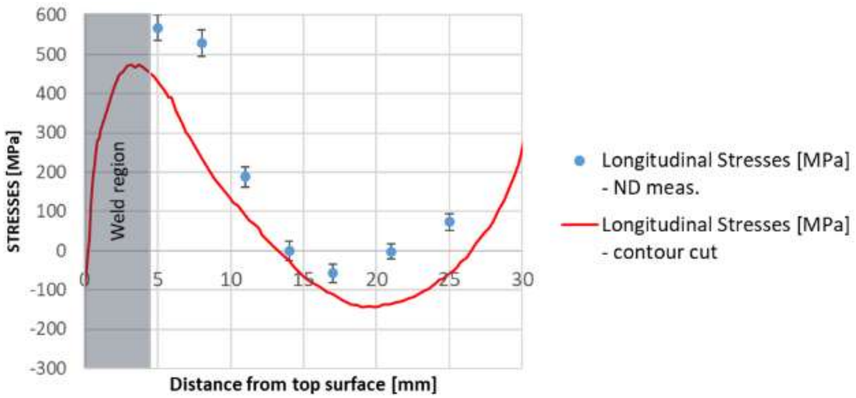


transverse stresses









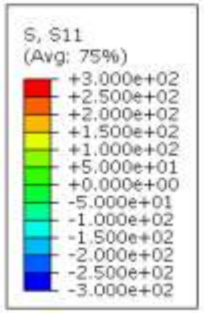
Contour method and neutron diffraction results, BD line (R.C WIMPORY (HZB), G. TRESPEUCH (SONATS)

- **Strong effects of Phase transformations**
- **“2,5D” assumption is valid**
- **Tempering influence on peak stresses**

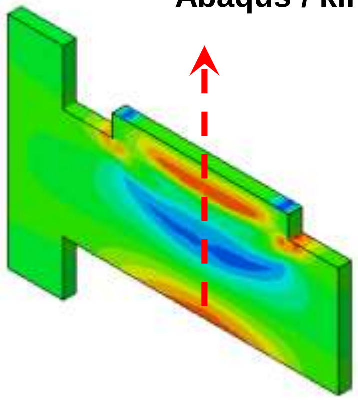
→ Still ongoing analyses

Numerical activities for the NeT Task Groups

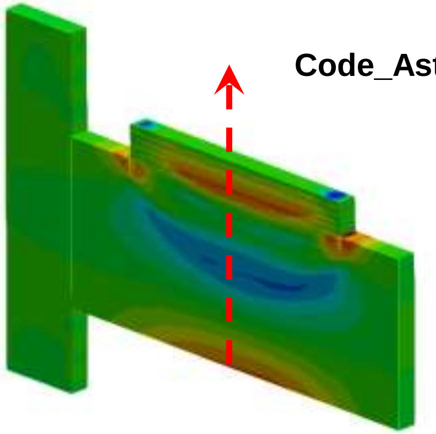
NET TG additive manufacturing : Main conclusions at this step

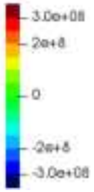


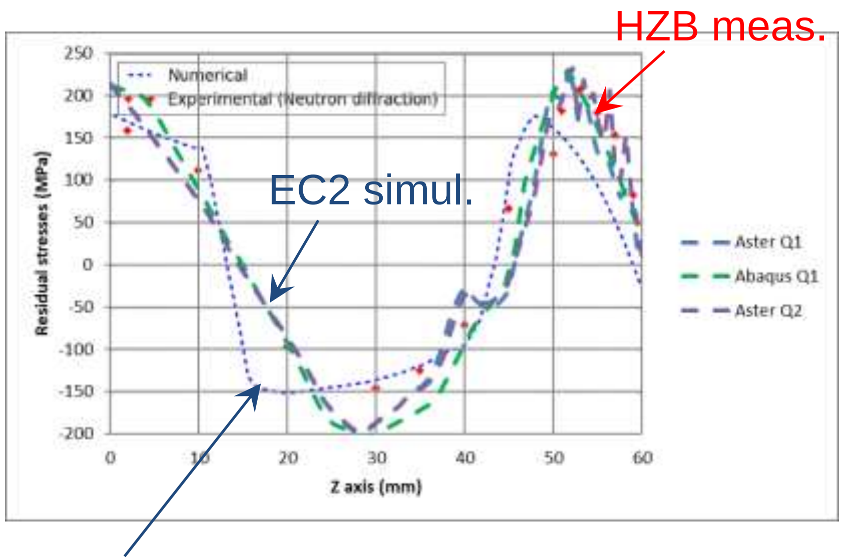
Abaqus / kinematic



Code_Aster / kinematic

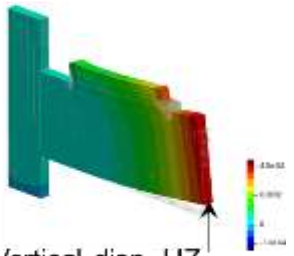




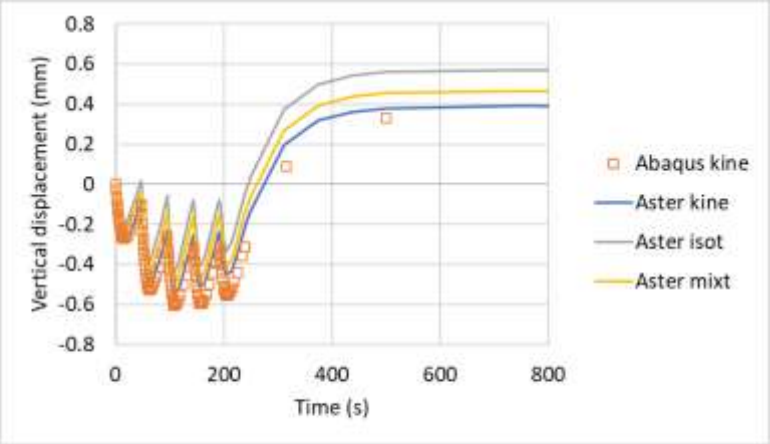


[Cambon&al]
Code_Aster simulation /
Chaboche model

→ **Still ongoing**



Vertical disp. UZ



Numerical activities for the NeT Task Groups

Main General conclusions :

- **Thermal simulation appears mature enough for reasonably satisfactory results ; However, weld pool shape precise prediction without any calibration data is still difficult (Weld pool convection due to Marangoni effect…)**
- **For austenitic steel and Nickel based alloys, mixed hardening and annealing parameters are dominating for RS prediction ; Effects are well understood, but correct material calibration is not straightforward**
- **Metallurgical phase transformations in ferritic steel have huge effects on RS ; if taken into account in the model, it leads to reasonably satisfactory results, yet some phenomena need to be clarified (TRIP influence,**
- **Geometry simplification assumptions as “2,5D” or “macro-bead” techniques are relevant in most cases**

Perspectives of enhancement

- **Viscous effects influence seems weak on RS prediction ; but has to be confirmed on different cases as it is difficult to unpack the effects of annealing, hardening and VP effects**
- **Self tempering effect in ferritic steels needs further understanding**
- **Mixed Hardening and annealing models calibration for ferritic steels require some improvement**
- **Material activation strategy effects on RS and distortion (especially for additive manufacturing) have to be further studied and clarified**