HSNV101 - Thermoplasticity and metallurgy uncoupled in simple traction

Summary:

One treats the determination of the mechanical evolution of a cylindrical bar subjected to thermal evolutions $T(t)$ and metallurgical $Z(t)$ known and uniform (the metallurgical transformation is of bainitic type).

The elements used are axisymmetric elements and the relation of behavior is the plasticity of Von Mises with linear isotropic work hardening (for modeling B, one also takes account of the plasticity of transformation).

The yield stress and the slope of the traction diagram depend on the temperature and the metallurgical composition.

The dilation coefficient α depends on the metallurgical composition.

The metallurgical transformations take place with $\dot{\boldsymbol{\varepsilon}}^p=0$ (it is in the sense that the test **uncouple** the plasticity of transformation of classical plasticity).

Results provided by *Code_Aster* are very satisfactory with errors lower than 2% .

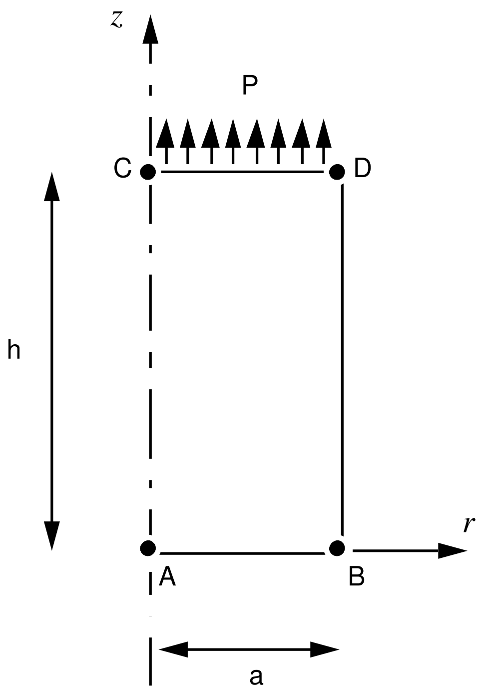
Modeling A, B, D use grids made up of two meshs QUAD8, modeling C uses meshs TRIA6, and modeling E validates the metallurgy on material point.

Modelings A, C and E use behavior META_P_IL, modeling B validates behavior META_P_IL_PT, and modeling D uses META_P_CL.

1 Problem of reference

1.1 Geometry

Rayon : a = 0.05 m.
Hauteur : h = 0.2 m.



1.2 Properties of materials

Following convention is adopted in order to distinguish the parameters from the hot phase (austenitic) parameters of the cold phases (ferrito-perlitic, bainitic and martensitic):

$*^{aust}$ = characteristics relating to the austenitic phase
$*^{fbm}$ = characteristics relating to the phases ferrito-perlitic, bainitic and martensitic

Metallurgical parameters:
TRC to model a metallurgical evolution of bainitic type, on all the structure, of the form:

$$Z_{fbm}=\begin{cases} 0. & si \;\; t\leq\tau_1 \quad \tau_1=60\,s \\ \dfrac{t-\tau_1}{\tau_2-\tau_1} & si \;\; \tau_1\leq t<\tau_2 \quad \tau_2=112\,s \\ 1. & si \;\; t\geq\tau_2 \end{cases}$$

Thermal parameters:
Heat-storage capacity: $\rho C_p=2.\,10^6\,J.m^{-3}.\,{}^\circ C^{-1}$
Conductivity: $\lambda=9999.9\,W.m^{-1}.\,{}^\circ C^{-1}$

Thermomechanical parameters:

- Thermoelastic parameters:

Young modulus $E=200000\,10^6\,Pa$
Poisson's ratio $\nu=0.3$

Dilation coefficients thermal

$$\alpha_{fbm}=15.10^{-6}\,°C^{-1}$$

$$\alpha_{aust}=23.5\,10^{-6}\,°C^{-1}$$

Temperature of definition of the dilation coefficient: $T_{ref}=900\,°C$

Thermal state of deformation of reference: $\Delta\varepsilon_{f\gamma}^{T_{ref}}=2.52\,10^{-3}$

Elastic limit:

$$\sigma_y^{fbm}=\sigma_0^{fbm}+s^{fbm}(T-T^0) \text{ with } \sigma_0^{fbm}=400.10^6\,Pa \text{ and } s^{fbm}=0.5\,10^6\,Pa.°C^{-1}$$
$$\sigma_y^{aust}=\sigma_0^{aust}+s^{aust}(T-T^0) \text{ with } \sigma_0^{aust}=530.10^6\,Pa \text{ and } s^{aust}=0.5\,10^6\,Pa.°C^{-1}$$

- Thermoplastic parameters (law with linear work hardening)

  Tangent modules: E_T^{fbm} and E_T^{aust} are selected such as:

  $$H^{fbm}=H_0^{fbm}+\lambda^{fbm}(T-T^0) \text{ with } H_0^{fbm}=-50.10^6\,Pa \text{ and } \lambda^{fbm}=-5.10^6\,Pa.°C^{-1}$$
  $$H^{aust}=H_0^{aust}+\lambda^{aust}(T-T^0) \text{ with } H_0^{aust}=1250.10^6\,Pa \text{ and } \lambda^{aust}=-5.10^6\,Pa.°C^{-1}$$

  It is pointed out that $H=\dfrac{EE_T}{E-E_T}$

- Parameters for the plasticity of transformation:

  Recall:

In the case of one metallurgical evolution of bainitic type, the model of the plasticity of transformation is the following: $$\dot{\boldsymbol{\varepsilon}}^{pt}=\frac{3}{2}\tilde{\boldsymbol{\sigma}}\,k^{fbm}F'(Z_{fbm})\dot{Z}_{fbm}$$

Parameters of the model: $k^{fbm}=1.10^{-10}\,Pa^{-1}$ and $F'(Z_{fbm})=2(1-Z_{fbm})$

1.3 Boundary conditions and loadings

- $u_Z=0$ on the side AB (condition of symmetry).
- traction imposed on the side CD

  $$p(t)=\begin{cases} p_0 t & si\ \ t<\tau_1 \\ p_0\tau_1 & si\ \ t\geq\tau_1 \end{cases}$$

  with $p_0=6.10^6\,Pa$ and $\tau_1=60\mathrm{s}$
- temperature imposed on all the structure:

  $T(t)=T^0+\mu t$

  with $\mu=-5\,°C.s^{-1}$

1.4 Initial conditions

$T^o=900°\text{C}=T^{ref}$

2 Reference solution

2.1 Method of calculating used for the reference solution

Before transformation, thermoelastic solution for $t<\tau_1^{'}$.

$$\begin{cases}\varepsilon_{zz}(t)=\varepsilon_{zz}^{e}(t)+\varepsilon_{zz}^{th}(t)\\ \sigma_{zz}(t)=p_0 t\\ \varepsilon_{zz}^{e}(t)=\dfrac{\sigma_{zz}(t)}{E}\\ \varepsilon_{zz}^{th}(t)=\alpha_{aust}(T-T^0)\end{cases}$$

The yield stress is reached for:

$$\tau_1^{'}=\frac{\sigma_0^{aust}}{p_0-s^{aust}\mu}=47.06\,s$$

Before transformation, thermoelastoplastic solution, $\tau_1^{'}\le t\le\tau_1$, $\tau_1=60\ s$.

$$\begin{cases}\varepsilon_{zz}(t)=\varepsilon_{zz}^{e}(t)+\varepsilon_{zz}^{th}(t)+\varepsilon_{zz}^{p}(t)\\ \sigma_{zz}(t)=p_0 t\\ \varepsilon_{zz}^{e}(t)=\dfrac{\sigma_{zz}(t)}{E}\\ \varepsilon_{zz}^{th}(t)=\alpha_{aust}(T-T^0)\\ \varepsilon_{zz}^{p}(t)=\dfrac{\sigma_{zz}(t)-(\sigma_0^{aust}+s^{aust}\mu t)}{H_0^{aust}+\lambda^{aust}\mu t}\end{cases}$$

During the transformation, thermo-élasto-metallurgical solution, $\tau_1<t<\tau_2$, $\tau_2=112\ s$.

$$\begin{cases}\varepsilon_{zz}(t)=\varepsilon_{zz}^{e}(t)+\varepsilon_{zz}^{th}(t)+\varepsilon_{zz}^{p}(\tau_1)+\varepsilon_{zz}^{pt}(t)\\ \sigma_{zz}(t)=p_0\tau_1\\ \varepsilon_{zz}^{e}(t)=\dfrac{\sigma_{zz}(t)}{E}\\ \varepsilon_{zz}^{th}(t)=Z_{aust}\alpha_{aust}(T-T^0)+Z_{fbm}\left(\alpha_{fbm}(T-T^0)+\Delta\varepsilon_{f\gamma}^{T_{ref}}\right)\\ \varepsilon_{zz}^{pt}(t)=k^{fbm}F(Z_{fbm})\,p_0\tau_1\end{cases}$$

with $F(Z_{fbm})=Z_{fbm}(1-Z_{fbm})$

After the transformation, thermoelastoplastic solution, $\tau_2<t<\tau_3$, $\tau_3=176\ s$.

$$\begin{cases} \varepsilon_{zz}(t)=\varepsilon_{zz}^{e}(t)+\varepsilon_{zz}^{th}(t)+\varepsilon_{zz}^{p}(t)+\varepsilon_{zz}^{pt}(\tau_2) \\ \sigma_{zz}(t)=p_0\tau_1 \\ \varepsilon_{zz}^{e}(t)=\dfrac{\sigma_{zz}(t)}{E} \\ \varepsilon_{zz}^{th}(t)=\alpha_{fbm}(T-T^0)+\Delta\varepsilon_{f\gamma}^{T_{ref}} \\ \varepsilon_{zz}^{p}(t)=\dfrac{\sigma_{zz}(t)-(\sigma_0^{fbm}+s^{fbm}\mu t)}{H_0^{fbm}+\lambda^{fbm}\mu t} \end{cases}$$

2.2 Results of reference

ε_{zz}^{p} , χ , σ_{zz} and ε_{zz} for $t=47,48,64$ and 114 seconds.

ε_{zz}^{p} for $t=60$ and 176 seconds.

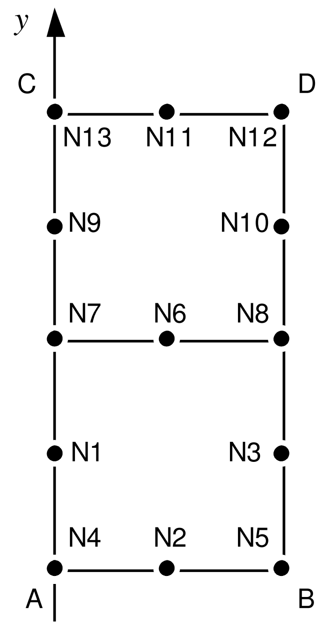
$\varepsilon_{zz}^{th}, \varepsilon_{zz}^{meca}$ and ε_{zz}^{plas} **in the case of modelings B and D**, for $t=47,48,64$ and 114 seconds.
with:
ε^{meca} : mechanical deformations
ε^{plas} : plastic deformations (including the plasticity of transformation)

2.3 Bibliographical references

1) DONORE A.M. - WAECKEL F.: Influence of structure transformations in the elastoplastic laws of behavior Notes HI-74/93/024.

3 Modeling A

3.1 Characteristics of modeling



$A=N4$, $B=N5$, $C=N13$, $D=N12$.

3.2 Characteristics of the grid

Many nodes: 13

Many meshs and types: 2 meshs QUAD8, 6 meshs SEG3

3.3 Sizes tested and results

One tests the structural parameters of data results:

Identification	Reference
INST for NUME_ORDRE= 7 0	176
ITER_GLOB for NUME_ORDRE=70	5

Identification	Reference	Test	Tolerance
ε_{zz}^{p} $t=47\,s$	0	ANALYTICAL	1,0E-12 (absolute)
χ $t=47\,s$	0	ANALYTICAL	1,0E-12 (absolute)
σ_{zz} $t=47\,s$	$282.\ 10^{6}$	ANALYTICAL	0,1%
ε_{zz} $t=47\,s$	$-4.1125\ 10^{-3}$	ANALYTICAL	0,1%
ε_{zz}^{p} $t=48\,s$	$3.2653\ 10^{-3}$	ANALYTICAL	0,15%
χ $t=48\,s$	1	ANALYTICAL	0,1%
σ_{zz} $t=48\,s$	$288.\ 10^{6}$	ANALYTICAL	0,1%
ε_{zz} $t=48\,s$	$-9.3469\ 10^{-4}$	ANALYTICAL	0,007%
ε_{zz}^{p} $t=60\,s$	0.04	ANALYTICAL	0,1%
ε_{zz}^{p} $t=64\,s$	0,040	ANALYTICAL	0,022%
χ $t=64\,s$	0	ANALYTICAL	1,0E-12 (absolute)
σ_{zz} $t=64\,s$	$360.\ 10^{6}$	ANALYTICAL	0,01%
ε_{zz} $t=64\,s$	$3.4683\ 10^{-2}$	ANALYTICAL	0,025%
ε_{zz}^{p} $t=114\,s$	0.04107	ANALYTICAL	0,01%
χ $t=114\,s$	1	ANALYTICAL	0,1%
σ_{zz} $t=114\,s$	$360.\ 10^{6}$	ANALYTICAL	0,020%
ε_{zz} $t=114\,s$	0.03684	ANALYTICAL	0,026%
ε_{zz}^{p} $t=176\,s$	0.06206	ANALYTICAL	0,20%

3.4 Remarks

In this modeling: $\varepsilon_{zz}^{pt}=0$

4 Modeling B

4.1 Characteristics of modeling

The grid and the data are identical to modeling A; the only difference comes from behavior META_P_IL_PT (taken into account of the plasticity of transformation)

4.2 Sizes tested and results

Identification	Reference	Test	Tolerance
ε_{zz}^{p} $t=47\,s$	0	ANALYTICAL	0.1%
χ $t=47\,s$	0	ANALYTICAL	0.1%
σ_{zz} $t=47\,s$	282. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=47\,s$	-4.1125 10^{-3}	ANALYTICAL	0.1%
ε_{zz}^{th} $t=47\,s$	-0.0055225	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=47\,s$	0.00141	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=47\,s$	0	ANALYTICAL	0.1%
ε_{zz}^{p} $t=48\,s$	3.2653 10^{-3}	ANALYTICAL	1.1 %
χ $t=48\,s$	1	ANALYTICAL	0.1%
σ_{zz} $t=48\,s$	288. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=48\,s$	-9.3469 10^{-4}	ANALYTICAL	0.1%
ε_{zz}^{th} $t=48\,s$	-0.00564	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=48\,s$	0.004705	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=48\,s$	0.0032653	ANALYTICAL	0.1%
ε_{zz}^{p} $t=60\,s$	0.04	ANALYTICAL	0.1%
ε_{zz}^{p} $t=64\,s$	0.04	ANALYTICAL	0.1%
χ $t=64\,s$	0	ANALYTICAL	0.1%
σ_{zz} $t=64\,s$	360. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=64\,s$	4.00085 10^{-2}	ANALYTICAL	0.2%
ε_{zz}^{th} $t=64\,s$	-0.007117	ANALYTICAL	0.2%
ε_{zz}^{meca} $t=64\,s$	0.047125	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=64\,s$	0.04533	ANALYTICAL	0.1%
ε_{zz}^{p} $t=114\,s$	0.041071	ANALYTICAL	0.1%
χ $t=114\,s$	1	ANALYTICAL	0.1%
σ_{zz} $t=114\,s$	360. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=114\,s$	0.072841	ANALYTICAL	2.0%
ε_{zz}^{th} $t=114\,s$	-0.00603	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=114\,s$	0.07887	ANALYTICAL	2.0%
ε_{zz}^{plas} $t=114\,s$	0.07707	ANALYTICAL	2.0%
ε_{zz}^{p} $t=176\,s$	0.062069	ANALYTICAL	0.1%

4.3 Remarks

In this modeling, one takes into account the term due to the plasticity of transformation:

$$\dot{\varepsilon}^{pt}(T, Z) \neq 0 \text{ when } \dot{Z} \neq 0$$

5 Modeling C

5.1 Characteristics of modeling

Identical to modeling A, only the grid is different (triangular meshs).

5.2 Characteristics of the grid

Many nodes: 13

Many meshs and types: 4 meshs TRIA6

5.3 Sizes tested and results

One tests the structural parameters of data results:

Identification	Reference
INST for NUME_ORDRE= 7 0	176
ITER_GLOB for NUME_ORDRE=70	5

Identification	Reference	Test	Tolerance
ε_{zz}^{p} $t=47\,s$	0	ANALYTICAL	1,0E-12 (absolute)
χ $t=47\,s$	0	ANALYTICAL	1,0E-12 (absolute)
σ_{zz} $t=47\,s$	$282.\ 10^{6}$	ANALYTICAL	0,1%
ε_{zz} $t=47\,s$	$-4.1125\ 10^{-3}$	ANALYTICAL	0,1%
ε_{zz}^{p} $t=48\,s$	$3.2653\ 10^{-3}$	ANALYTICAL	0,15%
χ $t=48\,s$	1	ANALYTICAL	0,1%
σ_{zz} $t=48\,s$	$288.\ 10^{6}$	ANALYTICAL	0,1%
ε_{zz} $t=48\,s$	$-9.3469\ 10^{-4}$	ANALYTICAL	0,007%
ε_{zz}^{p} $t=60\,s$	0.04	ANALYTICAL	0,1%

ε_{zz}^{p} $t=64\,s$	0,040	ANALYTICAL	0,022%
χ $t=64\,s$	0	ANALYTICAL	1,0E-12 (absolute)
σ_{zz} $t=64\,s$	$360.\ 10^{6}$	ANALYTICAL	0,01%
ε_{zz} $t=64\,s$	$3.4683\ 10^{-2}$	ANALYTICAL	0,025%
ε_{zz}^{p} $t=114\,s$	0.04107	ANALYTICAL	0,01%
χ $t=114\,s$	1	ANALYTICAL	0,1%
σ_{zz} $t=114\,s$	$360.\ 10^{6}$	ANALYTICAL	0,020%
ε_{zz} $t=114\,s$	0.03684	ANALYTICAL	0,026%
ε_{zz}^{p} $t=176\,s$	0.06206	ANALYTICAL	0,20%

6 Modeling D

6.1 Characteristics of modeling

Grid identical to that of modeling A.
Linear kinematic work hardening: META_P_CL

6.2 Sizes tested and results

Identification	Reference	Test	Tolerance
ε_{zz}^{p} $t=47\,s$	0	ANALYTICAL	0.1%
χ $t=47\,s$	0	ANALYTICAL	0.1%
σ_{zz} $t=47\,s$	$282.\ 10^{6}$	ANALYTICAL	0.1%
ε_{zz} $t=47\,s$	$-4.1125\ 10^{-3}$	ANALYTICAL	0.1%
ε_{zz}^{th} $t=47\,s$	-0.0055225	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=47\,s$	0.00141	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=47\,s$	0	ANALYTICAL	0.1%
ε_{zz}^{p} $t=48\,s$	$3.2653\ 10^{-3}$	ANALYTICAL	1.1 %
χ $t=48\,s$	1	ANALYTICAL	0.1%
σ_{zz} $t=48\,s$	$288.\ 10^{6}$	ANALYTICAL	0.1%
ε_{zz} $t=48\,s$	$-9.3469\ 10^{-4}$	ANALYTICAL	0.1%
ε_{zz}^{th} $t=48\,s$	-0.00564	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=48\,s$	0.004705	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=48\,s$	0.0032653	ANALYTICAL	0.1%
ε_{zz}^{p} $t=60\,s$	0.04	ANALYTICAL	0.1%
ε_{zz}^{p} $t=64\,s$	0.04	ANALYTICAL	0.1%
χ $t=64\,s$	0	ANALYTICAL	0.1%

σ_{zz} $t=64\,s$	360. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=64\,s$	3.466810^{-2}	ANALYTICAL	0.1%
ε_{zz}^{th} $t=64\,s$	-0.007117	ANALYTICAL	0.2%
ε_{zz}^{meca} $t=64\,s$	0.04180	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=64\,s$	0.04	ANALYTICAL	0.1%
ε_{zz}^{p} $t=114\,s$	0.04107	ANALYTICAL	0.1%
χ $t=114\,s$	1	ANALYTICAL	0.1%
σ_{zz} $t=114\,s$	360. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=114\,s$	0.036841	ANALYTICAL	0.1%
ε_{zz}^{th} $t=114\,s$	-0.00603	ANALYTICAL	0.2%
ε_{zz}^{meca} $t=114\,s$	0.0428701	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=114\,s$	0.04107	ANALYTICAL	0.1%
ε_{zz}^{p} $t=176\,s$	0.06206	ANALYTICAL	0.20%
ε_{zz}^{p} $t=206\,s$	0.062069	ANALYTICAL	0.1%
σ_{zz} $t=206\,s$	180. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=206\,s$	0.052288	ANALYTICAL	0.1%
ε_{zz}^{th} $t=206\,s$	-0.01068	ANALYTICAL	0.2%
ε_{zz}^{meca} $t=206\,s$	0.062968	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=206\,s$	0.062069	ANALYTICAL	0.1%
ε_{zz}^{p} $t=251\,s$	0	ANALYTICAL	0.1% (absolute)
σ_{zz} $t=251\,s$	-90. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=251\,s$	-0.01113	ANALYTICAL	0.1%
ε_{zz}^{th} $t=251\,s$	-0.01068	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=251\,s$	-0.00045	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=251\,s$	0	ANALYTICAL	0.1% (absolute)
ε_{zz}^{p} $t=296\,s$	-0.062069	ANALYTICAL	0.1% (absolute)
σ_{zz} $t=296\,s$	-360. 10^6	ANALYTICAL	0.1%
ε_{zz} $t=296\,s$	-0.07455	ANALYTICAL	0.1%
ε_{zz}^{th} $t=296\,s$	-0.01068	ANALYTICAL	0.1%
ε_{zz}^{meca} $t=296\,s$	-0.063869	ANALYTICAL	0.1%
ε_{zz}^{plas} $t=296\,s$	-0.062069	ANALYTICAL	0.1% (absolute)

7 Modeling E

7.1 Characteristics of modeling

Not material (use of SIMU_POINT_MAT)

7.2 Sizes tested and results

One tests the structural parameters of data results (same values of reference as modeling A)

Identification	Reference	Tolerance
ε_{zz}^{p} $t=114\,s$	0.04107	0,0001%
ε_{zz} $t=114\,s$	0.03684	0,0001%
ε_{zz}^{p} $t=176\,s$	0.06206	0,0001%

8 Summary of the results

Results found with *Code_Aster* are very satisfactory, with percentages of error lower than 0.025% except for the deformation at the moment $114\,s$ where the error reached 2% for modeling B.