Note of use for calculations thermo-metal-worker-mechanics on steels

Summary

The objective of this note is to give the necessary information so that user can carry out a calculation thermo-metal-worker-mechanics easily in *Code_Aster*. This kind of calculation relates to steels which undergo during a heating or of a cooling of structure transformations.

Contents

1 Broad outlines of calculation thermo-metal-worker-mechanics

In *Code_Aster*, calculations thermics, metallurgical and mechanical are uncoupled. The successive stages of a complete calculation are the following ones:

1) One carries out a thermal calculation which makes it possible to obtain the field of temperature in each node.

2) One realizes in postprocessing of thermal calculation, the metallurgical calculation which makes it possible to obtain the proportion of the various metallurgical phases in each node and possibly associated hardness.
In *Code_Aster*, one can treat two different types of material, which undergo metallurgical transformations: steels or the ZIRCALOY. One is interested here only in materials of type steel.
For a steel, one can take into account five different metallurgical phases: ferrite, pearlite, the bainite, martensite, known as phase α , and austenite, known as phase γ .

3) Starting from the field of temperature and metallurgical phases, one carries out mechanical calculation by choosing a model of behavior which takes into account the various possible effects of the metallurgical transformations. One thus obtains the internal variable and deformation, stress fields in each point of Gauss.

2 What to make to carry out a calculation thermo-metal-worker-mechanics?

2.1 Stage 1: which documents lira – summary

2.1.1 For the thermal part

The document [R5.02.02] contains the necessary information with the comprehension of a nonlinear thermal calculation.

In *Code_Aster*, for a nonlinear calculation, one treats the diffusion of heat with a enthalpic formulation. One can provide either conductivity and the enthalpy according to the temperature, or conductivity and the specific heat ρC_p according to the temperature.

2.1.2 For the part models metallurgical behavior

The document [R4.04.01] of *Code_Aster* described the various metallurgical models.

Brief summary:

When a material is heated, phases α transform themselves into phase γ . When material is cooled, austenite is transformed, according to the speed of cooling, into ferrite and/or pearlite and/or bainite and/or martensite. It is thus necessary to define for the heating the kinetics of transformation $\alpha\rightarrow\gamma$ and for cooling the nature and the kinetics of the possible transformations $\gamma\rightarrow\alpha$.

Kinetics of transformation to the heating:

The law of evolution of austenite is given by the equation:

$$\dot{Z}_\gamma=\frac{Z_{eq}-Z_\gamma}{\tau}$$

with $Z_{eq}=\begin{cases} 0 & \text{si} \quad T\leq Ac1 \\ \dfrac{T-Ac1}{Ac3-Ac1} & \text{si} \quad Ac1\leq T\leq Ac3 \\ 1 & \text{si} \quad T\geq Ac3 \end{cases}$

and $\tau=\begin{cases} \tau_1 & \text{si} \quad T\leq Ac1 \\ \tau_1+\dfrac{T-Ac1}{Ac3-Ac1}(\tau_3-\tau_1) & \text{si} \quad Ac1\leq T\leq Ac3 \\ \tau_3 & \text{si} \quad T\geq Ac3 \end{cases}$

where Z_γ is the proportion of phase γ, $Ac1$ the quasi-static temperature of beginning of transformation of the phases, $Ac3$ α the quasi-static temperature of end of transformation of the phases α and τ_1, τ_3 two coefficients of material. Z_{eq} corresponds to the evolution of the austenite rate transformed during quasi-static evolutions. Initial temperatures $Ac1$ and of end $Ac3$ of austenitic transformation and parameters τ_1 and τ_3 can be identified starting from experimental data providing for different heating rates, the proportion of austenite formed according to the temperature. One will find in [bib1] precise details on the method of identification of the coefficients.

Example:

For a steel 16MND5, the coefficients are worth $Ac1=716\,°C$, $Ac3=802\,°C$, $\tau_1=12\text{s}$ *and* $\tau_3=0.5\text{s}$.

Kinetics of transformation to cooling:

For the ferritic, perlitic and bainitic transformations, the kinetics is given by the following relation:

$$\dot{Z}=f(T,\dot{T},Z,M_s,d^c)\frac{(T-M_s)^+}{(T-M_s)} \text{ with } Z=\{Z_F,Z_P,Z_B\}$$

where M_s represent the martensitic initial temperature of transformation, d^c austenitic size of grain and $(X)^+$ the positive part of X. For the functions of evolution f, one does not impose particular forms and the identification of f summarizes itself with the definition of diagrams of the type TRC (transformation into Continuous Cooling). This diagram makes it possible to define the evolutions of ferrite, pearlite and bainite associated with a thermal history with the cooling and conditions of austenitization given (for a size with grain d^c data).

For the martensitic transformation, one uses the kinetics of Koistinen-Marburger given by the equation:

$$Z_M=(1-Z_F-Z_P-Z_B)\left[1-\exp(\alpha(M_s-T^+))\right]$$
$$M_s=\begin{cases} M_{s0} & \text{si} \quad Z_F+Z_P+Z_B\leq seuil \\ M_{s0}+Akm(Z_F+Z_P+Z_B)+Bkm & \text{si} \quad Z_F+Z_P+Z_B>seuil \end{cases}$$

where M_{s0} represent the martensitic initial temperature of transformation when that Ci is total and α, Akm, Bkm and $seuil$ are parameters materials.

In the simplest case, one can take the temperature M_s constant and thus equalizes with M_{s0}. For a steel 16MND6, M_{s0} is worth $365\,°C$.

Note:

Diagrams TRC are relative to conditions of austenitization given to which correspond a value of size of grain d *. This size of grain results from the thermal history undergone* *with the heating and does not evolve any more with cooling. In Code_Aster, it is possible to calculate starting from the thermal history with the heating, the evolution of the size of grain and to take account of its effect on the metallurgical behavior with cooling (see case test of reference hsnv126a.comm, hsnv126b.comm and mtlp102a.comm for the use).*

Note:

It is possible in Code_Aster to calculate hardness Hv multiphase mixture given by the relation $Hv=\sum_{k=1}^{5} Z_k Hv_k$ where Hv_k is hardness associated with the phase k and well informed under the operator `DEFI_MATERIAU` under the keyword 'DURT_META'. The hardness of the multiphase mixture is obtained by the operator `CALC_META` with the option 'DURT_ELNO' (hardness with the nodes by element).

2.1.3 For the part mechanical behavior with effects of the metallurgical transformations models

The reference document of *Code_Aster* is the note [R4.04.02].

Several models of behavior are available in the code. They make it possible to model the various following phenomena: plastic behavior or viscous behavior, linear isotropic work hardening or not linear or linear kinematic work hardening, plasticity of transformation, restoration of metallurgical work hardening of origin, restoration of work hardening of viscous origin. One can carry out a calculation in small deformations but also in great deformations (attention the great deformations for a model with kinematic work hardening are not activated). For a comprehension on the aspect great deformations, lira the reference documents [R5.03.21] (great deformations without metallurgical effect) and [R4.04.03] (great deformations with metallurgical effects).

Brief summary:

The effects of structure transformations on the mechanical behavior are of 4 types:

- the mechanical characteristics of the material which undergoes transformations are modified. In particular, the plastic characteristics (limit elastic in particular) and the thermal dilation coefficient are strongly affected. For the elastic limit of the multiphase point, one uses a non-linear law of the mixtures given by:

$$\sigma_y=\left[1-g\left(\sum_{i=1}^{4} Z_i\right)\right]\sigma_{y\gamma}+g\left(\sum_{i=1}^{4} Z_i\right)\sigma_{y\alpha}\ ,\quad \sigma_{ya}=\frac{\sum_{i=1}^{4} Z_i\sigma_{y\alpha i}}{\sum_{i=1}^{4} Z_i}$$

  where Z_i is the proportion of each phase α and g a function of Z_i.

- the expansion or the voluminal contraction which accompanies structure transformations translates by a spherical deformation "of transformation" which is superimposed on the thermal deformation. In general, one gathers this effect with that due to the modification of the thermal dilation coefficient. The thermal deformation is given by:

$$\varepsilon^{th}=Z_\gamma\left[\alpha_\gamma(T-T_{ref})-(1-Z_\gamma^r)\Delta\varepsilon_{f\gamma}^{T_{ref}}\right]+\sum_{i=1}^{4} Z_i\left[\alpha_f(T-T_{ref})+Z_\gamma^r\Delta\varepsilon_{f\gamma}^{T_{ref}}\right]$$

  where α_γ and α_f are the dilation coefficients of the austenitic and ferritic phases, respectively. $\Delta\varepsilon_{f\gamma}^{T_{ref}}$ translated the difference in compactness between the two phases at the temperature of reference. One has $Z_\gamma^r=1$ when the phase of reference is the austenitic phase and $Z_\gamma^r=0$ when the phase of reference is the ferritic phase.

- a transformation proceeding under constraints can give rise to an unrecoverable deformation and this, even for levels of constraints much lower than the elastic limit of material. One calls this phenomenon the plasticity of transformation. In small deformations, this additional term appears in the expression of the total deflection. The law of evolution of the deformation which accompanies this phenomenon writes:

$$\dot{\boldsymbol{\varepsilon}}^{pt}=\frac{3}{2}\tilde{\boldsymbol{\sigma}}\sum_{i=1}^{4}K_i F'_i(Z_\gamma)\cdot\langle\dot{Z}_i\rangle$$

  where $\tilde{\boldsymbol{\sigma}}$ is the diverter of the tensor of the constraints, $\langle X\rangle$ the positive part of X, K_i and F_i, coefficients of the 4 ferritic phases. It is considered that this phenomenon does not exist at the time of austenitic transformations.

- finally, one can have at the time of the transformation a phenomenon of restoration of work hardening: the work hardening of the mother phase (or not completely) is not transmitted to the phases lately created. The phases lately created can either be born with a virgin state of work hardening, or to inherit only part of work hardening of the mother phase or or to inherit totality work hardening the mother phase.
  In the case of an isotropic work hardening, plastic deformation p is not characteristic any more of the state of work hardening and it is necessary to define other variables for each phase, noted r_k. Isotropic work hardening is written then:

$$R=\left(1-\bar{f}(Z)\right)R_\gamma+\frac{\bar{f}(Z)}{Z}\sum_{i=1}^{4}Z_i\cdot R_i\ ,\quad Z=\sum_{i=1}^{4}Z_i$$

  where R_k is the variable of work hardening of the phase k who can be linear or not linear compared to r_k and $\bar{f}(Z)$ a function depending on Z such as $\bar{f}(Z)\in[0,1]$.
  Laws of evolution of the variables r_i are given by:

$$\dot{r}_\gamma=\dot{p}+\frac{\sum_{i=1}^{4}\langle-\dot{Z}_i\rangle(\theta_{i\gamma}r_i-r_\gamma)}{Z_\gamma}-\underbrace{(C\,r_{moy})^m}_{\text{uniquement en viscosité}}\qquad \text{si}\quad Z_\gamma>0$$

$$\dot{r}_i=\dot{p}+\frac{\langle Z_i\rangle(\theta_{\gamma i}r_\gamma-r_i)}{Z_\gamma}-\underbrace{(C\,r_{moy})^m}_{\text{uniquement en viscosité}}\qquad \text{si}\quad Z_i>0$$

$$r_{moy}=\sum_{k=1}^{5}Z_k r_k$$

$$C=\sum_{k=1}^{5}Z_k C_k$$

$$m=\sum_{k=1}^{5}Z_k m_k$$

C_k and m_k are the coefficients of viscous restoration associated with the phase k, $\theta_{i\gamma}$ and $\theta_{\gamma i}$ characterize the proportion of work hardening transmitted at the time of the transformation $\alpha\rightarrow\gamma$ and of the transformation $\gamma\rightarrow\alpha$, respectively. The memory is non-existent if $\theta=0$, supplements if $\theta=1$.

In an equivalent way, a kinematic work hardening in the case of is written:

$$X=\left(1-\bar{f}(Z)\right)+\frac{\bar{f}(Z)}{Z}\sum_{i=1}^{4} Z_i \cdot X_i\ ,\ Z=\sum_{i=1}^{4} Z_i$$

where X_k is the kinematic variable of work hardening of the phase k who is linear compared to the variable α_k :

$$X_k=\frac{2}{3} H_k \alpha_k$$

Laws of evolution of variable kinematics α_k are given by:

$$\dot{\boldsymbol{\alpha}}_\gamma=\dot{\boldsymbol{\varepsilon}}^p+\frac{\sum_{i=1}^{4}\langle\dot{Z}_i\rangle(\theta_{i\gamma}\boldsymbol{\alpha}_i-\boldsymbol{\alpha}_\gamma)}{Z_\gamma}+\underbrace{\frac{3}{2}(C\alpha_{eq})^m\frac{\boldsymbol{\alpha}}{\alpha_{eq}}}_{\text{uniquement en viscosité}}\quad \text{si}\quad Z_\gamma>0$$

$$\dot{\boldsymbol{\alpha}}_i=\dot{\boldsymbol{\varepsilon}}^p+\frac{\langle\dot{Z}_i\rangle(\theta_{\gamma i}\boldsymbol{\alpha}_\gamma-\boldsymbol{\alpha}_i)}{Z_i}+\underbrace{\frac{3}{2}(C\alpha_{eq})^m\frac{\boldsymbol{\alpha}}{\alpha_{eq}}}_{\text{uniquement en viscosité}}\quad \text{si}\quad Z_i>0$$

$$\dot{\boldsymbol{\varepsilon}}^p=\frac{3}{2}\dot{p}\frac{(\tilde{\boldsymbol{\sigma}}-\boldsymbol{X})}{(\sigma-X)_{eq}}$$

where H_k are the slopes of work hardening associated with each phase k .

For a model of plasticity, the plastic multiplier is obtained by writing the condition of coherence $\dot{f}=0$ and one a:

$$\dot{p}\geq 0\ ,\ f\leq 0 \text{ and } \dot{p}\,f=0$$

In the viscous case, $\dot{p}$ is written:

$$\dot{p}=\left(\frac{\langle f\rangle}{\eta}\right)^n$$

where f is the threshold of plasticity given by:

$f=\sigma_{eq}-R-\sigma_y$ in the case of an isotropic work hardening
$f=(\sigma-X)_{eq}-\sigma_y$ in the case of a kinematic work hardening

2.2 Stage 2: construction of the command file

2.2.1 Parts thermics and metallurgical

1) **Definition of diagram TRC** : to see the order DEFI_TRC in the document [U4.43.04]. This order is made up of three parts: a part where one defines the evolutions of ferrite, pearlite and bainite associated with a set of thermal history with the cooling and of the conditions of austenitization given (size of grain), one second part which defines the parameters related to the change of temperature ms and a third part which defines the influence of the size of grain on the metallurgical transformations in cooling by diagram TRC. This last part is not obligatory.

2) **Definition of the initial metallurgical phases** : to see the order CREA_CHAMP in the document [U4.72.04]. This order makes it possible to define the initial metallurgical phases present in material.

3) **Definition of material** : to see the order DEFI_MATERIAU (document [U4.43.01]). For the thermal part, it is necessary to inform the keyword THER_NL who contains the values of thermal conductivity and those of the enthalpy, functions possibly of the temperature. For the metallurgical part, it is necessary to inform the keyword META_ACIER the structure is the following one:

META_ACIER: (
- ♦ TRC : name of diagram TRC defines in 1)
- ♦ AR3 : quasi-static temperature of beginning of decomposition of austenite to cooling.
- ♦ ALPHA : coefficient has law of Koïstinen-Marbürger
- ♦ MS0 : martensitic initial temperature of transformation when this one is total.
- ♦ AC1 : quasi-static temperature of beginning of transformation into austenite with the heating.
- ♦ AC3 : quasi-static temperature of end of transformation into austenite.
- ♦ TAUX_1 : parameter intervening in the kinetics with the heating.
- ♦ TAUX_3 : parameter intervening in the kinetics with the heating.
- ◊ LAMBDA : parameter material intervening in the model of evolution of size of grain.
- ◊ QSR_K : parameter energy of activation intervening in the model of evolution of size of grain.
- ◊ D10 : parameter material intervening in the model of evolution of size of grain.
- ◊ WSR_K : parameter energy of activation intervening in the model of evolution of size of grain.

4) **Realization of thermal calculation** : to see documentation of Use and Reference of the thermal operators: THER_LINEAIRE and THER_NON_LINE.

5) **Realization of metallurgical calculation** : to see the order CALC_META (document [U4.85.01]). This order makes it possible to obtain starting from preceding thermal calculation, the proportions of the various metallurgical phases. It is on this level that one informs the initial metallurgical state (order CREA_CHAMP).

2.2.2 Mechanical part

1) **Definition of material** : to see the order DEFI_MATERIAU (document [U4.43.01]). According to the phenomena which one wishes to model, several keywords must be indicated.
In all the cases, the user must supplement the keywords:

   - ELAS_META (_FO) who contains information on the elastic characteristics, of thermal dilations and elastic limits,
   - META_ECRO_LINE to define an isotropic or kinematic work hardening linear and META_TRACTION to define a nonlinear isotropic work hardening.

The other possible phenomena (nonobligatory) are the following:

- viscoplasticity + restoration of viscous origin: keyword factor META_VISC (_FO)
- plasticity of transformation: keyword factor META_PT
- metallurgical restoration of origin: keyword factor META_RE

Note:

_FO mean that the coefficients can possibly depend on the temperature.

2) Realization of mechanical calculation : order STAT_NON_LINE (document [U4.51.03]). Under the keyword BEHAVIOR, one must specify under RELATION, the name of the model chosen among the 24 models below and under RELATION_KIT, the material 'STEEL'.

The various models are:

```
/ 'META_P_IL'
/ 'META_P_INL'
/ 'META_P_IL_PT'
/ 'META_P_INL_PT'
/ 'META_P_IL_RE'
/ 'META_P_INL_RE'
/ 'META_P_IL_PT_RE'
/ 'META_P_INL_PT_RE'
/ 'META_P_CL'
/ 'META_P_CL_PT'
/ 'META_P_CL_RE'
/ 'META_P_CL_PT_RE'
/ 'META_V_IL'
/ 'META_V_INL'
/ 'META_V_IL_PT'
/ 'META_V_INL_PT'
/ 'META_V_IL_RE'
/ 'META_V_INL_RE'
/ 'META_V_IL_PT_RE'
/ 'META_V_INL_PT_RE'
/ 'META_V_CL'
/ 'META_V_CL_PT'
/ 'META_V_CL_RE'
/ 'META_V_CL_PT_RE'
```

Significance of the letters:

P = plasticity, V = viscoplasticity, IT = linear isotropic work hardening, nonlinear INL = isotropic work hardening, linear CL = kinematic work hardening, Pt = plasticity of transformation, RE = restoration of metallurgical work hardening of origin.

2.2.3 Example of command file

The example that we present now is that of a thin steel 16MND5 disc which is heated on its face higher by a laser beam then cooled than the ambient air. Modeling is axisymmetric. The imposed loading is a flow on part of the higher face, the undergoing rest of the faces of the conditions of natural convection and radiation. Initially the disc is composed of 61% of ferrite and 39% of bainite. With the heating, ferrite and the bainite are transformed into austenite. With cooling, austenite is transformed into bainite and martensite (there is thus no pearlite). This study is presented in detail in document HI-74/99/002.

One presents Ci below the command file of this simulation. One gives only the principal orders which refer to a metallurgical calculation.

Command file
 # CALCULATION ON A STEEL 16MND5 DISC
 # I - THERMAL AND METALLURGICAL PART
 # I.1 - DEFINITION OF THE GRID
 # I.2 - DEFINITION OF THE MODEL

```
moth=AFFE_MODELE (
   MAILLAGE=mail,
   AFFE=_F (
      TOUT=' OUI',
      PHENOMENE=' THERMIQUE',
      MODELISATION=' AXIS',),);
```

 # I.3 - DEFINITION OF MATERIAL
 # I.3.1 - DEFINITION OF DIAGRAM TRC

```
TRC   = DEFI_TRC (
HIST_EXP= (
_F (VALE = (
-1.000D+00,  1.000D+01,  0.000D+00,  0.0000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  0.0000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  8.3000D+02,
 0.000D+00,  0.000D+00,  0.000D+00,  5.6520D+02,
 0.000D+00,  0.000D+00,  1.000D-02,  5.6000D+02,
 0.000D+00,  0.000D+00,  2.400D-02,  5.5062D+02,
 0.000D+00,  0.000D+00,  7.600D-02,  5.3670D+02,
 0.000D+00,  0.000D+00,  12.00D-02,  5.2960D+02,
 0.000D+00,  0.000D+00,  22.70D-02,  5.1380D+02,
 0.000D+00,  0.000D+00,  32.50D-02,  5.0155D+02,
 0.000D+00,  0.000D+00,  41.80D-02,  4.8748D+02,
 0.000D+00,  0.000D+00,  52.80D-02,  4.6595D+02,
 0.000D+00,  0.000D+00,  57.60D-02,  4.5422D+02,
 0.000D+00,  0.000D+00,  60.00D-02,  4.4531D+02,
 0.000D+00,  0.000D+00,  69.00D-02,  4.0712D+02,
 0.000D+00,  0.000D+00,  72.20D-02,  3.9157D+02,
 0.000D+00,  0.000D+00,  7.500D-01,  3.6600D+02,
 0.000D+00,  0.000D+00,  7.600D-01,  3.6080D+02,)),
_F (VALE = (
-3.400D+00,  1.000D+01,  0.000D+00,  0.0000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  0.0000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  8.3000D+02,
 0.000D+00,  0.000D+00,  0.000D+00,  5.6530D+02,
 0.000D+00,  0.000D+00,  1.000D-02,  5.6000D+02,
 0.000D+00,  0.000D+00,  5.980D-02,  5.4326D+02,
 0.000D+00,  0.000D+00,  35.00D-02,  5.0750D+02,
 0.000D+00,  0.000D+00,  44.00D-02,  4.9711D+02,
 0.000D+00,  0.000D+00,  52.50D-02,  4.7641D+02,
 0.000D+00,  0.000D+00,  65.00D-02,  4.2853D+02,
 0.000D+00,  0.000D+00,  6.840D-01,  3.8393D+02,
 0.000D+00,  0.000D+00,  6.800D-01,  3.8200D+02,
 0.000D+00,  0.000D+00,  6.900D-01,  3.7670D+02,)),
_F (VALE = (
-8.000D+00,  1.000D+01,  0.000D+00,  0.000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  0.000D+00,
 0.000D+00,  0.000D+00,  0.000D+00,  8.300D+02,
 0.000D+00,  0.000D+00,  0.000D+00,  5.570D+02,
 0.000D+00,  0.000D+00,  1.000D-02,  5.500D+02,
 0.000D+00,  0.000D+00,  1.800D-02,  5.4746D+02,
 0.000D+00,  0.000D+00,  10.80D-02,  5.2087D+02,
```

```
 0.000D+00,  0.000D+00,  27.00D-02,  4.8780D+02,
 0.000D+00,  0.000D+00,  37.30D-02,  4.5920D+02,
 0.000D+00,  0.000D+00,  44.40D-02,  4.2560D+02,
 0.000D+00,  0.000D+00,  49.70D-02,  3.7440D+02,
 0.000D+00,  0.000D+00,  5.115D-01,  3.6400D+02,
 0.000D+00,  0.000D+00,  5.215D-01,  3.5660D+02,))),
TEMP_MS = _F (
   THRESHOLD = 1.000D+00,
   AKM = 0.000D+00,
   BKM = 0.000D+00,
   TPLM = -5.000D-01));
```

 # I.3.3 DEFINITION OF MATERIAL

```
ACIER=DEFI_MATERIAU (
   THER_NL=_F (
      LAMBDA= conductivity,
      BETA=enthalpie,),
   META_ACIER=_F (
      TRC=TRC,
      AR3=830.0,
      ALPHA=-0.0247,
      MS0=365.0,
      AC1=716.29,
      AC3=802.58,
      TAUX_1=12.0,
      TAUX_3=0.5,),);
```

 # I.3.4 - ASSIGNMENT OF MATERIAL
 # I.4 - BOUNDARY CONDITIONS AND LOADING
 # I.5 - CALCULATION THERMAL
 # I.5.1 - LIST D URGENT
 # I.5.2 - RESOLUTION WITH THE HEATING AND COOLING

```
TEMPE=THER_NON_LINE (
   MODELE=moth,
   CHAM_MATER=matc,
   EXCIT=_F (CHARGE=char_c,),
   INCREMENT=_F (
      LIST_INST=list,
      NUME_FIN=70,),
   TEMP_INIT=_F (VALE=28.0,),
   CONVERGENCE=_F (
      RESI_GLOB_RELA=5.E-05,
      ITER_GLOB_MAXI=40,),);

TEMPE=THER_NON_LINE (
   reuse =tempe,
   MODELE=moth,
   CHAM_MATER=matr,
   EXCIT=_F (CHARGE=char_r,),
   INCREMENT=_F (
      LIST_INST=list,
      NUME_INIT=70,),
   TEMP_INIT=_F (
      EVOL_THER=tempe,
      NUME_INIT=70,),
   NEWTON=_F (REAC_ITER=1,),
   CONVERGENCE=_F (
      RESI_GLOB_RELA=5. E-05,
      ITER_GLOB_MAXI=40,),);
```

 # I.6 - CALCULATION METALLURGICAL
 # I.6.1 - STARTING STATE METALLURGICAL
'v1' = Proportion of ferrite
'v2' = Proportion of pearlite
'v3' = Proportion of bainite
'v4' = Proportion of martensite

```
PHASINIT=CRÉA_CHAMP (
   OPERATION=' AFFE',
   TYPE_CHAM=' CART_VAR2_R',
   MAILLAGE=MAIL,
   AFFE=_F (
      ALL = 'YES',
      NOM_CMP = ('V1', 'V2', 'V3', 'V4',),
      VALE = (0.61,0.0,0.39,0.0,)))
```

 # I.6.2 - RESOLUTION METALLURGICAL

```
TEMPE=CALC_META (
   reuse =TEMPE,
   MODELE=moth,
   CHAM_MATER=matr,
   RESULTAT=tempe,
   ETAT_INIT=_F (META_INIT_ELNO=phasinit,),
   COMPORTEMENT=_F (RELATION=' ACIER',),);
```

 # II - CALCULATION MECHANICAL WITH AN ELASTOPLASTIC MODEL IN GREAT DEFORMATIONS WHICH TAKES INTO ACCOUNT THE PLASTICITY OF TRANSFORMATION AND THE RESTORATION D WORK HARDENING
 # II.1 DEFINITION OF THE MODEL

```
MOMECA=AFFE_MODELE (
   MAILLAGE=MAIL,
   AFFE=_F (
      TOUT=' OUI',
      PHENOMENE=' MECANIQUE',
      MODELISATION=' AXIS',),);
```

 # II.2 - DEFINITION OF MATERIAL
 # II.2.1 DEFINITION OF THE COEFFICIENTS ACCORDING TO THE TEMPERATURE
Young modulus E
Coefficient fish Nu
Limits D elasticity of austenite Sy_a, ferrite Sy_f, bainite Sy_b and of martensite Sy_m
function of multiphase plasticity for the elastic limit mixes
Slopes D work hardening for austenite H_a and for ferrite, bainite and martensite H_f
Dilation coefficients for austenite $AlphaA$
and for ferrite, bainite and martensite $AlphaF$
Functions of plasticity of transformation for bainite and martensite $FzBM$, for ferrite FzF
 # II.2.2 - DEFINITION OF MATERIAL

```
ACIERM=DEFI_MATERIAU (
   ELAS_META_FO=_F (
      E=E,
       NU=NU,
      F_ALPHA=ALPHAF,
      C_ALPHA=ALPHAA,
      PHASE_REFE=' FROID',
      EPSF_EPSC_TREF=1.E-2,
      F1_SY=SY_F,
       F2_SY=SY_F,
```

```
        F3_SY=SY_B,
        F4_SY=SY_M,
        C_SY=SY_A,
        SY_MELANGE=MELANGE,),
    META_ECRO_LINE=_F (
        F1_D_SIGM_EPSI=H_F,
        F2_D_SIGM_EPSI=H_F,
        F3_D_SIGM_EPSI=H_F,
        F4_D_SIGM_EPSI=H_F,
        C_D_SIGM_EPSI=H_A,),
     META_PT=_F (
        F1_K=7.E-11,
        F2_K=7.E-11,
        F3_K=7. E-11,
        F4_K=7. E-11,
        F1_D_F_META=FZF,
        F2_D_F_META=FZF,
        F3_D_F_META=FZBM,
        F4_D_F_META=FZBM,),
     META_RE=_F (
        C_F1_THETA=0.0,
        C_F2_THETA=0.0,
        C_F3_THETA=0.0,
        C_F4_THETA=1.0,
        F1_C_THETA=0.0,
        F2_C_THETA=0.0,
        F3_C_THETA=0.0,
        F4_C_THETA=0.0,),);
```

 # II.2.3 - ASSIGNMENT OF MATERIAL

```
CHMATM=AFFE_MATERIAU (
    MAILLAGE=MAIL,
    AFFE=_F (
        TOUT=' OUI',
        MATER=ACIERM,
        TEMP_REF=28.0,),);
```

 # II.3 - CONDITION LIMITING AND LOADING
 # ONE IMPOSES THE FIELD OF TEMPERATURE AND THE METALLURGICAL MAP OBTAINED OUT OF I
 # II.4 - CALCULATION MECHANICAL
 # II.4.1 - LIST D URGENT
 # II.4.2 - MECHANICAL RESOLUTION

```
U=STAT_NON_LINE (
     MODELE=MOMECA,
    CHAM_MATER=CHMATM,
    EXCIT=_F (CHARGE=CHMECA,),
    COMPORTEMENT=_F (
        RELATION=' META_P_IL_PT_RE',
        RELATION_KIT=' ACIER',
        DEFORMATION=' SIMO_MIEHE',
        TOUT=' OUI',),
    INCREMENT=_F (LIST_INST=LISTM,),
    NEWTON=_F (
        REAC_INCR=1,
        MATRICE=' TANGENTE',
        REAC_ITER=5,),
```

```
     RECH_LINEAIRE=_F (ITER_LINE_MAXI=3,),
    CONVERGENCE=_F (
       RESI_GLOB_RELA=5.E-06,
        ITER_GLOB_MAXI=34,),);
```

3 Bibliography

1) WAECKEL F.: Modeling of the austenitic transformation in *Code_Aster*. Note EDF/DER/IMA, note HI-74/95/017/0