Models of metallurgical behavior of steels

Summarized :

This document presents the models of metallurgical behavior to the heating and cooling making it possible to describe structure transformations of thermal steels during cycles exceeding of the temperatures about $800\,°C$.

For the two types of transformations (with the heating and cooling) a detailed description of the models available is made and of the methods of identification are given.

Lastly, one presents the model computation of hardness associated with the metallurgy.

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1 Introduction

the operations of assembly and of thermomechanical processing that the metal components of the power stations REFERENCE MARK undergo, can generate, in the materials which constitute them, of the stress fields, known as residual, which exist before any loading of service. The metallurgical transformations and mainly structure transformations are an important cause of these stress fields because they modify the behavior (by modifying the physical characteristics) and generate thermomechanical requests within the materials which undergo them (latent heats, strains due to the differences in density of the various metallurgical phases).

These structure transformations are due essentially to the succession of a heating (often beyond $800\,°C$) and of a more or less fast cooling of the parts during their fabrication. These thermal "cycles" can be desired (case of the heat treatments) or "undergone" (case of welding). In all the cases, they are very variable of a point to another of the part.

This document relates to the modelization of these structure transformations to the heating and cooling for low alloy steels and this, with a scale which, while remaining "reasonable" for the metallurgist, is easily usable by the mechanic.

This kind of modelization is realizable within *Code_Aster* for all the elements (PLANE, AXIS, 3D) of the PHENOMENE "THERMAL" by the use of operator CALC_META in "postprocessing" of a thermal computation of evolution. The behavior model dedicated to steel, by difference with that dedicated to the zircaloys, to use under key word COMP_INCR of the operator is a relation "ACIER". For the definition of the metallurgical behavior of steel information of the command DEFI_TRC and key word factor META_ACIER under command DEFI_MATERIAU is necessary. Lastly, the definition of the initial metallurgical state is realizable using command CREA_CHAMP, under the key word factor ETAT_INIT of operator CALC_META. The computation of metallurgy is necessary to the realization of mechanical computations which take account of the mechanical consequences of these metallurgical phenomena [R4.04.02].

The models presented (with the heating and cooling) are formulated in the frame of the behavior models with local variables (or mémoratrices), and authorize a simple identification and rapid based on the experimental diagrams (diagrams TRC of Transformations in Continuous Cooling). The choice of the variables and the forms of the laws of evolution selected is given and the description of the placement of the models (method of identification) is also presented.

Lastly, one the model presents computation of hardness which can if necessary come to supplement metallurgical computations.

Note:

- *The basic metallurgical notions necessary to comprehension of the general problem and the adopted approach are gathered in [bib1] and [bib2] where a study bibliographical of the problem will be also found.*
- *This document is extracted from [bib3] and [bib4] where one makes a more detailed presentation of the models and some elements of validation. More complete elements of validation can also be found in [bib5] for the model of cooling and in [bib14] for the model of hardness.*

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2 Model metallurgical behavior with cooling

2.1 Introduction

On the basis of test of dilatometry [Figure 2.1-a], only knowledge, a given time, of the temperature of an undergoing steel of structure transformations does not allow to know its strain state. On the other hand, the steel reaction of such seems to be able to be described in the frame of the models of behavior to variables mémoratrices or interns [bib6]. Indeed, if one introduces:

- $Z=\left(Z_i ; i=1,p\right)$ p - uplet of the proportions of the possible metallurgical components present in a given M point and at one t time (here, $Z_1+Z_2+Z_3+Z_4$ will be the proportions of ferrite, pearlite, bainite and martensite and the proportion of austenite M will be equal to: $1-(Z_1+Z_2+Z_3+Z_4)$);

- $\varepsilon_\gamma^{th}(T)=\alpha_\gamma\left(T-T^\gamma\right)$ et $\varepsilon_\alpha^{th}(T)=\alpha_\alpha\left(T-T^\gamma\right)+\Delta\varepsilon_{\alpha\gamma}\left(T^\gamma\right)$ thermal strains of austenite and the phases ferritic, perlitic, bainitic and martensitic; while noting:

  - α_γ the average thermal coefficient of thermal expansion of austenite;
  - T^γ the reference temperature to which one considers ε_γ^{th} null;
  - α_α the average thermal coefficient of thermal expansion presumedly identical for ferrite, the pearlite, bainite and martensite;
  - $\Delta\varepsilon_{\alpha\gamma}^{\gamma}$ strain, with the temperature T^γ, of the phases ferritic, perlitic, bainitic and martensitic compared to austenite (by taking the latter like the phase of reference);

- if one considers, moreover, that the strain of a multiphase mixture can be obtained starting from the strains of each phase by a linear model of mixture, one can then describe the evolution of the strain state during a dilatometric test by:

$$\begin{aligned}\varepsilon^{th}(Z,T)&=\left(1-\sum_{i=1}^{i=4}Z_i\right)\varepsilon_\gamma^{th}(T)+\left(\sum_{i=1}^{i=4}Z_i\right)\varepsilon_\alpha^{th}(T)\\&=\left(1-\sum_{i=1}^{i=4}Z_i\right)\left[\alpha_\gamma\left(T-T^\gamma\right)\right]+\left(\sum_{i=1}^{i=4}Z_i\right)\left[\alpha_\alpha\left(T-T^\gamma\right)+\Delta\varepsilon_{\alpha\gamma}^{\gamma}\right].\end{aligned}\qquad \text{éq 2.1-1}$$

the problem resides then in the determination of Z or, more precisely and in the frame of the simple materials with variables mémoratrices, in the determination of the function of evolution f such as: $\dot{Z}=f(T,Z,...)$.

To give an account of an effect the velocity of cooling on the evolution of structure transformations, we propose, in the frame of the simple materials with variables mémoratrices, a modelization of the metallurgical behavior of steels to the cooling which includes, a priori, $\dot{T}$ among its variables of state.

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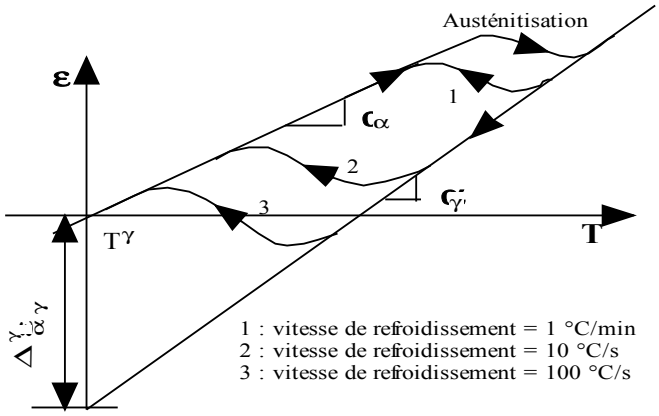

Appear 2.1-2.1-a2.1-a : Diagrammatic curves of dilatometry

2.2 Assumptions

H1 : *A steel likely to undergo structure transformations is a simple material with variables mémoratrices among which one can choose the quadruplet Z characterizing metallurgical structure in a given point and at one time .*

One thus models structure transformations with a scale where the material point can be multiphase. This scale of modelization which can appear coarse métallurgiquement is in conformity with the notion of material point used in mechanics of the continuums and of which the test-tube of dilatometry, presumedly homogeneous, is representative.

H2: *The supplemented DIAGRAMS trc martensitic kinetics of transformation of Koistinen-Marburger [bib7] completely characterize the metallurgical behavior of a steel austenitized during a continuous cooling.*

This assumption results directly from the metallurgical practice and specifies the first of the purposes to be fixed at the model: to be compatible with all the experimental data relating to the metallurgical behavior which accompanies cooling by austenitized steels. In addition, this assumption also generates a “natural” choice and restrictions as for the variables to be introduced into the model.

H3 : *The transformations ferritic, perlitic and (especially) bainitic are impossible in on this side martensitic initial temperature of transformation Ms .*

This assumption, in conformity with the representation of diagrams TRC, makes it possible to uncouple the transformations by diffusion from the martensitic transformation.

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2.3 Choices of the Variable variables of

state of state pilots

Into thermomechanical of the continuums, the pilot variables of state are generally the temperature and the stress state or of strains. However, because of the assumption H2, the temperature is only the variable pilot retained. Indeed, the influence of the stress state on structure transformations does not appear in diagrams TRC. Moreover, it does not exist (except an effect of the type Châtelier) of ideal model even if experimental data relative to this influence in isothermal conditions were obtained for certain steels [bib8].

Variables of state mémoratrices

the first variable mémoratrice to be introduced is the quadruplet Z characterizing the metallurgical structure and to which knowledge is enough, a priori, to describe from a mechanical point of view a dilatometric test [§2.2].

In addition to the temperature T, its derivative $\dot{T}$ and the stress state σ, the austenitic size of grain d and the percentage of changing C carbon of austenite also influence the metallurgical behavior of steels to cooling. However, always because of the assumption H2, one chooses not to introduce C like variable mémoratrice. Indeed, the diffusion of carbon does not appear explicitly on diagrams TRC, although she is implicitly taken into account, at least partially, in the notion even of component metallurgical. In addition Giusti showed that if the taking into account of C were theoretically possible, it led to coupled equations of evolution enters C and Z whose experimental identification "seems very difficult, not to say impossible" [bib9]. Nevertheless, an effect of the percentage of carbon on the decomposition of austenite to cooling appears indirectly on diagrams TRC. It is the phenomenon of stabilization of the austenite which results in a decrease of the martensitic temperature of transformation Ms [Figure 2.3-a].

Contrary to the percentage of carbon, the austenitic size of grain d appears on the diagrams TRC which are relative to conditions of austenitization to which correspond a value of d. We thus choose to introduce d like variable mémoratrice. However, austenitic size of grain, which results from the thermal history undergone with the heating does not evolve more with cooling and d intervenes only as a parameter in the model of behavior to cooling.

In addition, the martensitic temperature of transformation Ms, which depends on the undergone thermo-metallurgical history, intervenes in the model of Koistinen-Marburger adopted on the assumption **H2** to describe the martensitic transformation. One thus chooses to introduce Ms like variable mémoratrice.

The character memorator of the variables mémoratrices introduced here besides Z appears clearly: d characterize the thermal history undergone during the transition in austenitic phase and Ms connects the decomposition of austenite to the conditions of its transformation out of martensite.

Relation "ACIER" of operator CALC_META thus comprises 7 local variables:

$V1$: $Z1$, proportion of ferrite
$V2$: $Z2$, proportion of the pearlite
$V3$: $Z3$, proportion of bainite
$V4$: $Z4$, proportion of martensite
$V5$: d, austenitic size of grain,
$V6$: temperature with Gauss points.
$V7$: Ms temperature of transformation martensitic,

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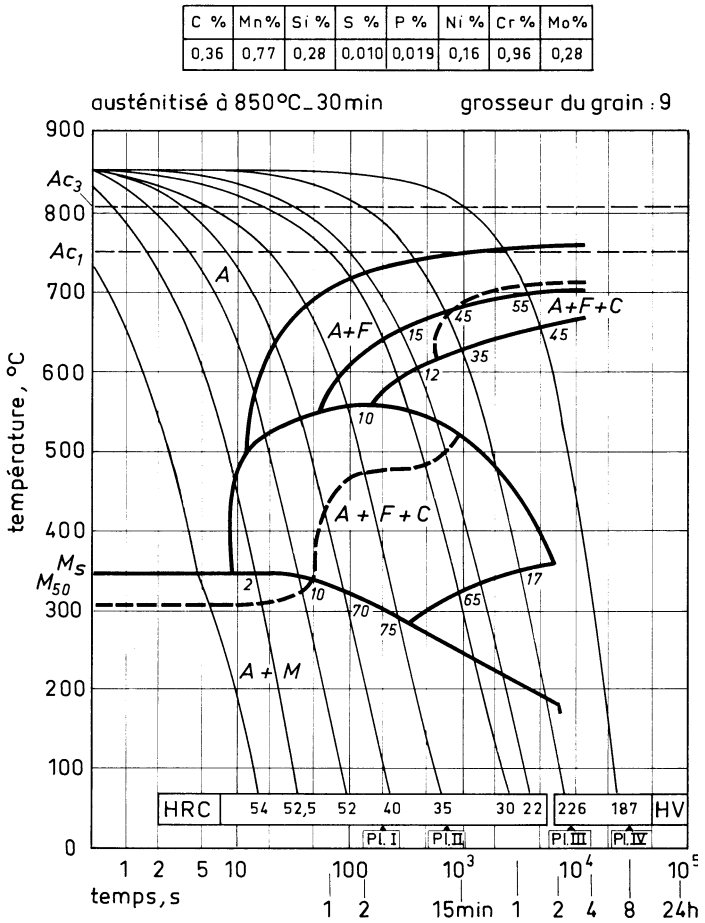

Figure 2.3-2.3-a2.3-a : Example of diagram TRC

It is also necessary to model all the phenomena concerned during an operation of welding to introduce other variables mémoratrices such as the strain tensors anelastic which can correspond to plastic strains, of plasticity of transformation or viscosity. But, in accordance with the assumption **H2**, one considers that these variables do not intervene in the functions of evolutions of Z and of Ms .

Lastly, the following assumptions make it possible to simplify and specify more the general form of the model.

H4 : *∇T intervenes only in the behavior model expressing the vector running of heat q ; its temporal derivative first $\dot{\nabla} T$ is not a variable of state and the behavior model expressing the vector running of heat is the Fourier analysis: $q=-\lambda(T,Z,d)\nabla T$.*

H5 : *A diagram TRC makes it possible to identify an empirical relation enters Ms , d and $\sum_{i=1}^{i=3} Z_i$:*

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$$Ms\left(Z_1, Z_2, Z_3; d\right)=Ms_0(d)+AM(d)\left[\sum_{i=1}^{i=3} Z_i-Z^s(d)\right]^+ \text{ .éq} \qquad \text{2.3-1}$$

the assumption **H5** means that the martensitic initial temperature of transformation is constant (for a given size of grain) and equal to Ms_0 as long as the proportion of transformed austenite is lower than a threshold Z^s and that its variation is a linear function of the quantity of transformed austenite. This assumption seems relatively well checked in experiments [fig 2.3 - has]. It makes it possible to exclude Ms from all the behavior models other than that expressing z and Z_4.

With $\boldsymbol{z}=\left(Z_1, Z_2, Z_3\right)$ one will distinguish well from $Z=\left(Z_i; i=1, p\right)$ definite with the § 2.1.

Finally, and taking into account the assumptions **H2** and **H3** the relations defining the model are thus written:

$$\dot{z}(t)=f\left(T, \dot{T}, \boldsymbol{z}, \mathrm{Ms}; d\right)=f\left(T, \dot{T}, \boldsymbol{z}; d\right)\frac{\left[T-Ms\right]^+}{T-Ms} \text{ with } \boldsymbol{z}=\left(Z_1, Z_2, Z_3\right) \qquad \text{éq 2.3-2}$$

$$Z_4\left(T, \boldsymbol{z}, \mathrm{Ms}; d\right)=\left[1-\sum_{i=1}^{i=3} Z_i\right]\left\{1-\exp\left(\beta(d)\left[\mathrm{Ms}-T\right]^+\right)\right\} \qquad \text{éq 2.3-3}$$

and

$$Ms(t)=Ms_0(d)+A_M(d).\left[\sum_{i=1}^{i=3} Z_i-Z^s(d)\right]^+ \qquad \text{éq 2.3-4}$$

where: β is a characteristic of the material ($^\circ C^{-1}$) (possibly function of d);

and $\left[X\right]^+$ indicates the positive part of X.

Lastly, as it seems difficult to propose a simple form of dependence of the model with respect to these variables, one chose not to impose of form particular to the functions of evolution f_i [bib2]. The approach to compute: the velocities of evolution of the metallurgical variables uses techniques of interpolation then and rests on the fact that any thermometallurgic history in experiments known (dilatometric test for example) is a particular solution of the differential equation of evolution [éq 2.3-2].

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3 Identification and placement of the model to cooling

3.1 Principle

the identification of the model and the use of the experimental data that diagrams TRC constitute to determine the value taken by the function f in a given thermo-metallurgical $(T, \dot{T}, z; d)$ state are founded on the following observation and the assumption:

- the thermo-metallurgical stories being reproduced on a diagram TRC are all of the particular solutions of the differential equation [éq 2.3-2]. They thus make it possible to calculate in each thermodynamic state met in experiments and present in a diagram TRC the value taken by the function f .
- the function f is regular; i.e. if two points E_k et E_j are close $\left(E_k=\left\{T(t_K), \dot{T}(t_K), z(t_K); d(t_K)\right\}\right)$, their velocities of evolution of it z are also close that is to say:

$$E_k \approx E_j \Rightarrow f(E_k)\frac{[T-Ms]^+}{T-Ms} = \dot{z}(E_k) \approx f(E_j)\frac{[T-Ms]^+}{T-Ms} = \dot{z}(E_j) \ .$$

One determines then the velocities of structure transformations of an unspecified state per interpolation among all the “couples” $\left(E_k, f(E_k)\right)$ defined by diagrams TRC.

3.2 Integration of the experimental data to the model

3.2.1 Principle

In general, a diagram TRC defines in a reference $[\ln(t)-T]$ the structure transformations associated with a series of thermal stories traced on this diagram [Figure 2.3-a]. The integration of the experimental data then consists in recording for each history of these diagrams the successive values of $T, \dot{T}, z$ so that for any temperature T the model knows the values taken by the function f in $(T, \dot{T}(T), z(T))$. In order to be able, from a reduced number of numerical data, continuously to reconstitute the thermometallurgic evolutions, one formulates some assumptions on the thermal evolutions and the metallurgical behavior of steels.

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3.2.2 Rules of interpretation of thermal diagrams

TRC Evolutions

to define the thermo-metallurgical stories present in a diagram TRC their thermal evolutions should be characterized. One can notice that, in a reference $\left[1\mathrm{n}(t)-T\right]$ and for temperatures lower than $820\ °C$, the thermal stories of diagrams TRC can, with a rather good approximation, to result from/to each other by a horizontal adjustment [Figure 2.3 - has]. It is thus possible to define a thermal history $T^i(t)$ from the data of a curve controls $T_p(t)$ and the time (in second) for which this history crosses the isotherm 820 °C by:

$$t^i(T)=\exp\left\{\ln\left[tp(T)\right]+\ln\left[t^i(820)\right]-\ln\left[tp(820)\right]\right\} \qquad \text{éq 3.2.2-1}$$

where: $t^i(T)$ and $tp(t)$ indicate the reciprocal functions of $T^i(t)$ and $T_p(t)$.

In fact, one has more easily information relating at the speeds of cooling of the thermo-metallurgical stories of diagrams TRC than to times of crossing of the isotherm $820\,°C$. It is in particular the case of steels of welding, whose diagrams TRC are plotted in a reference “velocity of cooling with $700\,°C$ - temperature”. Taking into account [éq 3.2.2 - 1], one can then express the time of crossing of the isotherm $820\ °C$ according to $T_p(t)$ and from $\dot{T}^i(700)$ and one obtains like characterization of $T^i(t)$:

$$t^i(T)=\exp\left[F(T)-F(700)-\ln\left(\dot{T}^i(700)F'(700)\right)\right] \qquad \text{éq 3.2.2-2}$$

With $F(T)=1\mathrm{n}\left[tp(T)\right]$ and, in particular $\dot{T}^i(t(T))=\dfrac{1}{F'(T)t^i(T)}$

Concretely, one interpolates the function $F(T)$ by a polynomial of degree 5. An experimental thermal evolution thus is completely defined by the data of the coefficients of the polynomial characterizing its pilot curve and by its velocity of cooling in $700\,°C$. The validation of this method of parameterization of the thermal stories “read” on diagrams TRC is presented in [bib2]. As a whole, and taking into account the relative inaccuracies of the layout of diagrams TRC, reading of $T^i(t)$ and determination of $\dot{T}^i(700)$, the agreement between the thermal stories read and recomputed seems very sufficient.

If one has the records of the thermal evolutions of diagrams TRC, one can define each experimental thermal evolution by considering that it is its clean curved pilot. In addition, if the dilatometric tests defining diagram TRC used for the identification of the model are carried out with constant velocities of cooling, one characterizes this kinetics of cooling only by their velocities of cooling with $700\,°C$ and a function F identically null.

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And end initial temperatures of transformation

a diagram TRC provides, for a series of known thermal stories, the proportions of the various metallurgical components which were formed during cooling as well as the temperatures for which one observes on a swelling behavior a significant variation of the total coefficient of thermal expansion of the test-tube [Figure 2.1-a]. These temperatures are then regarded as and the end initial temperatures of the transformations. More precisely:

- the initial temperatures of transformation indicated on diagrams TRC correspond to 1% of component already formed;
- the temperatures of end of transformation correspond to the final proportion of the component in the course of training minus 1%.

Kinetics of the ferritic, perlitic and bainitic transformations

the observation of a swelling behavior shows that, except in the vicinity of initial temperatures and end of transformation, the evolution of the strain according to the temperature is almost linear. Taking into account the equation [éq 2.1-1] the evolution of the quantity of phase transformed according to the temperature is then not very distant from a function refines and one thus supposes only:

- for the ferritic transformations, perlitic and bainitic, the velocity of transformation is, between the experimental temperatures of beginning and end of transformation, a linear function of the temperature;
- the velocities of these transformations are twice slower at the beginning (from 0 to 1% of transformed component) and at the end of the transformation (of $Z_{final}-1\%$ with Z_{final}) which between the experimental temperatures of beginning and end of transformation.

Martensitic transformations

It is supposed that the martensitic transformations are described by the model of Koistinen - Marburger [éq 2.3-3] and the phenomenologic equation [éq 2.3-4] expressing Ms. One uses each diagram TRC then to determine the coefficients β, A and Z^s as well as the temperature Ms_0. Lastly, to prevent that the model transforms systematically into martensite remaining austenite when the temperature is reached Ms, one introduces an additional parameter, called TPLM, characterizing (by its velocity of cooling with $700°C$) slowest of the kinetics of cooling which generates a martensitic transformation. More precisely [Figure 3.2.2-a]:

- Ms_0 is regarded as the martensitic initial temperature of transformation when this one is total;
- β is supposed to be constant and calculated in order to check, in the case of a total martensitic transformation:

  $$Z_4(Mf)=0,99$$

  where Mf is the experimental temperature of end of transformation;
- finally, A and Z^s are determined by linear regression starting from the experimental metallurgical stories thermo - leading to a partial martensitic transformation.

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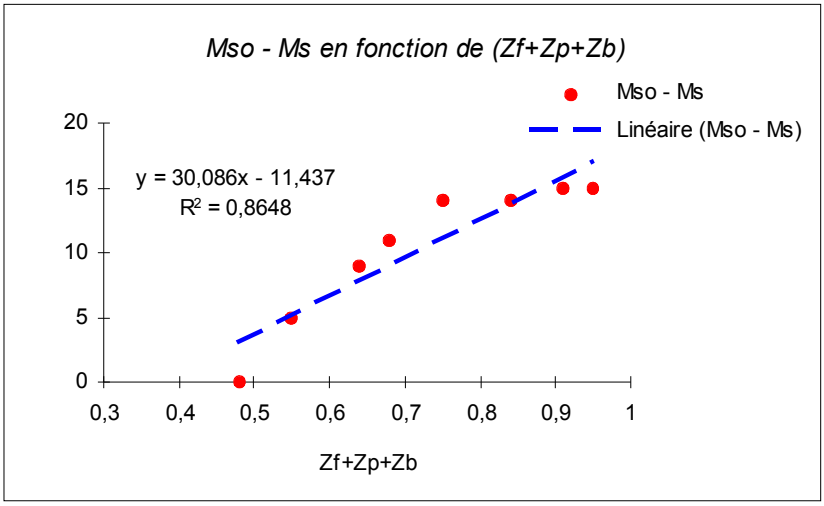
Mso = 415°C ; Mso - Mf = 185°C

d'où une valeur de ☎ supposée constante pour une taille de grain donnée) de -0.0249

A = -30,086

Zs = 0,38

et TPLM = -9°C/s



Appear 3.2.2-a: Evolution of $(Ms_0 - Ms)$ according to $(Z1+Z2+Z3)$; for steel 16MND5 austenitized 5 minutes with $900\ °C$.

3.2.3 Effect of the austenitic size of grain on the kinetics of the transformations to cooling.

The transformations of phase proceed by germination and growth. The stage of germination is done primarily on the grain boundaries. The size of grain of austenite thus plays an important role on the transformations with cooling. For this reason diagrams TRC are established for conditions of austenitization given and should not in any rigor be used only for similar conditions of austenitization. The experimental results tend to show that the size of austenitic grain modifies more the kinetics of transformation than and the end initial temperature of transformations, which results relatively well in a translation of diagram TRC according to the axis of times. A each point M of a diagram TRC corresponds the tuple $(T, \dot{T}, z)$. To relocate the TRC according to the axis of times amounts multiplying $\dot{T}$ by a coefficient different from the unit (the axis of times is given in logarithmic scale) [bib15]. One thus defines a velocity of cooling "effective" $\dot{T}_{eff}$:

$$\dot{T}^{eff} = \dot{T} \cdot \exp(a(d - d_{ref}))$$

with

d_{ref} : cut austenitic of reference of diagram TRC, homogeneous grain with a length.

a : homogeneous coefficient material contrary to a length.

The law of evolution retained is thus written:

$$\dot{z}(t) = f(T, \dot{T}_{eff}, z, \mathrm{Ms}) = f(T, \dot{T}_{eff}, z) \frac{[T - Ms]^+}{T - Ms} \quad \text{avec } z = \{Z_1, Z_2, Z_3\} .$$

This writing has the advantage of limiting the interpolation to only one diagram TRC, of reference.

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Note:

Assumption: the germination and the growth of martensite are regarded as instantaneous and the density of the sites of nucleation has little influence on this transformation. The effect of the size of grain thus does not relate to the evolution of the martensitic phase and relates here only to the evolution of the phases ferritic, perlitic and bainitic.

3.2.4 Seized by diagrams TRC

Taking into account the preceding assumptions, the experimental acquisition data contained in diagrams TRC thus understands:

- for diagram TRC :
  - the value of the austenitic size of grain d_{ref} of the diagram and which will be the size of grain of reference,
  - the coefficient of translation a for the taking into account of the effect of the austenitic size of grain,
  - the initial temperature of total martensitic transformation Ms_0 ,
  - the value of the coefficient of the model of Koistinen-Marburger,
  - the value of the coefficients A and Z^s intervening in the equation [éq 2.3-4],
  - the values of the six coefficients of the polynomial of degree five interpolating the function $\ln\left[tp(T)\right]$ (if the thermal stories explicitly are known, each one of them is regarded as being its clean curved pilot and the definition of its six coefficients is to be renewed for each history);

- for each thermal history of a diagram TRC :

  - velocity of cooling with $700\,°C$,
  - final proportions of ferrite, pearlite and bainite $(Zff\,,Zfp\,,Zfb)$,
  - initial temperatures of each transformation $(Tdf\,,Tdp\,,Tdb)$,
  - and the temperatures of end of each transformation $(Tff\,,Tfp\,,Tfb)$.

The seizure of a diagram TRC is realizable by a programme of seizure (available available with the mtlp100a `benchmark` in the file `mtlp100a.66` ; the file contains FORTRAN which it is necessary to compile). It is a simple and fast operation (approximately an hour for the seizure of about fifty stories).

Result of this procedure of seizure of diagrams TRC (cf [§An1]) is directly insertable in a file of command of Code_Aster as a command `DEFI_TRC`, command which thus contains the data identifying the metallurgical behavior of steel.
The complete definition of the models of metallurgical behavior (values of the parameters Ar_3 "quasi static" temperature of ferritic transformation, of Ms0, and the complete definition of the model to the heating and austenitic growth of grain) is carried out within the command `DEFI_MATERIAU` under the key word factor `META_ACIER`.

An example of the procedure of seizure is presented in appendix [§An1].

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3.3 Evaluating of the function of evolution starting from the experimental data

3.3.1 Evaluating of the function of evolution for the experimental stories

Taking into account the assumptions concerning the evolution of the structure transformations associated with the thermo-metallurgical stories H_i of a diagram TRC, one thus has a set of particular solutions parameterized by d_{ref} differential equation (for $T^3 Ms$):

$$\dot{z}(t)=f\left(T,\dot{T},z;d_{ref}\right)$$

who allow for any thermo-metallurgical state $E_k=\left\{T,\dot{T},z;d_{ref}\right\}$ of an experimental history H_i to calculate:

$$\dot{z}\left(E_k(t)\right)=f\left(E_k\right)$$

Indeed:

$$\dot{z}\left(E_k(t)\right)=\frac{dz}{dT}\left(E_k\right)\dot{T}\left(E_k\right)$$

however, taking into account the assumptions of linearity on the evolutions of $Z_i(t)$ between two consecutive states E_k^i and E_k^{i+1} the same discretized history:

$$\frac{dz}{dT}\left(E_k\right)=\frac{z\left(E_{k^i}\right)-z\left(E_{k^{i+1}}\right)}{T\left(E_{k^i}\right)-T\left(E_{k^{i+1}}\right)}$$

where $\dot{T}\left(E_k\right)$ can be estimated by derivative of the analytical statement selected to represent $T_i(t)$.

Thus, one can, for any temperature T, to know the values taken by the function f in the thermo-metallurgical states $E_i=\left\{T,\dot{T}_i(T),z_i(T);d_{ref}\right\}$ where the index i refers to in experiments known stories.

3.3.2 Computation of the advance of the transformations for an unspecified state

It acts, knowing $T,\dot{T},z,Ms$ and d at a given t time, to determine the values of the metallurgical variables at next $\left(t+\Delta t\right)$ time. More precisely:

- If $T(t)\geq Ar_3$ or if $\dot{T}>0$,

  the model of metallurgical transformation to cooling is inactive [§4.4].

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- If $Ar_3 > T(t) \geq Ms(t)$,

  $\dot{z}(t) = f(T, \dot{T}, z; d) = f(T, \dot{T}_{eff}, z; d_{ref})$ and $z(t+\Delta t) = z(t) + \dot{z}(t)\Delta t$

  then:

$$Ms(t+\Delta t) = Ms_0 + A\left[\sum_{i=1}^{i=3} Z_i(t+\Delta t) - Z^s\right]^+$$

  and, if $T(t+\Delta t) \geq Ms(t+\Delta t) : Z_4(t+\Delta t) = Z_4(t)$

  or, if not:

$$Z_4(t+\Delta t) = \left[1 - \sum_{i=1}^{i=3} Z_i(t+\Delta t)\right]\left\{1 - \exp\left(\beta\left[Ms(t+\Delta t) - T(t+\Delta t)\right]^+\right)\right\}$$

- If $T(t) < Ms(t)$

$$z(t+\Delta t) = z(t)\,;\; Ms(t+\Delta t) = Ms(t)$$

  and

$$Z_4(t+\Delta t) = \left[1 - \sum_{i=1}^{i=3} Z_i(t+\Delta t)\right]\left\{1 - \exp\left(\beta(d^c)\left[Ms(t+\Delta t) - T(t+\Delta t)\right]^+\right)\right\} .$$

In the case where $Ar_3 > T(t) \geq Ms(t)$, one determines (thanks to the assumption of regularity of f) the value taken by f in $(T, \dot{T}, z; d)$ from knowledge for any temperature T of the values taken by f in the thermo-metallurgical states $E_i\left(T, \dot{T}_i(T), z_i(T); d_{ref}(T)\right)$ of in experiments known stories, where $\dot{T}_i(T)$ is the velocity of cooling for the history H_i with the temperature T (obtained by interpolation). More precisely, one will determine a linear approximation of f in the vicinity of $(T, \dot{T}, z; d)$. f is a function of $\mathbb{R}^5$ (because the dependence compared to the parameter d is included in the possible modification current velocity of cooling [§ 3.2.3]) in $\mathbb{R}$, to determine a linear approximation of f in the vicinity of $(T, \dot{T}, z; d)$ come down to determine the equation of a hyperplane in $\mathbb{R}^6$ and thus to have the value taken by F in six points $\left(E_i, f(E_i)\right)$ “close” to $(T, \dot{T}, z; d)$.

Concretely, the stages of this interpolation of the values of f $(T, \dot{T}, z; d)$ are the following ones:

- one calculates an “effective” temperature $\dot{T}_{eff}$ allowing to take account of the effect of the austenitic size of grain if it is different from that of the diagram, and one then seeks the value taken by f in $(T, \dot{T}_{eff}, z; d_{ref})$

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- one calculates for all the known experimental H_i stories the values taken by the function f in the following thermo-metallurgical states (in order to know a set of values of f in a vicinity of $\left(T, \dot{T}_{eff}, z; d_{ref}\right)$ rather dense in temperature):

$$E_i^1(t)=\left\{T, \dot{T}_i(T), z_i(T); d_{ref}(T)\right\}$$

$$E_i^2(t)=\left\{T+5°C, \dot{T}_i(T+5°C), z_i(T+5°C); d_{ref}(T+5°C)\right\};$$

$$E_i^3(t)=\left\{T-5°C, \dot{T}_i(T-5°C), z_i(T-5°C); d_{ref}(T-5°C)\right\};$$

- one determines the six closer neighbors of $E(t)=\left\{T(t), \dot{T}_{eff}(t), z(t); d_{ref}(t)\right\}$ among all defining $E_i^j(t)\left(j=1,3\right)$ them the metallurgical behavior of the material in the vicinity of the temperature $T(t)$ by minimizing the distance from $E(t)$ in each one of $E_i^j(t)$;
- one calculates the barycentric coordinates from $E(t)$ ratio with his closer neighbors $E^v(t)\left(v=1,6\right)$. For that, one solves the linear system associated with this computation within the meaning of the least squares and by choosing the solution with minimal norm if its determinant is null (it is the case when the closest neighbors belong to a variety closely connected of size lower than six - [R6.03.01]);
- it is not retained that the neighbors $E^w(t)\left(w\leq 6\right)$ such as all the barycentric coordinates λ_w of $E(t)$ are positive (so that $E(t)$ is located inside the convex polyhedron leaning on these points);
- one calculates then:

$$\dot{z}\left(E_k(t)\right)=f\left(E_k\right)=\lambda_w . f\left[E^w(t)\right] / \sum_w \lambda_w \quad ;$$

- finally, one calculates z with time step according to $z\left(t+\Delta t\right)$ according to the diagram clarifies according to:

$$z\left(t+\Delta t\right)=z(t)+\dot{z}(t)\Delta t$$

Note:

The definition of a distance used in the criterion of proximity is not obvious, taking into account the nonadimensional character of space Des. $\left\{T, \dot{T}, z, d\right\}$ Currently, the search of the closest neighbors is carried out by adimensionnalisant each variable simply but one could plan to introduce weight coefficients into each "direction" (T, $\dot{T}$ or z) in order to give an account of a paramount role played by such or such variable.

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4 Model metallurgical behavior with the heating

4.1 Assumptions

During the heating, the only transformation likely to occur is the transformation out of austenite, which one supposes the velocity independent the heating rate. In addition, it is also supposed that all the phases ferritic, perlitic, bainitic and martensitic transform in an identical way into austenite. These assumptions are generally common to all the models of austenitization [bib9], [bib10] and [bib11]. Consequently the model retained is form:

$$\dot{z}_\gamma = f\left(T\,,\, z_\gamma\right)\,.$$

It is pointed out that the model metallurgical transformation proposed by Leblond and Devaux and established in the code Sysweld [bib11] is form (for the transformations with the heating and cooling):

$$\dot{Z}\left(T\,,\, Z\right) = \lambda\,\frac{Z_{eq}\left(T\right) - Z}{\tau\left(T\right)}$$

where, for the austenitic transformation, the parameter λ is taken constant.

Comparative data to the experiment presented in [bib11], [bib12] and [bib13] show that, with the help of the identification of the functions $Z_{eq}\left(T\right)$ and $\tau\left(T\right)$ from tests with various heating rates, this model allows a completely satisfactory description of the austenitic transformation of steels. Nevertheless, it seems that the identification of the function $\tau\left(T\right)$ remains difficult [bib4].

In *Code_Aster*, the model of austenitic transformation is form:

$$\dot{z}_\gamma\left(T\,,\, z_\gamma\right) = \frac{Z_{eq}\left(T\right) - z_\gamma}{\tau\left(T\right)}$$

but with a simple form for the function $\tau\left(T\right)$, in order to keep a set of metallurgical models of easy and fast identification.

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4.2 Is such that form model

retained In its continuous form, the model retained:

$$\dot{z}_\gamma\left(T,z_\gamma\right)=\frac{Z_{eq}\left(T\right)-z_\gamma}{\tau\left(T\right)} \qquad \text{éq 4.2-1}$$

where :

- z_γ indicate the proportion of austenite;
- $Z_{eq}(T)$ is the function (with Ac_1 and Ac_3 positive constants):

$$Z_{eq}(T)=\begin{cases}0 & \text{si } T\le Ac_1\\ \dfrac{T-Ac_1}{Ac_3-Ac_1} & \text{si } Ac_1\le T\le Ac_3\\ 1 & \text{si } T\ge Ac_3\end{cases} \qquad \text{éq 4.2-2}$$

- $\tau(T)$ is the function (with τ_1 and τ_3 positive constants):

$$\tau(T)=\begin{cases}\tau_1 & \text{si } T\le Ac_1\\ \tau_1+\dfrac{T-Ac_1}{Ac_3-Ac_1}\left(t_3-t_1\right) & \text{si } Ac_1\le T\le Ac_3\\ \tau_3 & \text{si } T\ge Ac_3\end{cases} \qquad \text{éq 4.2-3}$$

Remark 1: definition of the function $Z_{eq}(T)$

the definition of the function $Z_{eq}(T)$ is identical to that given by Leblond and Devaux in [bib11] and [bib12]. It corresponds to the evolution of the austenite rate transformed for very low heating rates. Indeed, with T built-in, $Z_{eq}(T)$ is the asymptotic solution towards which the solution of the differential equation [éq 4.2-1] tends with the time-constant $\tau(T)$. For low heating rates, the asymptotic solution can be regarded as attack at every moment and $Z_{eq}(T)$ thus corresponds to the evolution of the austenite rate transformed during "quasi-static" evolutions. The function $Z_{eq}(T)$ thus is entirely defined by the data of Ac_1 and Ac_3 which is done under single-ended spanner keys `AC1` *and* `AC3` *under the key word factor* `META_ACIER` *of the command* `DEFI_MATERIAU` *.*

Notice 2: form function $\tau(T)$

In the model proposed by Leblond and Devaux, the form of the function $\tau(T)$ is not specified and this function is identified in order to obtain a satisfactory agreement between the initial temperatures and end of transformation experimental and calculated. In order to obtain a model of identification simple and rapid we chose a simple form for the function $\tau(T)$. More precisely, to be able to integrate the equation of evolution [éq 4.2-1] one first of all considered the case where the function $\tau(T)$ is constant. In this case, one can then propose two possibilities of simple identification of this constant τ function. The first possibility consists in identifying a value τ_1 of τ making it possible to describe the beginning of the transformations correctly whereas the second consists in identifying a value τ_3 of τ making it possible to describe the end of the transformations correctly. One then tested the model obtained with a function $\tau(T)$ refines definite starting from the values τ_1 and τ_3 above definite. The got results being completely satisfactory and comparable to those obtained with the model available in Sysweld, one chose to introduce into Code_Aster a model where the function $\tau(T)$ is closely connected and is defined by τ_1 and τ_3 which are indicated with `AC1` *and* `AC3` *.*

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4.3 Integration of the equation of evolution

In *Code_Aster,* one chose to integrate the equation of evolution [éq 4.2-1] exactly in z_γ and explicitly in $\dot{T}$ and τ on each time step (i.e while considering and $\dot{T}$ constants τ on the step and equal to their values at the beginning of time step). One obtains then: .

$$z_\gamma(t+\Delta t)=\frac{-\tau(t)\dot{T}(t)}{Ac_3-Ac_1}+Z_{eq}(t+\Delta t)-\left\{-\frac{\tau(t)\dot{T}(t)}{Ac_3-Ac_1}+Z_{eq}(t)-z_\gamma(t)\right\}\exp\left[-\frac{\Delta t}{\tau(t)}\right]$$

The consequent evolution of the proportions of all the other metallurgical components is then defined by: .

$$Z_i(t+\Delta t)=Z_i(t).\left(1-\frac{z_\gamma(t+\Delta t)-z_\gamma(t)}{1-z_\gamma(t)}\right)$$ In other words

, each phase present is transformed into austenite to the amount of its proportion at the beginning of time step. Evolution

4.4 of the austenitic size of grain to the Once austenized

heating, steel sees its size grain to increase more or less quickly according to the temperature, but this growth always takes place since austenite appears with a size of grain null. The austenitic growth of grain is a thermically activated process. The model of growth selected is that of Grey and Higgins, adapted to treat the material in the course of transformation [bib15]: Model

growth: Growth

$$\frac{d}{dt}(d)=\frac{1}{\lambda}\left(\frac{1}{d}-\frac{1}{d_{\lim}}\right)$$

in the course of transformation, austenite appearing with a size of grain null: with

$$\frac{d}{dt}(d)=\frac{1}{\lambda}\left(\frac{1}{d}-\frac{1}{d_{\lim}}\right)-\frac{dz/dt}{z}d$$

$$\lambda=\lambda_0\cdot\exp\left(\frac{Q_{app}}{RT}\right)$$

$$d_{\lim}=d_{10}\exp\left(-\frac{W_{app}}{RT}\right)$$

:

z *proportion* of the austenitic phase:
d diameter of austenitic grain homogeneous to a length:
$d_{\lim}$ cut limiting grain, dependant on homogeneous d_{10} material parameter to a length and
Q_{app} : W_{app} materials parameters homogeneous with energies of activation (): $J.mol^{-1}$
R constant of perfect gases (): $8.314\,J.K^{-1}.mol^{-1}$
d_{10} homogeneous material parameter at seconds per unit of length Note:

Materials parameters are with being informed under key word META_ACIER of DEFI _MATERIAU. Digital processing

4.4.1 The computation

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of the size of grain is carried out after the computation of proportion of phase and the integration of the equation of evolution is made according to an implicit scheme in. D From where: One

$$\Delta d = \frac{1}{\lambda}\left(\frac{1}{d} - \frac{1}{d_{\lim}}\right)\cdot \Delta t - \frac{\Delta z}{z^{+}}\cdot d$$

$$d = d^{-} + \Delta d = d^{-} + \frac{1}{\lambda}\left(\frac{1}{d} - \frac{1}{D_{\lim}}\right)\cdot \Delta t - \frac{\Delta z}{z^{+}}\cdot d$$

solves a quadratic equation in. D Meanings

4.5 of the metallurgical evolution In

a structural analysis, certain zones can undergo a heating while others cool. Moreover, under certain conditions, an austenitic transformation initiated during the heating can continue at the beginning of cooling. There thus does not exist, strictly speaking, an austenitic model of transformation and a model of transformation to cooling but only one model of metallurgical transformations which according to the temperature considered and signs it velocity of evolution thermal is described either by the model decomposition of austenite, or by the model of training of austenite. With regard to

the model introduced into Code_Aster , the meaning of the metallurgical evolution (it is - with-to say training or decomposition of austenite) is given as follows: AUST

$T(t+\Delta t)$	$< Ac_1$	$\in [Ac_1 ; Ar_3]$	$> Ar_3$
$\dot{T}(t) > 0$		REFR	
$\dot{T}(t) = 0$	if	REFR $\mathbf{z}_\gamma \geq Z_{eq} \rightarrow$ *if* AUST $\mathbf{z}_\gamma < Z_{eq} \rightarrow$ *AUST*	REFR
$\dot{T}(t) < 0$		AUST	where

REFR *means* that the metallurgical evolution is determined by the model decomposition of austenite and where AUST *means* that the metallurgical evolution is determined by the model training of austenite. Note:

AR3

is also a characteristic of the metallurgical behavior to cooling already defined by the model of transformation in cooling. Identification

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5 of the model to the heating Determination

5.1 of the Zeq function (T) can

$Z_{eq}(T)$ be regarded as the quasi static solution of the differential equation [éq 4.2 - 1] and one chooses to define it (as in [bib11]) by the relation [éq 4.2-2]. In

this statement, the temperatures and Ac_1 are Ac_3 the quasi static temperatures "theoretical" of beginning and end of austenitic transformation which correspond toan austenite rate formed still equal to zero or already equal to one. In fact
, these temperatures are difficult to determine in experiments and one generally considers that the quasi static temperatures of beginning and end of austenitic transformation in experiments given correspond, respectively, to 5 and 95% of formed austenite. In other words, if one notes and Ac'_1 these Ac'_3 temperatures, they check: and

$$Z_{eq}(Ac'_1)=0,05 \text{ éq} \qquad Z_{eq}(Ac'_3)=0,95 \qquad \text{5.1-1}$$

to determine and Ac'_1 one Ac'_3 can use tests of dilatometry at low heating rate or apply formulas of the literature connecting the quasi static temperatures of beginning and end of austenitic transformation to the composition of steels. In general these temperatures are also indicated on diagrams TRC used for the identification of the model of transformation to cooling or can be estimated using formulas knowing the composition of steel [bib4]. Lastly,

knowing and Ac'_1 , Ac'_3 one can then determine the temperatures and Ac_1 defining Ac_3 the function from $Z_{eq}(T)$ the two equations [éq 5.1-1] above. A complete example of identification of the austenitic model of transformation is presented in [bib4]. Determination

5.2 of the function TAU (T) In

a general way, it is not easy to give off layer of a simple and fast identification of the function. $\tau(T)$ This is why one proposes to adopt for this function the form simplified below [éq 5.2-1]. If: $Ac_1 \le T \le Ac_3$ éq

$$\tau(T)=\tau_1+\frac{T-Ac_1}{Ac_3-Ac_1}(\tau_3-\tau_1) \qquad \text{5.2-1 where}$$

and τ_1 is τ_3 positive constants. For

the phase of identification, one considers the typical case initially where is τ constant enters and Ac_1 . Ac_3 One proposes two types of identification then allowing to determine either a value of τ_1 coherent τ with the experimental temperatures of beginning of transformation, or a value of τ_3 coherent τ with the experimental temperatures of end of transformation. One

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presents in [bib4] the results got by these two identifications and one shows (without another form of theoretical justification) that the function refines $\tau(T)$ definite with the values and τ_1 previously τ_3 given allows to obtain an agreement with the experiment completely comparable to that obtained with the model from Leblond. Identification

5.2.1 of TAU_3 from AC' 3 For

and $\dot{T}$ constants τ and the initial condition, $z_y(Ac_1)=0$ the solution of the equation of evolution [éq 4.2-1] is (as long as is $Z'_{eq}(T)$ constant, i.e. as long as) $T \leq Ac_3$: In particular

$$z_y(T)=Z_{eq}(T)-\tau.Z'_{eq}(T).\dot{T}.\left(1-\exp\left[\frac{Ac_1-T}{\tau.\dot{T}}\right]\right)$$

, one thus has, for: $T=Ac_3$

$$0,95=Z_{eq}(Ac'_3)-\tau.Z'_{eq}(T).\dot{T}.\left(1-\exp\left[\frac{Ac_1-Ac'_3}{\tau.\dot{T}}\right]\right)$$

A test of dilatometry at heating rate constant (and not very low) then makes it possible to determine the value of τ_3 making it possible τ to reach the agreement between the experimental and calculated values. Ac'_3 One presents in [bib4] comparisons between experiment and computation obtained by thus identifying the function considered τ as constant. Identification

5.2.2 of TAU_1 from AC' 1 In the same way

that previously, one can also write, for: $T=Ac'_1$ éq

$$0,05=Z_{eq}(Ac'_1)-\tau.Z'_{eq}(T).\dot{T}.\left(1-\exp\left[\frac{Ac_1-Ac'_1}{\tau.\dot{T}}\right]\right) \quad \text{5.2.2-1 There}$$

still, having a test at constant heating rate, the equation [éq 5.2.2-1] makes it possible to determine a value of τ_1 making it possible τ to obtain a good agreement on the calculated and Ac'_1 experimental temperatures. Model

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6 computation of hardness

metallurgical computations can be supplemented by a computation of hardness of “hardening” associated with metallurgical structure. The model

selected uses the assumption according to which the hardness of a polyphase material point is well represented by a linear model of mixture of the microhardnesses of the components (here phases austenite, ferrite, pearlite, bainite and martensite). The microhardnesses are taken as being constants of the material and phase considered. The model

is written then: : $HV=\sum_k z_k HV_k$

HV hardness (here Vickers for example) of the polyphase point:
z_k proportion of the phase k :
HV_k hardness of the phase. k Although

rather simple, this model gives very correct results [bib14]. In

Code_Aster the computation of hardness is done via the operator of postprocessing CALC _META; option “ DURT_ELGA” for computations of hardness to Gauss points and option “ DURT_ELNO” for computations with the nodes by elements.

Hardnesses of the various metallurgical phases are data materials provided by the user under factor key word the DURT_META of operator DEFI _MATERIAU. DURT_META

```
(F1_DURT
                  : HVf F2_DURT
                  : HVp F3_DURT
                  : HVf F4_DURT
                  : HVf C_DURT
                  : HV) Bibliography
```

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Aster Author (	S) Organization (S) Description	of the modifications 5 F.WAECKEL

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	, A.RAZAKANAIVO EDF-R&D /AMA addition of	the computation of hardness One presents

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Annexe 1

below an example of the procedure of seizure of an experimental thermo-metallurgical history (at nonconstant velocity of cooling). One first of all shows the furnished information by the user with the software of seizure: velocity of cooling with, composition $700\ ^\circ C$ with ambient, experimental temperatures of beginning and end of transformation,…. This information is registered in bold characters and Italic; the temperatures are indicated in and the $^\circ C$ velocities of cooling in. All $^\circ C/s$ the thermo-metallurgical states defining this experimental history and their data-processing storage are then presented and the figure [Annexe1-a] represents, always for this history and according to the temperature, the supposed metallurgical evolution solution of the differential equation [éq 2.3-2] as well as the recall of the abundant data during the seizure. SEIZED

BY the TRC SEIZED
BY the STORIES THERMOMETALLURGIQUES WHICH ONE WITH the EXPERIMENTAL
KNOWLEDGE FOR an ACIER GIVES Enter
the name of steel (8 alphabetical characters maximum) trcacier
Enter
the value of temperature 836 To enter Ar_3

the value of the temperature below which all the transformations are finished 200
LE
TRC
EAST CHARACTERIZES PAR: 1 -
the number of stories which composes it; 2 -
coefficients A, B, C, D, E, F of the polynomial: A + BT + CT2 + DT3 + ET4 + FT5
defining the curve F controls cooling (T) such as: T (T) =

exp {F (T) - F (700) - ln [Tp (700) F' (700) 1} where:
is Tp the derivative of and that $T(t)$ of F' ; 3 it F
value of the austenitic size of grain dref of the diagram; CAUTION
! THE FIRST HISTOIRE SEIZED MUST BE SLOWEST; I.E.
NEAREST TO do EQUILIBRE THERMODYNAMICS Enter
the number of sets which you want to seize? 1 CAUTION

! you will seize 1 set
(S) of thermo-metallurgical stories (OK = 0 ; Not = 1) 0 Enter

the number of stories of the group 1 1 Enter

the value of the coefficients and A, B, C, D, E, F 8.563 d
-0.0276 1.22D-4 -2.955D - 7 3.492D- 10 -1.517D - 13 11D-6 CAUTION
! the significant minimal proportion for a component with ambient of 0.03 History
number 1 Enter
the value of Tpoint 700 -0.00542
Enter
the final proportions of ferrite, pearlite and bainite for $(Zff, Zfp et Zfb)$ history
1 0.764
0.199 0.037 Entry
of and the end initial temperatures of transformation for history 1 Do enter
the initial temperatures and of ferritic end of transformation Tdf and Tff 792
657.5
Do enter

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the initial temperatures and of end from transformation perlitic and 657.5 Tdp Tfp
615 Do enter
the initial temperatures and of end from transformation bainitic and 490 Tdb 420 Tfb
is you
DO VALIDATE the HISTOIRE NUMBER? (YES = 1 NON = 0) 1 TPOINT
A 700 -5.420D DEGREES
- 03 Zff Tdf

```
Tff          7.640        D
1 7.920D+    2 6.575D+    2 Zfp Tdp
Tfp          1.990        D
01 6.575D+   2 6.150D+    2 Zfb Tdb
Tfb          3.700        D
02 4.900D+   2 4.200D+    2 1
                          DEFINITION
```

of the coefficient of translation used to compute:, modelling $\dot{T}_{eff}$ the influence of the size of grain on the kinetics of transforamtion: One thus

$$\dot{T}^{eff} = \dot{T} \cdot \exp(a(d - d_{ref}))$$

defines the value of. Enter a
the value of the coefficient of translation has for the effect cuts grain: 11200.
DEFINITION

OF the VARIATION OF ms According to One considers $Zf + Zp + Zb$
that the martensitic transformation is described by the model of Koistinen-Marburger: in which

$$Z_4(t) = \left[1 - \sum_{i=1}^{i=3} Z_i\right]\left\{1 - \exp\left(\beta\left[\mathrm{Ms} - T\right]^+\right)\right\}$$

the martensitic initial temperature of transformation is, beyond Ms of a certain threshold, function of: . One $Zf + Zp + Zb$ thus

$$Ms(t) = Ms_0 + A\left[\sum_{i=1}^{i=3} Z_i - Z^s\right]^+$$

defines the values of and . Ms_0 as well as β the values of Zs and A. Entrez the number of models of variation of ms according to Zf + Zp + Zb which you want to seize 1 Enter

the value of the Zs threshold and A for model 1 as well as
the value, TPLM, the velocity of cooling with 700 °C of the slowest history leading to a partial martensitic transformation and of (0.47 -32.76
-3,497 14.06 you
Validate the model such as (YES = 1 NON = 0): Zs = 0.47 AM = -
32.76 TPLM =
- 3,497 = 14.06
1 Example

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of procedure of seizure of the diagrams trc tracier

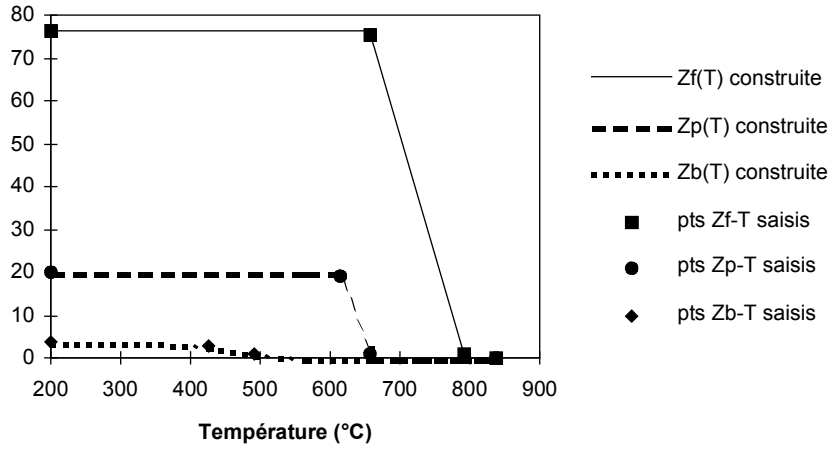
```
= DEFI_TRC (HIST_EXP
 = _F (VALE        = (-
5.420                      D-03 1.220D-     01 -2.955D    00 3.492D-    - 02 -1.517D
                             04 0.000D+    - 07 0.000D+   10 0.000D+    - 13 8.360D+
                             00 0.000D+     00 0.000D+    00 0.000D+     02 7.956D+
                             00 1.000D-     00 0.000D+    00 0.000D+     02 7.920D+
                             02 7.277D-     00 0.000D+    00 0.000D+     02 6.622D+
                             01 7.540D-     00 1.000D-    00 0.000D+     02 6.575D+
                             01 7.640D-     02 2.523D-    00 0.000D+     02 6.539D+
                             01 7.640D-     02 1.890D-    00 0.000D+     02 6.150D+
                             01 7.640D-     01 1.990D-    00 0.000D+     02 6.103D+
                             01 7.640D-     01 1.990D-    00 0.000D+     02 5.665D+
                             01 7.640D-     01 1.990D-    00 1.000D-     02 4.900D+
                             01 7.640D-     01 1.990D-    02 2.700D-     02 4.250D+
                             01 7.640D-     01 1.990D-    02 3.700D-     02 3.485D+
                             01 1.100D+     01 8.563D+    02 -2.760D     02),),),
                                                                        TEMP_MS

      = _F (P = 1.100D+01 SEUIL =
                 4.700D-01 AKM = -3.276
                 D+01 BKM.= 1.406
                 D+01 TPLM =
                 -3.497D+00), GRAIN_AUST

      = _F (DREF = 11.D-6 A = 11200
                       .),); Result
```

of the operation of seizure above providing in language of Aster command *the definition* of a metallurgical behavior to cooling. Appear

Visualisation des points saisis et calculés pour une histoire d'un TRC



Annexe1-a: Example of thermo-metallurgical history resulting from a trc and INTEGRATED into the model

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