

Models of metallurgical behavior steels

Summary :

This document presents the models of metallurgical behavior to the heating and cooling making it possible to about describe structure transformations of steels at the time of cycles thermal exceeding of the temperatures $800^{\circ}C$.

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 of calculation of hardness associated with the metallurgy.

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1 Introduction

The operations of assembly and thermomechanical treatment 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, deformations 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 $800^{\circ}C$) and of a more or less fast cooling of the parts during their manufacturing. 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 modeling of these structure transformations to the heating and cooling for low alloy steels and this, on a scale which, while remaining "reasonable" for the metallurgist, is easily usable by the mechanic.

This kind of modeling is realizable within *Code_Aster* for the whole of the elements (PLAN, AXIS, 3D) "THERMAL" PHENOMENON by the use of the operator CALC_META in "postprocessing" of a thermal calculation of evolution. The relation of behavior dedicated to steel, by difference with that dedicated to the zircalloys, to use under the keyword BEHAVIOR of the operator is the relation "STEEL". For the definition of the metallurgical behavior of steel the information of the order DEF1_TRC and of the keyword factor META_ACIER under the order DEF1_MATERIAU is necessary. Lastly, the definition of the initial metallurgical state is realizable using the order CREA_CHAMP, under the keyword factor ETAT_INIT of the operator CALC_META. The metallurgy calculation is necessary to the realization of mechanical calculations which take account of the mechanical consequences of these metallurgical phenomena [R4.04.02].

The models presented (with the heating and cooling) are formulated within the framework of the relations of behavior to internal variables (or mémoratrices), and authorize a simple identification and rapid based on the experimental diagrams (diagrams TRC Transformations into Continuous Cooling). The choice of the variables and the forms of the laws of evolution selected are given and the description of the implementation of the models (method of identification) is also presented.

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

Note:

- *The basic metallurgical notions necessary to comprehension of the problem general 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.*

2 Metallurgical model of behavior to cooling

2.1 Introduction

On the basis of test of dilatometry [Figure 2.1-a], only knowledge, a given moment, temperature of an undergoing steel of structure transformations does not make it possible to know its state of deformation. On the other hand, the behavior of such a steel seems to be able to be described within the framework of the models of behavior to variables mémoratives or interns [bib6]. Indeed, if one introduces:

- $Z = \{Z_i; i=1, p\}$ p - uplet of the proportions of the possible metallurgical components present in a point M and at one moment t given (here, $Z_1 + Z_2 + Z_3 + Z_4$ will be the proportions of ferrite, pearlite, bainite and martensite and the proportion of austenite in M will be equal to: $1 - (Z_1 + Z_2 + Z_3 + Z_4)$);
- $\varepsilon_y^{th}(T) = \alpha_y(T - T^y)$ et $\varepsilon_\alpha^{th}(T) = \alpha_\alpha(T - T^y) + \Delta \varepsilon_{\alpha y}^y(T^y)$ thermal deformations of austenite and the phases ferritic, perlitic, bainitic and martensitic; while noting:
 - α_y the thermal dilation coefficient average of austenite;
 - T^y the temperature of reference to which one considers ε_y^{th} worthless;
 - α_α the thermal dilation coefficient average presumedly identical for ferrite, the pearlite, bainite and martensite;
 - $\Delta \varepsilon_{\alpha y}^y$ deformation, at the temperature T^y , phases ferritic, perlitic, bainitic and martensitic compared to austenite (by taking the latter like the phase of reference);
- if one considers, moreover, that the deformation of a multiphase mixture can be obtained starting from the deformations of each phase by a linear law of mixture, one can then describe the evolution of the state of deformation during a dilatometric test by:

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

The problem lies then in the determination of Z or, more precisely and within the framework of simple materials with variables mémoratives, in the determination of the function of evolution f such as: $\dot{Z} = f(T, Z, \dots)$.

To give an account of an effect the speed of cooling on the evolution of structure transformations, we propose, within the framework as of simple materials with variables mémoratives, a modeling of the metallurgical behavior of steels to the cooling which includes, a priori, \dot{T} among its variables of state.

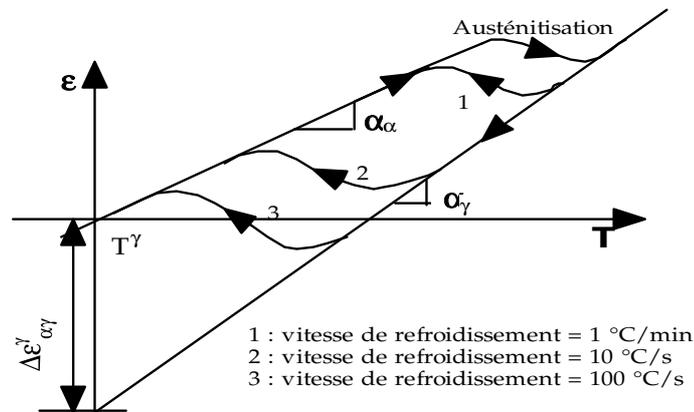


Figure 2.1-2.1-a : Schematic curves of dilatometry

2.2 Assumptions

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

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

H2 : *Diagrams TRC supplemented 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 objectives to be fixed at the model: to be compatible with the whole of 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 M_s .*

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

2.3 Choice of the variables of state

Pilot variables of state

Into thermomechanical of the continuous mediums, the pilot variables of state are generally the temperature and the state of constraints or deformations. However, because of the assumption H2, the temperature is only the variable pilot retained. Indeed, the influence of the state of stresses on structure transformations does not appear in diagrams TRC. Moreover, there 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 state of stresses σ , austenitic size of grain d and percentage of carbon C austenite changing 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 concept even of component metallurgical. In addition Giusti showed that if the taking into account of C was 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 M_s [Figure 2.3-a].

Contrary to the percentage of carbon, 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, who 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 M_s , which depends on the undergone thermo-metallurgical history, intervenes in the law of Koistinen-Marburger adopted on the assumption **H2** to describe the martensitic transformation. One thus chooses to introduce M_s like variable mémoratrice.

The character memorator of the variables mémoratrices introduced here besides Z appears clearly: d characterize the thermal history undergone at the time of the passage in austenitic phase and M_s connect the decomposition of austenite to the conditions of its transformation into martensite.

The relation '`STEEL`' of the operator `CALC_META` thus comprise 7 internal 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 at the points of Gauss.
- $V7$: M_s martensitic temperature of transformation,

C %	Mn%	Si %	S %	P %	Ni %	Cr %	Mo%
0,36	0,77	0,28	0,010	0,019	0,16	0,96	0,28

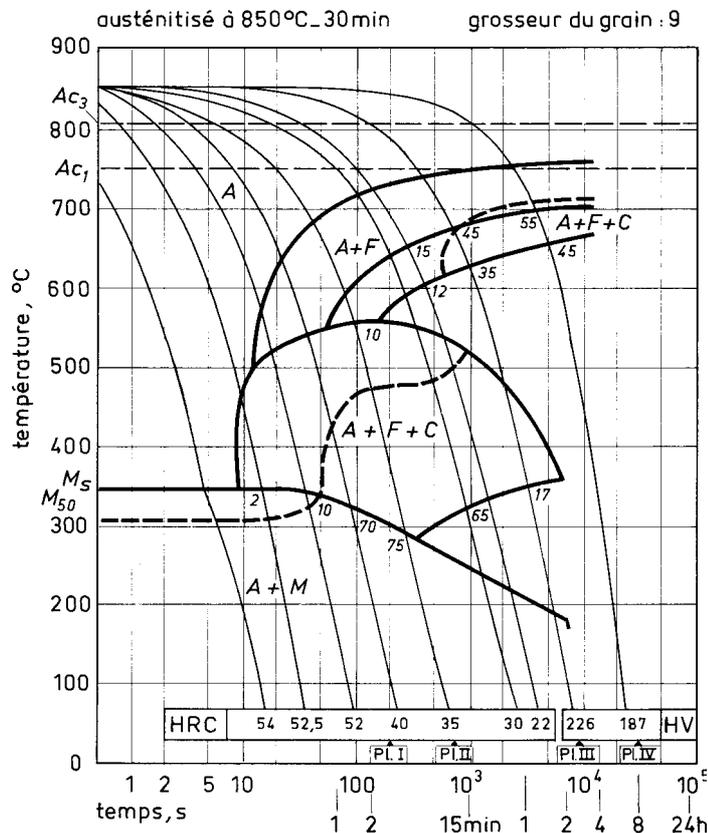


Figure 2.3-2.3-a : Example of diagram TRC

It is also necessary to model the whole of the phenomena concerned at the time of an operation of welding to introduce other variables mémoratives such as the unelastic tensors of deformations which can correspond to the plastic deformations, of plasticity of transformation or viscosity. But, in accordance with the assumption **H2**, it is considered 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 relation of behavior expressing the current vector of heat q ; its temporal derivative first $\dot{\nabla} T$ is not a variable of state and the relation of behavior expressing the current vector 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

$$\sum_{i=1}^{i=3} Z_i :$$

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

The assumption **H5** mean that the martensitic initial temperature of transformation is constant (for a given size of grain) and equalizes with 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 of all the relations of behavior other than that expressing z and Z_4 .

With $z = \{Z_1, Z_2, Z_3\}$ that one will distinguish well from $Z = \{Z_i; i=1, p\}$ defined in the § 2.1.

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

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

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

and

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

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

and $[X]^+$ indicate 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 calculate speeds 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].

3 Identification and implementation of the model to cooling

3.1 Principle

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

- 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 $(E_k = (T(t_K), \dot{T}(t_K), z(t_K); d(t_K)))$, their speeds of evolution in z are also close is:

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

One determines then speeds of structure transformations of an unspecified state per interpolation among all the "couples" $(E_k, f(E_k))$ 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 mark $[\ln(t) - T]$ 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 consist 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, starting 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.

3.2.2 Rules of interpretation of diagrams TRC

Thermal 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 mark $[\ln(t) - T]$ and for temperatures lower than $820\text{ }^{\circ}\text{C}$, 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 $T^i(t)$ starting from the data of a pilot curve $T_p(t)$ and of the moment (in second) for which this history crosses the isotherm $820\text{ }^{\circ}\text{C}$ by:

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

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

In fact, one has relative information more easily at the speeds of cooling of the thermo-metallurgical stories of diagrams TRC that at moments of crossing of the isotherm $820\text{ }^{\circ}\text{C}$. It is in particular the case of steels of welding, of which diagrams TRC are traced in a reference mark "speed of cooling with $700\text{ }^{\circ}\text{C}$ - temperature". Taking into account [éq 3.2.2 - 1], one can then express the moment of crossing of the isotherm $820\text{ }^{\circ}\text{C}$ according to $T_p(t)$ and of $\dot{T}^i(700)$ and one obtains like characterization of $T^i(t)$:

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

With $F(T) = \ln[tp(T)]$ and, in particular $\dot{T}^i(t(T)) = \frac{1}{F'(T)t^i(T)}$

Concretely, the function is interpolated $F(T)$ 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 speed of cooling in $700\text{ }^{\circ}\text{C}$. 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 of the determination of $\dot{T}^i(700)$, the agreement between the thermal stories read and recomputed seems very sufficient.

If one has the recordings 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 dilatometric tests defining diagram TRC used for the identification of the model are realized with constant speeds of cooling, one characterizes these kinetics of cooling only by their speeds of cooling with $700\text{ }^{\circ}\text{C}$ and a function F identically worthless.

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 behaviour a significant variation of the total coefficient of dilation of the test-tube [Figure 2.1-a]. These temperatures are then regarded as and the end initial temperatures of the transformations. More precisely:

- 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 formation minus 1%.

Kinetics of the ferritic, perlitic and bainitic transformations

The observation of a swelling behaviour shows that, except in the vicinity of initial temperatures and end of transformation, the evolution of the deformation 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 speed of transformation is, between the experimental temperatures of beginning and end of transformation, a linear function of the temperature;
- speeds 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}) that enters the experimental temperatures of beginning and end of transformation.

Martensitic transformations

It is supposed that the martensitic transformations are described by the law of Koistinen - Marburger [éq 2.3-3] and the phenomenologic equation [éq 2.3-4] expressing M_s . Each diagram TRC then is used to determine the coefficients β , A and Z^s as well as the temperature M_{s_0} . Lastly, to prevent that the model systematically transforms into martensite remaining austenite when the temperature is reached M_s , one introduces an additional parameter, called TPLM, characterizing (by his speed of cooling with $700^\circ C$) slowest of the kinetics of cooling which generates a martensitic transformation. More precisely [Figure 3.2.2-a]:

- M_{s_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.

$M_{s0} = 415^{\circ}\text{C}$; $M_{s0} - M_f = 185^{\circ}\text{C}$

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

$A = -30,086$

$Z_s = 0,38$

et $TPLM = -9^{\circ}\text{C/s}$

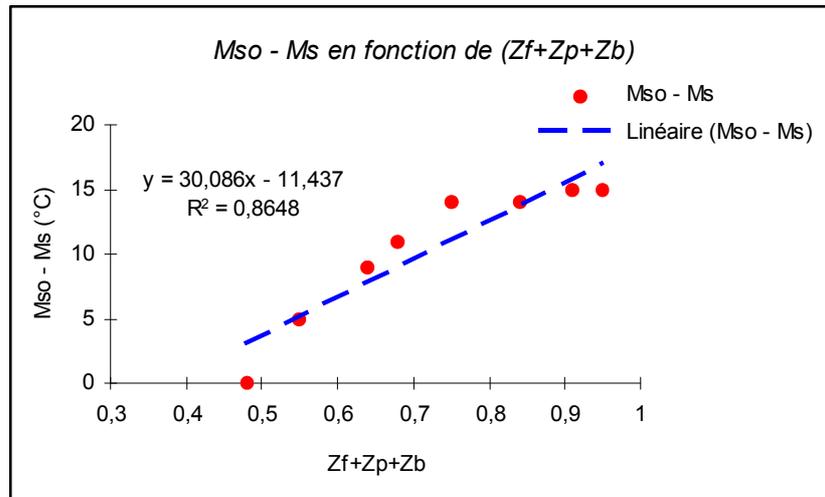


Figure 3.2.2-a: Evolution of $(M_{s0} - M_s)$ according to $(Z_1 + Z_2 + Z_3)$; for steel 16MND5 austenitized 5 minutes with 900°C .

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. Size of grain of austenite thus an important role exploits the transformations with cooling. For this reason diagrams TRC are established for conditions of austenitization given and should not in any rigour 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. With each point M of a diagram TRC the tuple corresponds (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 speed of cooling "effective" \dot{T}_{eff} :

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

with

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

a : homogeneous coefficient material contrary to a length.

The law of evolution retained is thus written:

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

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

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 Seizure of diagrams TRC

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

- for diagram TRC :
 - the value of the austenitic size of grain d_{ref} 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 law of Koistinen-Marburger,
 - the value of the coefficients A and Z^s intervening in the equation [éq 2.3-4],
 - values of the six coefficients of the polynomial of degree five interpolating the function $\ln[tp(T)]$ (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 :
 - the speed of cooling with $700^\circ C$,
 - final proportions of ferrite, pearlite and bainite (Z_{ff} , Z_{fp} , Z_{fb}),
 - initial temperatures of each transformation (T_{df} , T_{dp} , T_{db}),
 - and temperatures of end of each transformation (T_{ff} , T_{fp} , T_{fb}).

The seizure of a diagram TRC is realizable by a programme of seizure (available available with the CAS-test `mtlp100a` 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).

The result of this procedure of seizure of diagrams TRC (cf [§An1]) is directly insertable in a command file of *Code_Aster* as an order `DEFI_TRC`, order 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 Ms_0 , and the complete definition of the model to the heating and austenitic growth of grain) is carried out within the order `DEFI_MATERIAU` under the keyword factor `META_ACIER`.

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

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

3.3.1 Evaluation 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 $T^3 Ms$):

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

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

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

Indeed:

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

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} of the same discretized history:

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

where $\dot{T}(E_k)$ can be estimated by derivation of the analytical expression 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 $E_i = \{T, \dot{T}_i(T), z_i(T); d_{ref}\}$ where the index i refers to in experiments known stories.

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

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

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

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

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

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

then:

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

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

or, if not:

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

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

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

and

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

If $Ar_3 > T(t) \geq Ms(t)$, one determines (thanks to the assumption of regularity of f) the value taken by f in $(T, \dot{T}, z; d)$ starting from knowledge for any temperature T values taken by f in the thermo-metallurgical states $E_i(T, \dot{T}_i(T), z_i(T); d_{ref}(T))$ in experiments known stories, where

$\dot{T}_i(T)$ is the speed of cooling for the history H_i at 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 dependence compared to the parameter d is included in the possible modification the current speed 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 $\{E_i, f(E_i)\}$ "close" to $(T, \dot{T}, z; d)$.

Concretely, stages of this interpolation of the values of f in $(T, \dot{T}, z; d)$ 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 $(T, \dot{T}_{eff}, z; d_{ref})$

- one calculates for all the experimental stories H_i known 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 $(T, \dot{T}_{eff}, z; d_{ref})$ rather dense in temperature):

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

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

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

- one determines the six closer neighbors of $E(t) = (T(t), \dot{T}_{eff}(t), z(t); d_{ref}(t))$ among all them $E_i^j(t) (j=1,3)$ defining the metallurgical behavior of material in the vicinity of the temperature $T(t)$ by minimizing the distance from $E(t)$ with each one of $E_i^j(t)$;
- one calculates the barycentric coordinates of $E(t)$ compared to its closer neighbors $E^v(t) (v=1,6)$. For that, one solves the linear system associated with this calculation within the meaning of least squares and by choosing the solution with minimal standard 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]);
- only the neighbors are retained $E^w(t) (w \leq 6)$ such as all the barycentric coordinates λ_w of $E(t)$ are positive (so that $E(t)$ that is to say located inside the convex polyhedron being based on these points);
- one calculates then:

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

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

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

Note:

The definition of a distance used in the criterion of proximity is not obvious, taking into account the nonadimensional character of the space of (T, \dot{T}, z, d) . Currently, the research of the closest neighbors is carried out by adimensionnalisant each variable simply but one could plan to introduce weighting 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.

4 Metallurgical model of behavior to the heating

4.1 Assumptions

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

$$\dot{z}_y = f(T, z_y) .$$

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

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

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 $Z_{eq}(T)$ and $\tau(T)$ starting from tests at 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 $\tau(T)$ remain difficult [bib4].

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

$$\dot{z}_y(T, z_y) = \frac{Z_{eq}(T) - z_y}{\tau(T)}$$

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

4.2 Form of the model selected

In its continuous form, the model selected is such as:

$$\dot{z}_y(T, z_y) = \frac{Z_{eq}(T) - z_y}{\tau(T)} \quad \text{éq 4.2-1}$$

where • z_y indicate the proportion of austenite;
:

- $Z_{eq}(T)$ is the function (with Ac_1 and Ac_3 positive constants):

$$Z_{eq}(T) = \begin{cases} 0 & \text{si } T \leq Ac_1 \\ \frac{T - Ac_1}{Ac_3 - Ac_1} & \text{si } Ac_1 \leq T \leq Ac_3 \\ 1 & \text{si } T \geq Ac_3 \end{cases} \quad \text{éq 4.2-2}$$

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

$$\tau(T) = \begin{cases} \tau_1 & \text{si } T \leq Ac_1 \\ \tau_1 + \frac{T - Ac_1}{Ac_3 - Ac_1} (\tau_3 - \tau_1) & \text{si } Ac_1 \leq T \leq Ac_3 \\ \tau_3 & \text{si } T \geq Ac_3 \end{cases} \quad \text{éq 4.2-3}$$

Notice 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 fixed, $Z_{eq}(T)$ 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 who is done under the simple keywords `AC1` and `AC3` under the keyword factor `META_ACIER` order `DEFI_MATERIAU`.

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

In the model suggested by Leblond and Devaux, the form of the function is not $\tau(T)$ 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 function τ constant. The first possibility consists in identifying a value τ_1 of τ allowing to describe the beginning of the transformations correctly whereas the second consists in identifying a value τ_3 of τ allowing to describe the end of the transformations correctly. One then tested the model obtained with a function $\tau(T)$ refine definite starting from the values τ_1 and τ_3 defined above. Completely satisfactory and comparable got results being with 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 who are well informed with `AC1` and `AC3`.

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_y and explicitly in \dot{T} and τ on each step of time (i.e while considering \dot{T} and τ constants on the step and equal to their values at the beginning of step of time). One obtains then:

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

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

$$Z_i(t+\Delta t) = Z_i(t) \cdot \left(1 - \frac{z_y(t+\Delta t) - z_y(t)}{1 - z_y(t)} \right).$$

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

4.4 Evolution of the austenitic size of grain to the heating

Once austenized, 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 worthless size of grain. The austenitic growth of grain is a thermically activated process. The selected model of growth is that of Grey and Higgins, adapted to treat material in the course of transformation [bib15]:

Model of growth:

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

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

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

with

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

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

with

z : proportion of the austenitic phase

d : diameter of austenitic grain homogeneous to a length

d_{lim} : size of limiting grain, dependent on d_{10} homogeneous parameter material with a length

Q_{app} and W_{app} : homogeneous parameters materials with energies of activation ($J.mol^{-1}$)

R : constant of perfect gases ($8.314 J.K^{-1}.mol^{-1}$)

d_{10} : homogeneous parameter material at seconds per unit of length

Note:

The parameters materials are to be informed under the keyword `META_ACIER` of `DEFI_MATERIAU`.

4.4.1 Digital processing

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The calculation of the size of grain is carried out after the calculation of proportion of phase and the integration of the equation of evolution is made according to a diagram implicit in D . From where:

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

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

One solves a quadratic equation in D .

4.5 Direction 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 at the time it 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 speed of evolution thermal is described either by the model of decomposition of austenite, or by the model of formation of austenite.

With regard to the model introduces into *Code_Aster*, the direction of the metallurgical evolution (it is - with-to say formation or decomposition of austenite) is given as follows:

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

where REFR mean that the metallurgical evolution is determined by the model of decomposition of austenite and where AUST mean that the metallurgical evolution is determined by the model of formation of austenite.

Note:

AR3 is also a characteristic of the metallurgical behavior to cooling already defined by the model of transformation in cooling.

5 Identification of the model to the heating

5.1 Determination of the function $Z_{eq}(T)$

$Z_{eq}(T)$ can 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 expression, the temperatures Ac_1 and Ac_3 are the quasi static temperatures "theoretical" of beginning and end of austenitic transformation which correspond to an 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 Ac'_1 and Ac'_3 these temperatures, they check:

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

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

5.2 Determination of the function $\tau(T)$

In a general way, it is not easy to release means 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 $Ac_1 \leq T \leq Ac_3$:

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

where τ_1 and τ_3 are positive constants.

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

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

5.2.1 Identification of TAU_3 starting from AC' 3

For \dot{T} and τ constants and the initial condition $z_y(AC_1)=0$, the solution of the equation of evolution [éq 4.2-1] is (as long as $Z'_{eq}(T)$ is constant, i.e. as long as $T \leq AC_3$):

$$z_y(T) = Z_{eq}(T) - \tau \cdot Z'_{eq}(T) \cdot \dot{T} \cdot \left(1 - \exp \left[\frac{AC_1 - T}{\tau \cdot \dot{T}} \right] \right)$$

In particular, one thus has, for $T = AC_3$:

$$0,95 = Z_{eq}(AC_3) - \tau \cdot Z'_{eq}(T) \cdot \dot{T} \cdot \left(1 - \exp \left[\frac{AC_1 - AC_3}{\tau \cdot \dot{T}} \right] \right)$$

A test of dilatometry at heating rate constant (and not very low) then makes it possible to determine the value τ_3 of τ allowing to reach the agreement between the experimental and calculated values AC_3 . One presents in [bib4] comparisons between experiment and calculation obtained by thus identifying the function τ regarded as constant.

5.2.2 Identification of TAU_1 starting from AC' 1

In the same way that previously, one can also write, for $T = AC'_1$:

$$0,05 = Z_{eq}(AC'_1) - \tau \cdot Z'_{eq}(T) \cdot \dot{T} \cdot \left(1 - \exp \left[\frac{AC_1 - AC'_1}{\tau \cdot \dot{T}} \right] \right) \quad \text{éq 5.2.2-1}$$

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

6 Model of calculation of hardness

Metallurgical calculations can be supplemented by a calculation of hardness of “hardening” associated with the metallurgical structure.

The selected model uses the assumption according to which the hardness of a polyphase material point is well represented by a linear law of mixture of the microhardnesses of the components (here phases austenite, ferrite, pearlite, bainite and martensite). The microhardnesses are taken as being constants of 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 calculation of hardness is done via the operator of postprocessing `CALC_META` ; option `'DURT_ELGA'` for calculations of hardness at the points of Gauss and option `'DURT_ELNO'` for calculations with the nodes by elements.

Hardnesses of the various metallurgical phases are data materials provided by the user under the keyword factor `DURT_META` of the operator `DEFI_MATERIAU`.

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

7 Bibliography

- 1) WAECKEL F.: Metallurgy elements for the study of structure transformations in steels. Internal note EDF-DER, HI-71/8075, March 1993.
- 2) WAECKEL F.: A thermo-metallurgical law of behavior of steels for the mechanical calculation of the structures. Mechanical doctorate ès, Ensam Paris, March 1994.
- 3) ANDRIEUX S., WAECKEL F.: A metallurgical model of behavior of steels to cooling. Internal note EDF-DER, HI-74/94/072/0, October 1994.
- 4) WAECKEL F.: Modeling of the austenitic transformation in *Code_Aster*. Internal note EDF-DER HI-74/95/017/0, July 1995.
- 5) WAECKEL F., DECEIVED P.: Comparison of the metallurgical models of behavior established in *Code_Aster* and in sysweld. Note interns EDF - DER, HI-74/94/076/0 and HT - 26/94/033/A, March 1995.
- 6) MARIGO J.J. : The thermomechanical behavior of the simple mediums with variables mémoratives: I General information and first examples. Internal note EDF-DER HI/5147-07, 1985.
- 7) KOISTINEN DP, MARBURGER RE: With general equation prescribing extent of austenite - martensite transformation in pure Fe-C alloys and lime pit carbon steels. Recorded Metallurgica, vol.7, pp. 59-60, 1959.
- 8) AEBY-GAUTIER E.: Transformations perlitic and martensitic under tensile stress in steels. Science doctorate Physics, Institut National Polytechnique of Lorraine, 1985.
- 9) DENIS S. FARIAIS D. SIMON: With, Mathematical model coupling phase transformations and temperature evolutions in steels. International ISIJ, vol.32, n° 3.1992, pp. 316-325.
- 10) GIUSTI J.: Constraints and residual deformations of thermal origin. Application to the welding and the hardening of steels. Doctorate of State ès Physical science. University Paris 6.1981.
- 11) LEBLOND JB, DEVAUX JC: With new kinetic model for anisothermal metallurgical transformation in steels including effect of austenitic grain size, 1984. Recorded Metallurgica, vol.32, n° 1, pp. 137-146.
- 12) J.C. DEVAUX: Studies of the constraints of thermal origin in the zones affected by heat at the time of an operation of welding. Contract D.G.R.S.T., n° 79.1095, Report of end of research.
- 13) LEBLOND J.B., MOTTET G., DEVAUX J., DEVAUX J.C: 1985. Mathematical models of anisothermal phase transformation in steels and predicted plastic behaviour. Materials Science and Technology, vol.1, n° 10 october 1985, pp. 815-822.
- 14) RAZAKANAIVO A.: Introduction of a model of calculation of hardness into *Code_Aster*. Report MN, 97/005, January 1997.
- 15) MARTINEZ MR.: Junction 16MND5-Inconel 690-316LN by welding-diffusion, development and calculation of the residual stresses of process. Doctorate Mines of Paris, 12 1999.

8 Description of the versions of the document

Version Aster	Author (S) Organization (S)	Description of the modifications
5	F.WAECKEL, A.RAZAKANAIVO EDF-R&D/AMA	addition of the calculation of hardness

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Annexe 1

One presents below an example of the procedure of seizure of an experimental thermo-metallurgical history (at nonconstant speed of cooling). One first of all shows the furnished information by the user with the software of seizure: speed of cooling with $700\text{ }^{\circ}\text{C}$, composition with ambient, experimental temperatures of beginning and end of transformation,.... This information is registered in bold characters and Italic; the temperatures are indicated in $^{\circ}\text{C}$ and speeds of cooling in $^{\circ}\text{C}/\text{s}$. The whole of 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.

SEIZURE OF THE TRC

SEIZURE OF THE STORIES THERMOMETALLURGIQUES OF WHICH ONE WITH
THE EXPERIMENTAL KNOWLEDGE FOR A STEEL GIVES

Enter the name of steel (8 alphabetical characters maximum)

trcacier

Enter the value of the temperature Ar_3

836

To enter the value of the temperature below which all the transformations are finished

200

THE TRC EAST CHARACTERIZES BY:

1 - The number of stories which composes it;

2 - The coefficients A, B, C, D, E, F of the polynomial: $WITH + BT + CT^2 + DT^3 + AND^4 + FT^5$ defining the curve cooling $F(T)$ controls such as:

$$T(T) = \exp \{ F(T) - F(700) - \ln [Tp(700) F'(700) 1] \}$$

where: Tp is the derivative of $T(t)$ and F' that of F ;

3 it value of the austenitic size of grain dref of the diagram;

CAUTION! THE FIRST SEIZED HISTORY MUST BE SLOWEST;

I.E. NEAREST TO THERMODYNAMIC BALANCE

Enter the number of units which you want to seize?

1

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

0

Enter the number of stories of the unit 1

1

Enter the value of the coefficients A, B, C, D, E, F and of d

8,563 -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 is of 0.03

History number 1

Enter the value of Tpoint 700

-0.00542

Enter the final proportions of ferrite, pearlite and bainite (Z_{ff}, Z_{fp} et Z_{fb}) for the history 1

0,764 0,199 0,037

Entry end and initial temperatures of transformation for history 1

Enter and the ferritic end initial temperatures of transformation Tdf and Tff

792 657.5

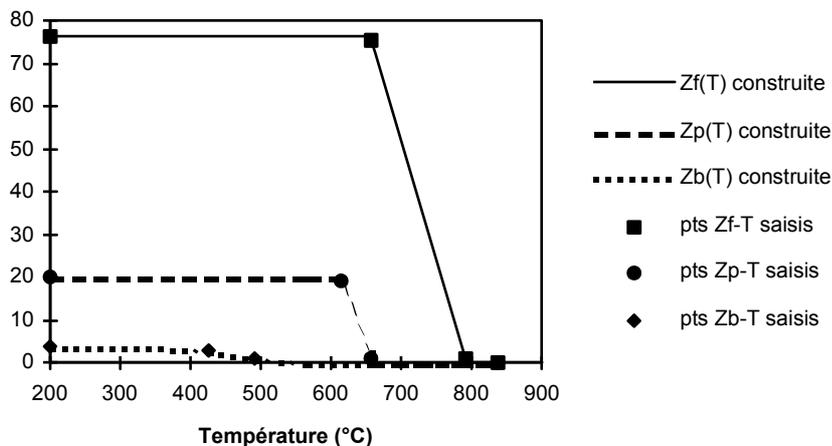
Example of procedure of seizure of the diagrams TRC

```

tracier = DEFI_TRC (
  HIST_EXP =      _F
  (VALE=
    (- 5.420D-03   1.100D+01   8.563D+00   -2.760D-02
     1.220D-04    -2.955D-07   3.492D-10   -1.517D-13
     0.000D+00    0.000D+00    0.000D+00    8.360D+02
     0.000D+00    0.000D+00    0.000D+00    7.956D+02
     1.000D-02    0.000D+00    0.000D+00    7.920D+02
     7.277D-01    0.000D+00    0.000D+00    6.622D+02
     7.540D-01    1.000D-02    0.000D+00    6.575D+02
     7.640D-01    2.523D-02    0.000D+00    6.539D+02
     7.640D-01    1.890D-01    0.000D+00    6.150D+02
     7.640D-01    1.990D-01    0.000D+00    6.103D+02
     7.640D-01    1.990D-01    0.000D+00    5.665D+02
     7.640D-01    1.990D-01    1.000D-02    4.900D+02
     7.640D-01    1.990D-01    2.700D-02    4.250D+02
     7.640D-01    1.990D-01    3.700D-02    3.485D+02),
  ),),
  TEMP_MS = _F (P = 1.100D+01
    THRESHOLD = 4.700D-01
    AKM = -3.276D+01
    BKM. = 1.406D+01
    TPLM = -3.497D+00),
  GRAIN_AUST = _F (DREF = 11.D-6
    To = 11200.),
);
  
```

Result of the operation of seizure above providing in process control language Aster the definition of a metallurgical behavior to cooling.

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



Annexe1-a figure: Example of thermo-metallurgical history resulting from one TRC and integrated into the model