Choice of the behavior élasto- (visco) - plastic

Résumé

the objective of this note is to give advices to an user wishing to carry out computations with nonlinear behaviors of elastoplastic type or élasto-visco-plastic to choose a model adapted to the modelizations considered. The materials concerned are mainly metals. For the other types of materials, the first paragraph returns to the suitable references.

Specificities and capacitances of the models élasto-visco-plastics are described. Then a description of the characteristics of the various types of hardening is made, which makes it possible to put forth some recommendations.

Some general advices on the identification of the parameters of the models are given.

One approaches also the effects of viscosity and the temperature. One gives finally elements of checking of the validity of the choices carried out concerning the behavior and his parameters.

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1 Introduction

1.1 Choix of the type of constitutive law

the choice of the constitutive law is of course function of the material which one modelizes, but also phenomena with treating: for example, the same steel will be elastoplastic with low-temperature, and viscoplastic at high temperature.

This document gives runways to advisedly use the behaviors élasto- (visco) - plastic (mainly for metals).

For other types of behaviors, the reading of the following documents is advised:

- For the models with damage (case of the concrete for example), see [U2.05.06] Réalisation of computations of damage in quasi-static
- Pour metallurgy, see [U2.03.04] Notice of use for computations thermometallomecanic on Pour
- steels porous environments in THM, see [U2.04.05] Notice of use of model THM and [R7.01.11] Model of behavior THHM
- Pour the use of elements CZM, see [U2.05.07] Notice of use of the models of cohesive areas
- Pour specific models of the discrete elements, see [R5.03.17] Behavior models of the Pour
- discrete elements models specific to elements 1D, see [R5.03.09] nonlinear Behavior models 1D
- For the models hyper elastics (of Mooney-Rivlin type) see [R5.03.19] Constitutive law hyper elastic. Almost incompressible material.
- For the constitutive laws specific to the fuel pins and metals under irradiation, see [R5.03.08] and [R5.03.23] elastoplastic Comportement under irradiation of metals: application to the internal reactor vessels
- Pour models of crystal plasticity, see [R5.03.11] Comportements elastoviscoplastic mono and polycrystalline

1.2 Quelles elastoplastic models choosing: which are their capacitances?

In this document elements of choice of the constitutive laws are provided, according to their capacitances, and the phenomena with modelizing.

Advices for the identification of the parameters will be given, while insisting on the field of validity of the models: the parameters are identified for strains, velocities, quite specific temperatures, which must correspond to the studies considered.

In addition, if the modelizations considered require it, it can be necessary to lead the identifications in the field of the large deformation. One will be able to use for that of the formalism adapted:

- `SIMO_MIEHE` for the behaviors of Von Mises with isotropic hardening, the models with effect of the metallurgical phases, the model of Rousselier,
- `GDEF_LOG` for most behaviors,
- `GROT_GDEP` for the models hyper elastics of the type `MOONEY-RIVLIN`.

2 Specificities and capacities of the models Nous

élasto-visco-plastics let us detail here the constitutive laws élasto- (visco) - plastic available in Code_Aster, (for modelizations 2D and 3D), and their specificities.

2.1 The elastoplastic models available

Hormis linear elasticity (ELAS), the elastoplastic models available are (cf [U4.51.11] Comportements nonlinear):

Elastoplasticity of Von Mises with isotropic hardening: VMIS_ISOT_TRAC, VMIS_ISOT_PUIS, VMIS_ISOT_LINE cf R5.03.02] Intégration of the behavior models elastoplastic of Von Mises
Élasto-plasticity of Von Mises with linear kinematic hardening (only or combined with isotropic hardening) : VMIS_CINE_LINE, cf R5.03.02] Intégration of the behavior models elastoplastic of Von Mises VMIS_ECMI_TRAC, VMIS_ECMI_LINE cf [R5.03.16] elastoplastic Comportement with isotropic and kinematical mixed hardening linear
Élasto-plasticity with nonlinear kinematic hardening (models of J.L.Chaboche) VMIS_CIN1_CHAB, VMIS_CIN2_CHAB, VMIS_CIN2_MEMO cf [R5.03.04] Behavior models élasto-visco-plastic of Chaboche
discrete Élasto-plasticity to semi intern variable for cyclic loadings VISC_TAHERI cf [R5.03.05] viscoplastic Behavior model TAHERI
Élasto-plasticity of Von Mise S to isotropic hardening of Jonhson-Cook (high velocities) VMIS_JOHN_COOK cf R5.03.02] Intégration of the behavior models elastoplastic of Von Mises
Élasticité nonlinear (models of Hencky) ELAS_VMIS_LINE, ELAS_VMIS_TRAC, ELAS_VMIS_PUIS cf [R5.03.20] elastic Behavior model nonlinear in large displacements

2.2 Les models élasto-visco-plastics available

Les behaviors élasto-visco-plastics available are:

Élasto-visco-plasticity with isotropic hardening LEMAITRE cf [R5.03.08] Intégration of viscoelastic behavior models VISC_ENDO_LEMA, VENDOCHAB cf [R5.03.15] viscoplastic Comportement with damage of CHABOCHE HAYHURST cf [R5.03.13] viscoplastic Comportement with damage of HAYHURST
Élasto-visco-plasticity to nonlinear kinematic hardening (models of J.L.Chaboche) VISC_CIN1_CHAB, VISC_CIN2_CHAB, V ISC_CIN2_MEMO cf [R5.03.04] Behavior models élasto-visco-plastic of Chaboche VISCOCHAB cf [R5.03.12] viscoplastic Comportement with effect of memory and restoration of Chaboche VISC_TAHERI cf [R5.03.05] viscoplastic Behavior model TAHERI
Model of viscosity in hyperbolic sine and isotropic hardening VISC_ISOT_LINE, VISC_ISOT_TRAC cf [R5.03.21] Modelization élasto (visco) plastic with isotropic hardening in large deformation

2.3 the choice type of isotropic

2.3.1 hardening Écrouissage

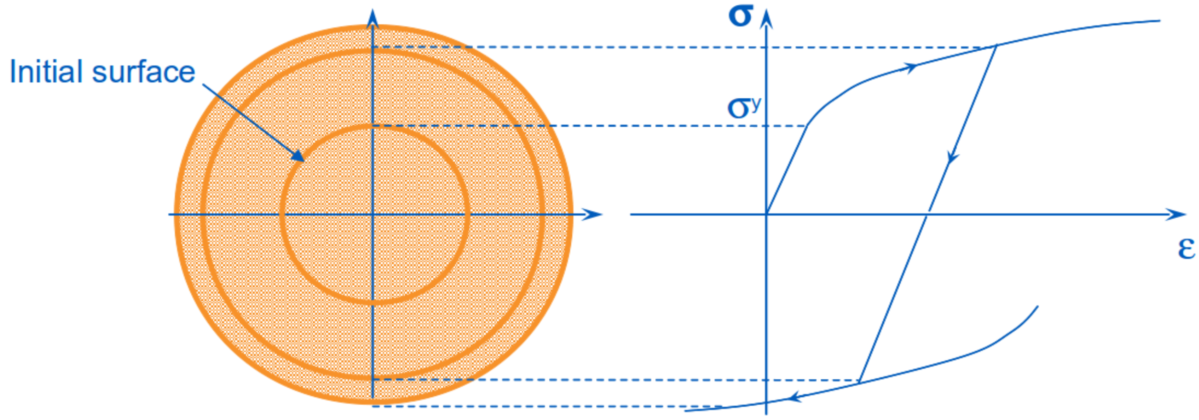
Les elastoplastic models with isotropic hardening make it possible to modelize an increase in the size of elastic domain with the identical plastic strain in all the directions. So certain materials can correspond to this kind of models, for most metals, which present a strong kinematic hardening, these models are adapted to the modelizations in which the total loadings are monotonous, or possibly with discharges of low amplitude, to remain in the elastic mode.

It is a requirement so that the response of the model is in conformity with reality (a complete model, to kinematic hardenings and isotropic nonlinear, would give in this case the same result). But it is not a sufficient condition: it can exist structures in which a total monotonic loading produces local discharges.

The validity of the approach with a hardening isotope can be checked a posteriori: it is enough that in any point, no discharge gave place to an input in plasticity. This checking is detailed E with the § 15

Pour to define the parameters of a model in isotropic hardening, it is necessary to identify the behavior on a traction diagram, by checking that the identification is well carried out in the range of strains likely to be met during the structural analysis considered.

The various types of hardening suggested (curved, model power) in general make it possible to reproduce well the traction test (see [R5.03.02] and the documents of training: 15-constitutive laws).

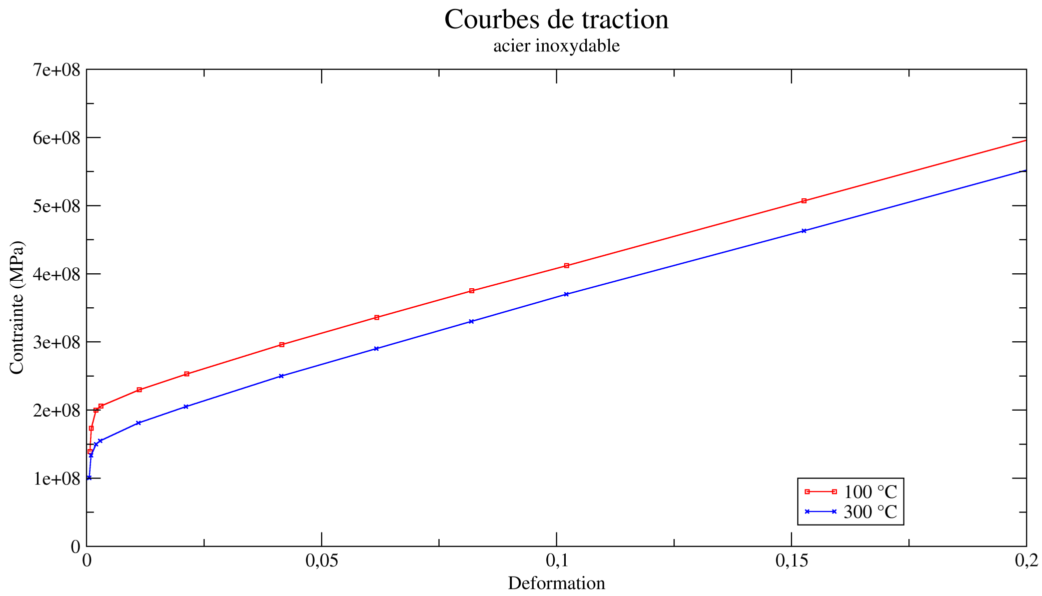


a) Évolution of the field of elasticity 3Db) Évolution of the field of elasticity in 1D

Figure 2.3.1-a . Criterion of Von Mises, isotropic hardening

Dans certain cases (fracture mechanics), it is necessary to approach the elastoplastic behavior by an equivalent nonlinear elastic behavior: they are the models of Hencky (`ELAS_VMIS_LINE`, `ELAS_VMIS_TRAC`, `ELAS_VMIS_PUIS`). There still, these models are valid only with one monotonic loading, and this time without any discharge, because they do not make it possible to modelize the plastic strain.

A way very simplified to use an isotropic hardening is to consider that it is linear (`VMIS_ISOT_LINE`). This can be valid in a range of strains, and nonvalid in another. Let us take for example traction diagrams of a stainless steel:



Appear 2.3.1-b . Traction diagrams up to 20% of strain

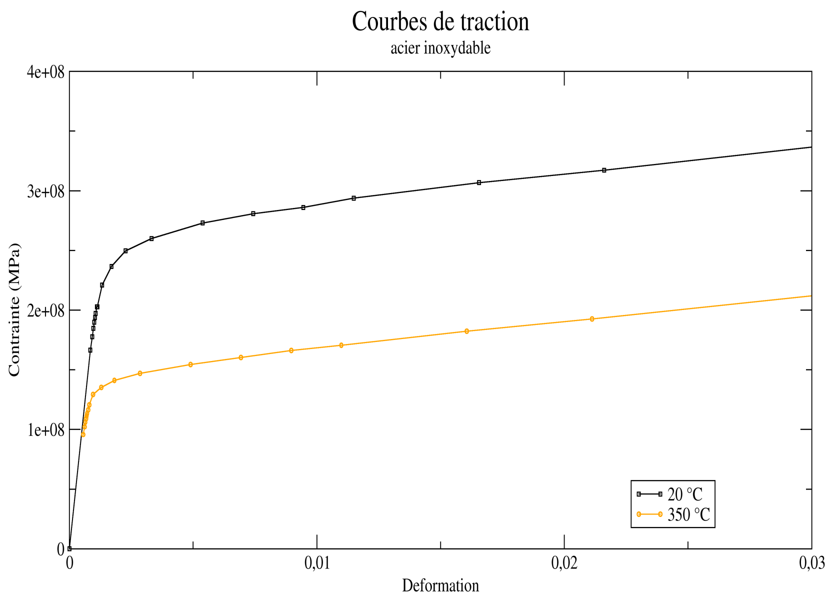


Figure 2.3.1-c . Traction diagrams up to 3% of strain

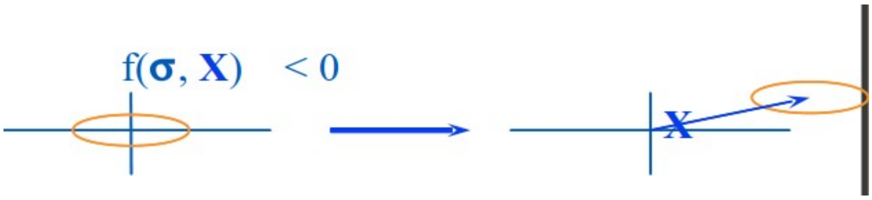
One notes on the figure 2.3.1-b that it is possible to modelize the traction diagram by a linear hardening, in large deformation, if one is not interested with accuracy in the small strains (lower than 1%). In the contrary case (figure 2.3.1-c), it seems quite delicate to build a linear hardening which is valid as of the input in plasticity.

Moreover, C E standard of hardening (like all the models with linear hardening) is likely **to over-estimate** the stresses in the event of strong strains, (or to underestimate the strains with imposed stress) because nothing does not limit the curve of hardening. A parade with this difficulty is described in paragraph 15 .

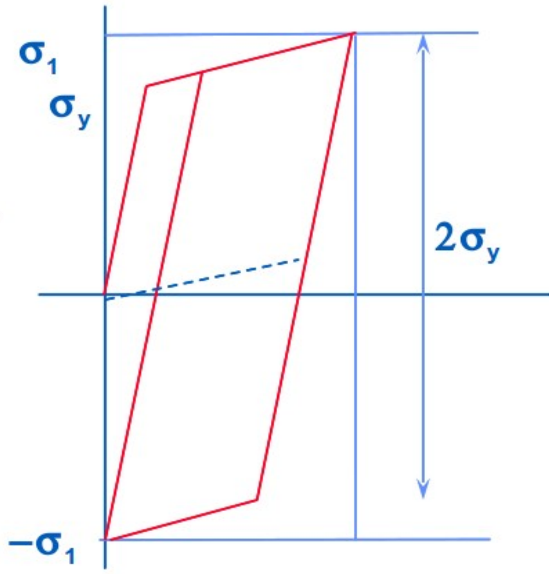
By using the behavior VMIS_ISOT_TRAC , the risks are less large: the traction diagram is defined by a function DEFI_FONCTION , and the maximum value of the X-coordinate (strain) makes it possible to define the field of validity and thus to avoid in the structural analysis exceeding this value (attention to leave the default value PROL_DROITE='EXCLU' in DEFI_FONCTION) .

2.3.2 Linear kinematic hardening

Les elastoplastic models with linear kinematic hardening are adapted to the modelizations in which the total loadings contain some discharges, and for which the approximation of the curve of hardening by a line is **acceptable** .
They make it possible to translate way very simplified the Bauschinger effect, present for most metals.
Let us examine model VMIS_CINE_LINE:



a) Évolution of the field of elasticity 3D (cut)



b) Évolution of the field of elasticity in 1D

Figure 2.3.2-a . Criterion of Von Mises, Avantage

kinematic hardening:
•The advantage of this model lies in its simplicity; It in particular makes it possible to test the effect of kinematic hardening quickly, because the identification and the resolution are very fast.
Limitations :

1.This model does not present **any** isotropic hardening.

2.The approximation of the real curve of traction and compression is often **poor** (cf preceding paragraph)

3.This model (like all the models with linear hardening) is likely **to over-estimate** the stresses in the event of strong strains, (or to underestimate the strains with imposed stress) because nothing does not limit the curve of hardening.

4.Lastly, if the loading comprises cycles, this model tends very quickly towards a stabilized cycle (in the uniaxial case, it is reached in only one cycle), which does not correspond to reality.

To raise the first limitation, it is possible to combine linear kinematic hardening with an isotropic hardening: in fact the models VMIS_ECMI_LINE (but presents the 3 other disadvantages), VMIS_ECMI_TRAC (which also makes it possible to answer the second limitation).

It is necessary to be very careful during the identification of VMIS_ECMI_TRAC (cf [R5.03.16] elastoplastic Comportement with isotropic and kinematical hardening mixed linear): indeed, the share of kinematic hardening, in the range of studied strain, must remain lower than the isotropic share of hardening, if not, one can obtain a negative isotropic hardening.

2.3.3 Nonlinear kinematic hardening: models of J.L.Chaboche

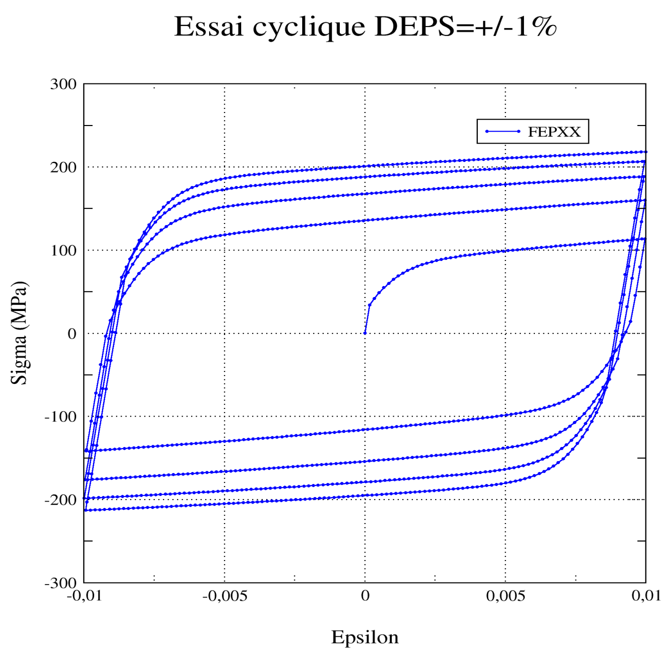
Ces models at the same time make it possible to translate the Bauschinger effect (kinematic hardening), its nonlinear evolution, and isotropic hardening, as well as other phenomena (effect of memory of the maximum plastic strain, restoration).

In their simplest form (VMIS_CIN1_CHAB) they lead to the particular shape of the curve of hardening, with a given asymptote. The idea which subtends these models is well to reproduce the cycles of tension compression, in the face and form. To improve the description of the real curves, one can introduce several independent kinematical variables, each one having a specific role to represent a level of strain. In Code_Aster, one limited oneself to two kinematical variables (VMIS_CIN2_CHAB).

Their identification is more complex than for the preceding models: the number of parameters increases, and it is necessary has minimum a cyclic test (traction and compression on several cycles) to identify them correctly. Moreover of the tests on several levels of strains are often necessary (and difficult to represent completely).

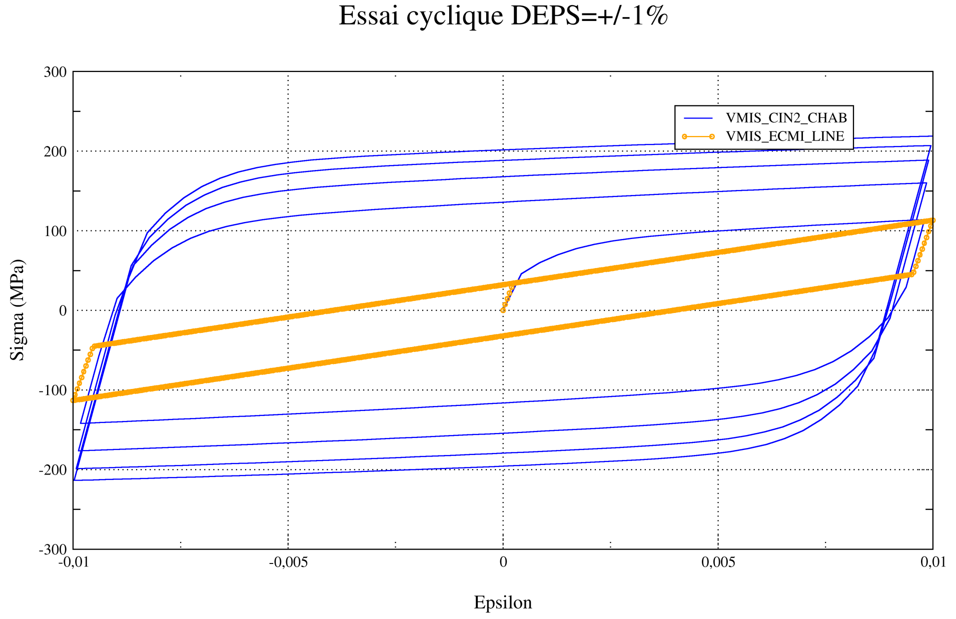
There still it is essential to target well the range of strain expected in the studies, so that the parameters are adjusted on level of strain. If one uses parameters coming from a former identification, it is necessary has minimum to check (via SIMU_POINT_MAT for example) on a modelization of the test of traction and compression) the response of the model for these parameters.

To illustrate the advantage of using a nonlinear kinematic hardening beyond some cycles of loading, let us consider an example of cycles of traction and compression to imposed strain:

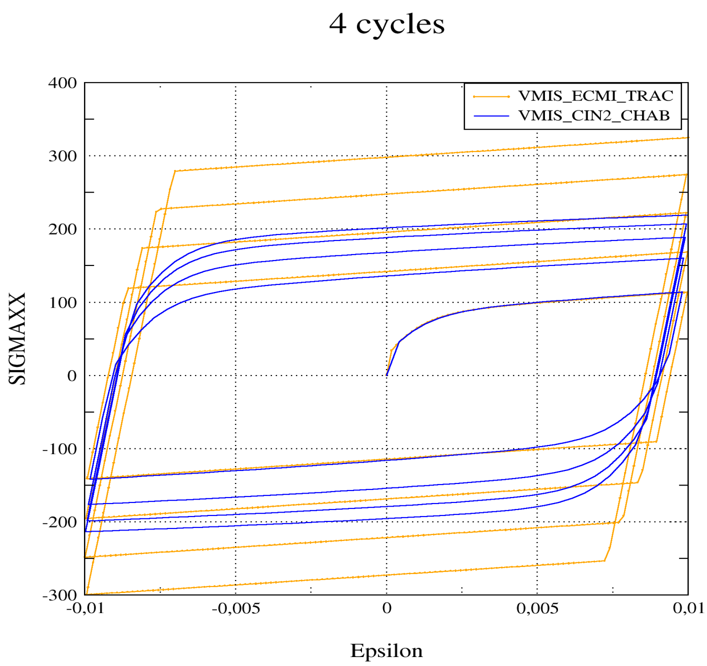


This curve is in fact a numerical curve (simulated with VMIS_CIN2_CHAB) but it correctly reproduces the experimental curves on the stainless steel considered. It will be used as reference for the illustrations below.

The approximation of this curve by a linear kinematic hardening (with an isotropic component, adjusted on the first traction diagram) shows that the response is very distant:



One can improve the representation of the very first cycles while choosing VMIS_ECMI_TRAC, and by readjusting the values of the coefficient of Prager. It is noted that if the first 2 cycles are well represented, model VMIS_ECMI_TRAC tends towards a state stabilized with an amplitude of stress much higher than the real curve.

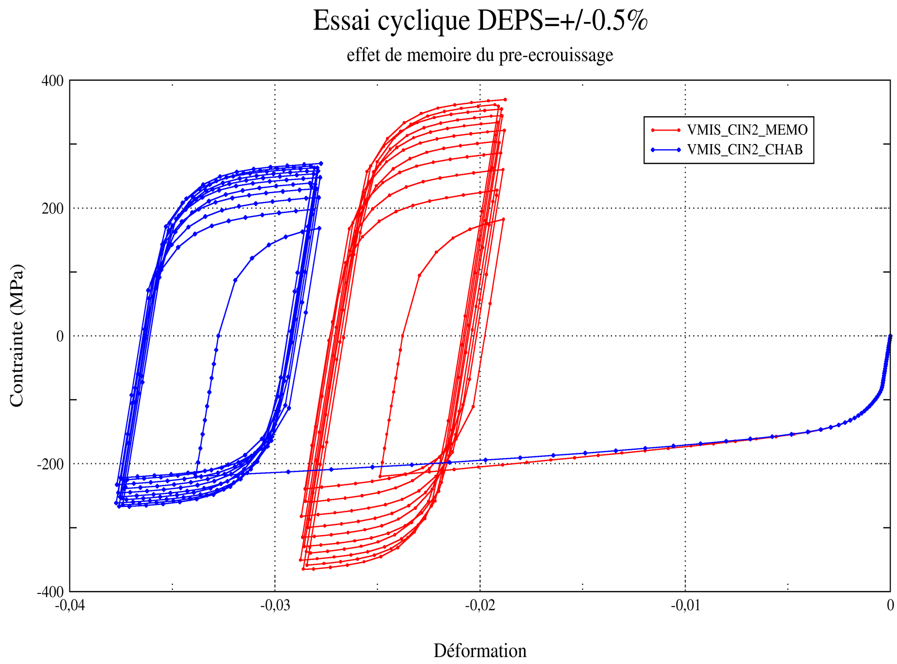


By continuing the cycles, this model would tend besides towards an adapted cycle, of amplitude $1600\,MPa$!

If the modelization aims at envisaging a phenomenon of progressive strain, the use of such models is delicate: indeed, they lead to a constant ratchet with non-zero mean stress, of value much higher than the experimental ratchet (unless choosing the parameters so that one of kinematic hardenings is linear, to which one quickly finds (too much) an adapted stabilized cycle).

It is preferable for these situations to use models it TAHERI.

If the studied situation implements a pre-hardening, it can be useful to identify model VMIS_CIN2_MEMO on cyclic tests with pre-hardening. (see for example [V6.08.105] SSND105 - Constitutive law visco-élasto-plastic with effect of memory).



Other aspects can be taken into account, in particular on-hardening due to cyclic loadings nonproportional. This is modelized in VMIS_CIN2_CHAB (without effect of memory) or VMIS_CIN2_MEMO (with effect of memory) via parameters DELTA1, DELTA2 .

2.3.4 Conclusions on the choice of the elastoplastic type of hardening

Les preceding paragraphs show that this choice is essential:

- for a monotonic loading, it is advisable to approach the traction diagram well in the range of strain concerned, and to check that the structural analysis remains in this interval
- to modelize one or two cycles of load-discharge, a model with linear kinematic hardening can be used, on condition that checking the response in one or more points well.
- To simulate several cycles of loading, a model of the Chaboche type (or Taheri) is necessary.

2.4 Influence velocity

Pour the purely elastoplastic materials, the time used in simulations is a simple parameter of the loading (even if it has a physical meaning in the thermomechanical cases) and does not have direct influence on the constitutive laws.

But it necessary to take it into account in the behavior in the following cases:
- high speed of loading: elastoplastic model of Johnson-Cook
- viscosity: models élasto-visco-plastics.

2.4.1 Model of Johnson-Cook

Cette model makes it possible to directly take into account the strainrate, and the temperature, in the evolution of isotropic hardening (cf R5.03.02] elastoplastic Intégration of the behavior models of Von Mises page 11). It makes it possible to deal with the problems of impact, and to implement the thermomechanical coupling (see for example [V7.20.105] HSNA105 - Expansion of an infinite hollow roll with taking into account of thermal dissipations due to the mechanical strains) .

2.4.2 Élasto-visco-plasticity with isotropic hardening

models It of élasto-visco-plastic of Lemaître makes it possible to take into account secondary creep (at constant velocity - it can be brought back for certain particular values of the parameters to a behavior model of Norton) and primary education creep. (cf [R5.03.08] Intégration of the viscoelastic behavior models).

The surface of load remains isotropic (not kinematic hardening). Creep tests, of relieving, or the traction tests with various strainrates are necessary to the identification of the parameters.

There still, it should be checked that the values thus obtained are valid in the studies considered, i.e. that the strainrates met in the studies are well in the range of those which were used for the identification.

If one wants to go further, i.e. to modelize tertiary creep (taken it into account of the large deformation is often necessary), one will be able to use the following models, which integrate a damage of creep:

•VISC_ENDO_LEMA, VENDOCHAB
cf [R5.03.15] viscoplastic Comportement with damage of CHABOCHE
•HAYHURST
cf [R5.03.13] viscoplastic Comportement with damage of HAYHURST

2.4.3 Élasto-visco-plasticity to nonlinear kinematic hardening

Les following behaviors make it possible to take into account kinematic hardening:
•VISC_CIN1_CHAB, VISC_CIN2_CHAB, VISC_CIN2_MEMO
cf [R5.03.04] Behavior models élasto-visco-plastic of Chaboche

Ces models are extensions of the elastoplastic models of J.L.Chaboche to the viscoplastic case. The different components of models of Chaboche previously described are present, and viscosity should moreover be integrated (of Lemaître type, i.e. allowing to reproduce creeps primary education and secondary). This means that their identification will have to take into account the strainrate (for example on the cyclic tests).

Other phenomena can be represented (hardening related to nonthe proportionality of the loading, restoration of hardening), by the following model:
•VISCOCHAB
cf [R5.03.12] viscoplastic Comportement with effect of memory and restoration of Chaboche
the complete identification of this model requires a large number of different tests: tests cyclic with various velocities, and different levels from strain, with pre-hardening, tests of tension-torsion, tests of relieving.

2.4.4 Model of viscosity in hyperbolic sine and isotropic hardening

Une autre forms model of viscosity is proposed in the following models:

•VISC_ISOT_LINE, VISC_ISOT_TRAC
cf [R5.03.21] Modelization élasto (visco) plastic with isotropic hardening in lls

large deformation are with isotropic hardening, and require the use of SIMO_MIEHE .

3 Identify the parameters: which tests are necessary?

The identification of the parameters of the models quickly becomes difficult manually, except for the simplest models (VMIS_CINE_LINE, VMIS_ISOT_LINE, VMIS_ISOT_TRAC).

One thus has recourse to a procedure of tweaking, available in command MACR_RECAL [U4.73.02] Macro-command MACR_RECAL.

There are several advantages to use this command:

- simulation making it possible to find the curves numerical (which will be compared with the experimental curves) is a conventional command file of Code_Aster, which can be launched in an off-line way, and which represents an unspecified computation (not inevitably on a material point);
- the readjusted coefficients are directly usable in the studies, since they are parameters of the file of simulation;
- many algorithms are available, as well as ways of calculating making it possible to use architectures multiprocessors so necessary.

Details on the algorithms used can be consulted in the document [R4.03.06] Algorithme of retiming .

But the tools do not do all! Indeed, for seeking to identify the parameters of a model, it is necessary to raise several questions:

- the number of tests which one lays out is it sufficient with respect to the number of parameters to be readjusted;
- the tests highlight the physical phenomena simulated by the constitutive law (already evoked previously): load-discharge, cycles, effects of memory, restoration, nonradiality, high speed, viscosity,…);
- can one separate these effects, in order to identify the parameters successively, which will reduce the task of tweaking and will make it possible to better apprehend the results.

To re-enter more in detail of the identification, of the documents specific to the various behaviors are to be written; With regard to the cyclic behaviors élasto-visco-plastic, a more detailed note is in the course of writing, resulting from EDF works/R & D [16] and [16].

In addition, a rather general methodology is proposed in [16] page 617 and [16].

4 Simulations Lors

anisothermals of simulations anisothermals, it is necessary most of the time to take into account the variation of the parameters with the temperature. It is thus necessary to take care of the good identification of these parameters.

In this paragraph, one illustrates some induced conventional errors by the interpolation or the extrapolation of S values according to the temperature.

The tests are carried out with models VMIS_ISOT_TRAC and VMIS_CIN1_CHAB. However, the conclusions selected are not exclusive with a particular model.

4.1 Dangers of extrapolation:

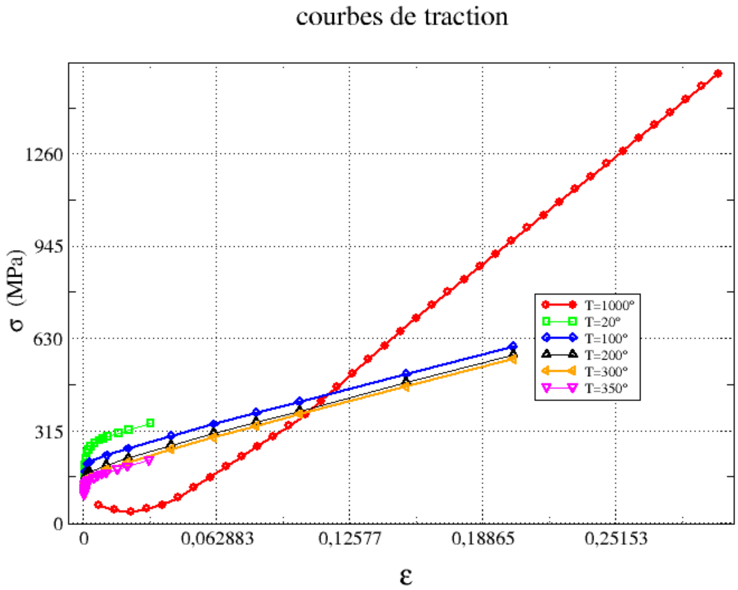
To undertake a thermomechanical study with a constitutive law whose coefficients depend on the temperature, the user can want to extrapolate his curves to carry out his study with a given temperature. This is strongly disadvised. An example:

In the case of an isotropic hardening, it is current to use experimental traction diagrams for some temperatures, variable for example enters $20°$ and $350°$. The traction diagrams are indicated in the command file for various temperatures with command " DEFI_NAPPE'. Let us suppose that one defined the prolongations by PROL_DROITE='LINEAIRE" and PROL_GAUCHE='LINEAIRE' .

It is supposed that the user wishes to carry out a computation with a temperature which exceeds the maximum temperature to which the identifications of the traction diagrams were made, that is to say 1000°C for example (it is a voluntarily exaggerated example, but which makes it possible to illustrate the matter). The coefficients materials of the model of this fact would be obtained with $1000°C$ by extrapolation.

This can lead to aberrant results (Appear 4.1-a) : the traction diagram obtained with the extrapolated temperature of $1000°C$ present a dishing and a contradictory slope of hardening compared to the other curves and compared to reality .

To avoid this kind of error, **it is necessary to avoid any extrapolation compared to the temperature .**



Appear 4.1-a . Traction diagrams according to the temperature - result with $1000°C$

4.2 Erreur in the interpolation of the temperature

Cet example highlights a possibility of error in the interpolation of the temperature generally due to a nonmonotonous evolution of the coefficients materials with the temperature. It is enough that only one of the coefficients does not evolve in a monotonous way so that the interpolation between two traction diagrams leads to a curve which does not lie between the two extremes.

For exhiber this kind of error, with a standard constitutive law ` VMIS_CIN1_CHAB' , one set up the following test:

Let us suppose known three traction diagrams identified in experiments with 3 different temperatures: $20°$, $100°$ and $200°C$. One seeks to identify the parameters of the model ` VMIS_CIN1_CHAB' with these three temperatures. For understanding well, briefly let us point out L has form of hardening of model " VMIS_CIN1_CHAB' :

•Criterion: $(\boldsymbol{\sigma}-C\boldsymbol{\alpha})_{eq}-R(p)\leq 0$

•kinematic hardening : $\dot{\boldsymbol{\alpha}}=\dot{\boldsymbol{\varepsilon}}^p-\gamma\boldsymbol{\alpha}\dot{p}$

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

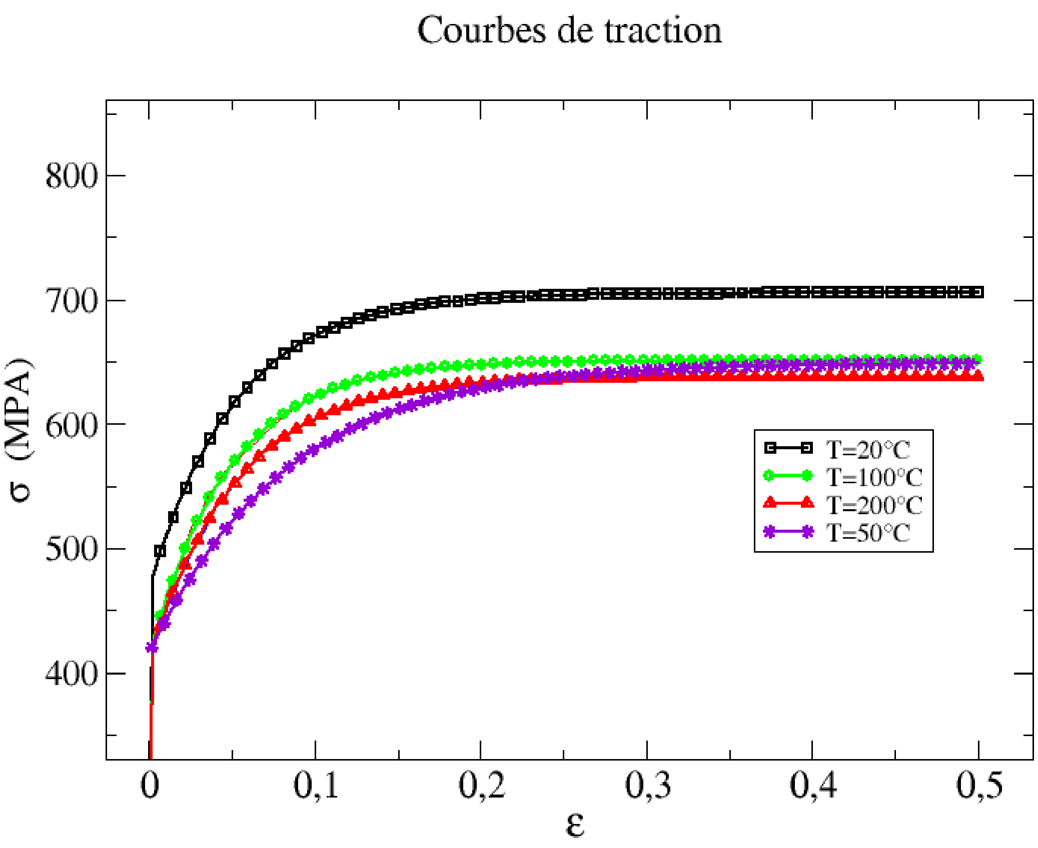
Let us suppose that the results of 3 identifications to three different temperatures are:

- with $T=20°$; the parameters identified materials are: C_1 γ_1 R_0 , non-zero, and $R_\infty \simeq R_0$ $b \simeq 0$, (either a quasi pure kinematical behavior);
- with $T=100°$; the coefficients identified materials are: $C_2 \simeq 0$ R_0 R_∞ , b_2 null .non, (that is to say a quasi pure isotropic behavior)
- with $T=200°$; the coefficients materials are: C_3 γ_3 R_0 , non-zero $R_\infty \simeq R_0$ $b_3 \simeq 0$, (either again a pure kinematical behavior) .

Each one of these identifications is sufficiently precise, and makes it possible to find, for each temperature, of the numerical curves very close to the experimental curves.

The simulation of the traction diagram to the temperature of $50°C$ is represented on the figure 4.2-a)

One notes that the curve obtained by interpolation with $50°C$ is erroneous:



Appear 4.2-a . Traction diagrams according to the temperature - result with 50°

Ceci comes owing to the fact that the identification were made independently, without checking the coherence of the results. The variations of each coefficient with the temperature are enormous: for example

Température °C	C	b

20	C_1	$\simeq 0$
	$\simeq 0$	b_2
	C_3	$\simeq 0$

Cet example is of course extreme, but it makes it possible to put forth a recommendation:

- either check the monotonous evolution of the parameters material according to the temperature, and start again the identification for the suspect values,
- or , if possible, carry out the identification in once and for all the temperatures.

5 The field of validity

Plusieurs checks are possible to check that the constitutive law chosen, and the values of the parameters used, are valid for simulation.

In addition to the advices given previously, for choosing well the constitutive law according to what one wants to modelize, certain additional checks can be carried out using specific tools.

5.1 Validity of the parameters in the range of strain and velocity.

The parameters of the selected model being identified in a certain range of strain, it is important to check that in the studies using these parameters, these strains remain well in the interval of the identification.

The traction diagrams defined by `DEFI_FONCTION` integrate a “parapet”: the maximum value of X-coordinate (`EPSI`) cannot be exceeded in the study. But if ever that occurs, instead of defining a prolongation constant (or worse: linear) it is advisable to take again the identification to define additional points in the traction diagram.

The hardenings linear (`ECRO_LINE`), or defined by an analytical function (`ECRO_PUIS` , `VMIS_CINx*_CHAB` , etc.) are much more dangerous. Nothing will prevent in the studies from largely exceeding the level of strain of the identification. This is why a protection should be installation in a forthcoming version.

In any case, it is relatively easy, in postprocessing of a study, to calculate (`CALC_CHAMP`) the norm of the strain field (`EPEQ_ELGA`) and from of extracted maximum (`POST_ELEM / MINMAX` , or graphic postprocessing in `SALOME_MECA`).

If the study results in using a formalism of large deformation, it is necessary that the identification uses it too.

With regard to the strainrate, there still a checking is necessary. Its automatic computation should be proposed in a forthcoming version.

5.2 Discharge: validity of isotropic hardening (and the models of Hencky)

Comment check that the discharges are sufficiently small so that computation with an isotropic hardening is valid? There exists in `CALC_ FIELD` an indicator of discharge `DERA_ELGA` (cf [U4.81.04] Operator CALC_CHAMP).

- Components `DCHA_V, DCHA_T` indicate if there exist discharges on the stresses (either on Von Mises, or the total tensor), thus invalidating computation with a nonlinear elastic model.

- Component `IND_DCHA` provides an indicator which indicates if there is a risk to re-enter in plasticity in discharge, thus invalidating computation with isotropic hardening.

For more precise details on their computation, see [R4.20.01] Indicateurs of discharge and loss of proportionality of the loading in elastoplasticity).

5.3 Radiality: effects of nonproportionality

In the case of cyclic loadings strongly nonproportional, the effect of on-hardening can be been unaware of by the selected behavior. While using, in CALC_ FIELD the indicator of discharge and radiality of the loading: DERA_ELGA (cf [U4.81.04] Operator CALC_CHAMP), component ERR_RADI measures the error made by the rotation of the norm on the surface of load. If this value is important, it is then necessary to use a model making it possible to take into account this effect (for example VISCOCHAB).

6 References

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