

Note of use for the digital simulation of welding

Summary

The objective of this document is to give the necessary information so that user can carry out multirun calculations of welding with *Code_Aster*. It constitutes a methodological guide on the tools available and the good practices to be set up to lead a study of quality in digital simulation of welding.

The various advices given to the user come primarily from the experience feedback resulting from three studies:

- A piping in 316L chamfered welded by process TIG, with filler on the thirteen ways (card CEA/EDF 3488); the first 2 master keys of this example constitute a CAS-test *Code_Aster* [V7.42.100]);
- A plate chamfered in 316L welded by process TIG, with filler on the two ways of welding (card CEA/EDF 2425); the various command files attached to this study are stored in the base of studies of *Code_Aster* (SERVICE/BDD Studies);
- A plate in 316L not chamfered, with creation of a line of fusion by process TIG, but without filler (thesis INSA de Lyon of L. Depradeux supported in 2004).

Contents

1	References (IMPORTANT).....	4
2	General information on welding.....	6
2.1	What is this welding?.....	6
2.2	Phenomenon concerned during welding.....	6
2.3	Review of the various interactions.....	6
2.3.1	Thermal interaction - Metallurgical.....	6
2.3.2	Thermal interaction - Mechanics.....	6
2.3.3	Metallurgical interaction - Mechanics.....	7
2.4	What does one understand by melted zone, ZAT, returned zone?.....	7
2.5	Why is it important to simulate the process of welding?.....	7
3	The digital simulation of welding.....	8
3.1	Visual representation of an operation of welding.....	8
3.2	What does one seek T to calculate?.....	9
3.3	Which are the main difficulties of simulation?.....	9
3.4	Specificities of Code_Aster.....	9
3.4.1	Which are the couplings considered?.....	9
3.4.2	Standard diagram of a command file Code_Aster.....	10
3.4.3	Restrictions of Code_Aster [5].....	10
4	Methodology for simulation.....	12
4.1	Type of modeling: 2D or 3D?.....	12
4.2	Grid.....	13
4.3	Thermal calculation.....	14
4.3.1	Introduction.....	14
4.3.2	Management of the matter addition (weld beads).....	14
4.3.3	Modeling of the source of heat.....	15
4.3.4	Boundary conditions thermal with the environment.....	18
4.3.5	Thermophysical characteristics.....	18
4.4	Metallurgical calculation.....	20
4.4.1	Introduction.....	20
4.4.2	Models of behavior to the heating and cooling.....	20
4.4.3	Thermal interaction => Métallurgique.....	20
4.5	Mechanical calculation.....	21
4.5.1	Principle of mechanical calculation.....	21
4.5.2	Management of the matter addition (weld beads).....	21
4.5.3	Law of behavior.....	21
4.5.4	Notice on the great deformations.....	22
4.5.5	Boundary conditions.....	22

[4.6 Computing time.....](#) [22](#)

1 References (IMPORTANT)

In this part, we give the references quoted in this document but also of other references which could serve the engineer during a digital simulation of welding.

Quoted references

- [1] C. WOOD: Thermal simulation of welding multirun by pulsated process TIG of a stainless steel piping. Note FRAMATOME EER cd. 1509
- [2] X. DESROCHES: Digital simulation of a test of welding on tube on the 13 ways. Note EDF DER HI-75/00/016/A
- [3] L. DEPRADEUX: Digital simulation of welding, Steel 316L, Validation on case tests of increasing complexity, Thesis INSA, Note INSA n°201/1AB/010, 3/11/04.
- [4] V. CANO: "Digital simulation of an operation of welding TIG on a plate chamfered out of material 316L on the two ways (Model 2425)"; Note interns EDF/R & D, H-T64-2008-04060-FR, Publication during 2009.
- [5] L. DEPRADEUX & V. CANO: "Batch of validation for *Code_Aster* on the digital simulation of welding: Summary ", Notes intern EDF H-64-2007-00926, 9/27/07.
- [6] W. EL-AHMAR: "Robustness of the digital simulation of welding TIG of structures 3D out of Steel 316L, Thesis INSA 2007

Not quoted references

- **Case test of *Code_Aster*** : we give the whole of the cases test of *Code_Aster* who implement orders *Code_Aster* useful within the framework of the digital simulation of welding.
 - ◆ Metallurgical transformation (order `CALC_META`): V4.61.100, V4.61.102 and V4.61.103
 - ◆ Models of mechanical behavior with effects of structure transformations (keyword `META_XXX_XXX` to inform under `STAT_NON_LINE`): V7.20.104, V7.22.101, V7.22.102, V7.22.103-B, V7.22.104, V7.22.105, V7.22.122, V7.22.127, V7.22.128 and V7.22.126;
 - ◆ Methodology: V7.42.100 (card 3488, tube).
 - ◆ The various command files (modelings A with G) attached under investigation on plate 2425 are stored in the base of studies of *Code_Aster* (SERVICE/BDD Studies). Modeling A is quasi-stationary calculation thermal 3D in pointer. Modelings B, C and D are transitory thermal simulations 3D with various methods of desactivation of metal not yet deposited, by assignment of a quasi-worthless conductivity (A), by encased thermal models (B), and finally, by unfolding of the nodes and sticking together of the nodes to the interface (D). Modelings E, F and G are simulations mechanics of the two master keys, with various laws of behavior of Von Mises with linear work hardening: isotropic (E), kinematics (F) or mixed (G).
- **Card 3488** (tests and simulations on a tube in 316L chamfered, welded on the 13 ways by process TIG)
 - ◆ F. WAECKEL: Synthesis of thermal modelings of an operation of welding realized in the co-operative card 3449. Note EDF DER HI-74/95/028/0
 - ◆ F. WAECKEL, L. BIRONNEAU: Mechanical simulations of an operation of welding multirun on autobridée plate. Note EDF DER HI-74/96/006/0

- ◆ J. DEVAUX: Tripartite card 3488. Digital simulation of welding. Mechanical calculations thermo - of master keys 1 to 5. Note FRAMATOME LL/99.4564
- ◆ X. DESROCHES, A. RAZAKANAIVO, C. WOOD, PH. GILLES, J. KICHENIN, Y. LEJAIL: Synthesis of the FC3488: "Simulation of welding multirun: experimental validation". Technical note ECA DER/SERI/LCS/01/4027
- **Card 2425** (tests and simulation on a plate in 316L chamfered, welded on the 2 ways by process TIG)
 - ◆ D. AYRAULT, O. BLANCHOT: "Instrumented models of welding multirun. Experimental database intended for the validation of calculations", Final report of card 2425 ECA DECS/UTA/02-RT-07, October 25th, 2002
- **Program INZAT on disc in 16MND5** heated by a laser (tests and simulations thermo-metal-worker-mechanics)
 - ◆ Y. VINCENT: "Consequences of structure transformations in the zone affected thermally. Validation on analytical tests – Steel 16MND5", Thesis INSA, Note INSA 201/1AB/005, 4/9/02.
- **Validation independent of the tools for digital simulation of welding in Code_Aster.** One will find these two notes on the site *Code_Aster* (Presentation/Approach Quality/Actions of validation independent and complementary, item Welding)
 - ◆ L. DEPRADEUX & V. CANO: "Batch of validation for the digital simulation of welding with *Code_Aster* : synthesis of the analyzed documents ", Notes intern EDF H-64-2007-00942, 9/27/07
 - ◆ (in reference) L. DEPRADEUX & V. CANO: "Batch of validation for *Code_Aster* on the digital simulation of welding: Summary ", Notes intern EDF H-64-2007-00926, 9/27/07.
- Data materials
 - ◆ **Materials 16MND5, Inconel 600 and 182 and steel 308L**, PH. DECEIVED & F. WAECKEL: "Bibliographical collection of thermo-mécaniques characteristics for the steel of tank, the coatings stainless and the alloys 600et 182", intern EDF-DER HI-74/93/097 and HT-26/93/058/A, 1/17/94 Notes
 - ◆ **Material 316L**, A. RAZAKAINAVO: "Introduction into *Code_Aster* of a model of take élasto-viscoplastic behavior into account of the metallurgical transformations ", intern EDF HI-74/97/020/0 Notes
 - ◆ **Material 316L**, V. CANO: "Bibliographical collection of thermomechanical characteristics of the stainless steel 316L", Notes EDF intern HT-64/05/021/A, 09/05
 - ◆ **Material 16MND5** , V. CANO: "Identification of the parameters materials of the 16MND5 associated with the models thermics, metallurgical and mechanical", Notes EDF intern/R & D H-T64-2008-03224, Publication during 2009.

2 General information on welding

2.1 What is this welding?

The welding of two metal parts is obtaining a continuity by fusion or local diffusion thanks to a contribution of heat and possibly of a metal contribution. Much of **processes of welding can thus be described physically like a short passage at very high temperature, of a small amount of metal, follow-up of a free or forced cooling**, generally by conduction in the mass of the welded parts and the elements of the work station. With time, this evolution of temperature determines the final metallurgical structure of the welded joint, sometimes different from the base metal.

2.2 Phenomenon concerned during welding

From a mechanical point of view, the very localised heat gradients concerned during the welding of two materials generate local dilations and contractions having for consequence the appearance of fields of strains and incompatible stresses, which remain after return to the room temperature.

For certain materials, the thermal history associated with the operation of welding generates changes of microstructures in a solid state which influence the state of residual stresses and distortions of the welded joint. These changes of microstructures intervene when the temperature reached a threshold which one calls initial temperature of transformation. These transformations stop when the temperature exceeds the temperature of end of transformation.

One can then distinguish two types of constraint: constraints of thermal origin generated during all the duration of the process of welding and the constraints of metallurgical origin (possibly) generated throughout transformation.

Consequently, a digital simulation of welding must take into account the phenomena coupled between them, thermics, metallurgical possibly and finally mechanics.

2.3 Review of the various interactions

2.3.1 Thermal interaction - Metallurgical

- Thermal direction => Métallurgique : thermophysical properties (conductivity, heat-storage capacity, diffusivity...) depend on the involved phases.
- Metallurgical direction => Thermique : the metallurgical transformations are accompanied by effects of latent heat which modify the distributions of temperature.

2.3.2 Thermal interaction - Mechanics

- Thermal direction => Mécanique : this influence results, on the one hand, of the variations of the mechanical characteristics with the temperature and, on the other hand, of dilations and contractions of thermal origin.
- Mechanical direction => Thermique : evolution of the unrecoverable deformation as well as internal variables of work hardening led to a dissipation of energy in the form of heat. However, this rise in mechanical temperature of origin is often negligible in comparison with that coming from the contribution of heat delivered by the process of welding, taking into account the deformations and relatively low speeds of deformation which are put concerned. This assumption valid any more is not in the case of proceeded bringing into play strong dissipations, for example, welding friction.

2.3.3 Metallurgical interaction - Mechanics

- Metallurgical direction => Mécanique : the influence of the metallurgical history on the mechanical history results mainly from four factors. The first lies in the dilations and contractions caused by the metallurgical transformations. The second factor is the phenomenon of plasticity of transformation. The third is the phenomenon of restoration of work hardening. Finally the last factor corresponds to the particular behavior related to the multiphase aspect of material.
- Mechanical direction => Métallurgique : the application of pressure modifies the energy stored in material and the atomic structure of the network. The presence of a mechanical request can thus play a part on the metallurgical transformations.

2.4 What does one understand by melted zone, ZAT, returned zone?

When one speaks about welding, the engineer of study will often hear spoken about melted zone, ZAT and returned zone, which corresponds to three distinct zones in a welded component. This is why, we give below a very general definition of these zones.

- **The Molten Zone (Z.F)** : it is the zone where **temperature is higher than the solidus of steel considered** or of the filler. The composition of the molten metal results from the chemistry of the filler, of the chemistry of the base metal and the interactions with the environment. This zone is separated from the Zone Affected Thermically (ZAT) by the line of fusion which characterizes the whole of the points having reached the temperature of solidus.
- **The Thermically Affected Zone (ZAT)** : in a very general way, it is **the solid zone** welded joint where it **behavior of material is strongly influenced by the field of temperature** with welding. Term ZAT has a very particular meaning when the material of the base metal or filler undergoes structure transformations: it is the zone where the transformation takes place. This Z.A.T breaks up itself into three great parts: the zone where the transformation is complete, the zone where the transformation is partial and finally **returned zone (Z.R)** where the maximum temperature reached is slightly lower than the initial temperature of transformation but where the behavior of material is slightly modified compared to that of the base metal.
- **The nonaffected zone thermically** : in a very general way, it is **the solid zone** welded joint where it **behavior of material is influenced little by the field of temperature**. For materials undergoing of structure transformations, it is the part of the welded joint where the maximum temperature reached is quite lower than the initial temperature transformation and where the operation of welding does not generate modification of the metallurgical and mechanical characteristics of the base metal.

2.5 Why is it important to simulate the process of welding?

The evolution of the processes of welding applied to steels made it possible to reach today a good reproducibility of the operation and a good quality of the welded joints. **The weldings constitute all the same the weak points of the structures.** The fields of strains and stresses induced by the operation of welding play a determining role on the quality and the mechanical resistance of the welded component; residual stresses induced by welding accentuating all the risks of damage by tiredness, creep, corrosion and brittle fracture...

This is why it is important to obtain robust and reliable tools to simulate this process.


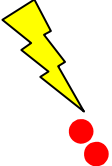

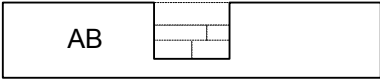
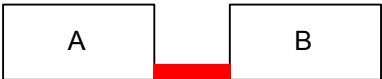
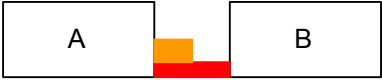
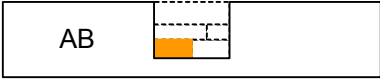

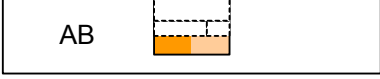
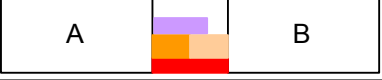


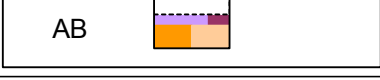


3 The digital simulation of welding

All that is written, thereafter, can be implemented in two situations of studies:

- When one simulates, obviously, the welding of two parts;
- But also, when one simulates the demounting of a coating on a part. One can apply same methodology as that adopted for an operation of welding.

3.1 Visual representation of an operation of welding

- **Reality** : there are two parts A and B which one wishes to weld to obtain a part AB by using a process of adapted welding (for example by contribution of heat). The two parts are never welded in only once but not successive master keys, the first master key being called the master key of root.
- **The digital representation** : the first master key of root is never modelled. It is thus supposed that initially, two parts A and B are in only one block. Thereafter, we will see that there exist several methods to activate the master keys. Generally (it is the configuration presented in the drawing below), one chooses to represent all the passes in the initial model and one activates them progressively.

Reality		The digital representation	
	The welder		
	The source of heat brought by the process of welding, with filler here		
	Two parts to be welded		The initial part to model, with here all the passes represented initially in the model
	1 ^{ère} master key = Master key of root		
	2 ^{ème} master key		Activation of the 1 ^{ère} master key to be simulated
	3 ^{ème} master key		Activation of the 2 ^{ème} master key to be simulated
	4 ^{ème} master key		Activation of the 3 ^{ème} master key to be simulated
	5 ^{ème} master key		Activation of the 4 ^{ème} master key to be simulated
	6 ^{ème} master key Welded part AB		5 ^{ème} master key Simulated part AB

Warning : The translation process used on this website is a "Machine Translation". It may be imprecise and inaccurate in whole or in part and is provided as a convenience.

3.2 What does one seek T to calculate?

The final goal of simulation is to determine the residual deformation and stress fields. With this intention, it is necessary to couple or chain calculations thermics, possibly metallurgical and finally mechanics.

3.3 Which are the main difficulties of simulation?

The great difficulties, questions and choices of methodology with which the engineer will be confronted can be summarized in six points:

- Representation 2D or 3D of the studied structure?
- Which adopted grid?
- How to take into account the contribution of heat?
- How to manage the matter addition, in thermics, mechanics?
- Which model of mechanical behavior (for the metallurgical transformations, there exists single model in *Code_Aster*)?
- Which physical data?

Notice : The choices which will be adopted with final for simulation depend on many the experimental data in the possession of the engineer. These data gather:

- Data material; As in any simulation, it is important to have data material to identify most properly possible the laws of behavior (thermal, metallurgical and mechanical). The implying welding of the very high temperatures (until the fusion of material), it is necessary to lay out, if possible, on the one hand, of parameters between 20°C and the melting point, and on the other hand, of tests making it possible to characterize the viscous phenomena.
- Data on the conditions of welding; Among many uncertainties on the data input which intervene during the digital simulation of an operation of welding or demounting of a coating, the indetermination of the contribution of heat is more penalizing. Indeed, even when it is about an automated welding, and that the parameters of welding are well-known, the modeling of the contribution of heat remains difficult in any event, and a retiming is almost always necessary (on temperature measurements or macrographies of molten zones) if one **predictive digital simulation is aimed**.

In paragraph 3 and for each one of these points, we will present various possible methodologies and, sometimes, the advised choices.

3.4 Specificities of *Code_Aster*

3.4.1 Which are the couplings considered?

In *Code_Aster*, it is currently possible to take into account the essence of the phenomena but in an uncoupled way, via **chained calculations thermal, then metallurgical (possibly) and finally mechanics**.

Possible metallurgical calculation is thus carried out in postprocessing of thermal calculation, without taking account of the influence of the metallurgy on thermics (difference in thermophysical properties according to the phases and latent heats of transformation).

In the same way, mechanical calculation is uncoupled from calculations thermics and metallurgical: the influence of intrinsic dissipation on the thermal fields is neglected, as well as the influence of the state of stresses on the metallurgical transformations.

To summarize, here interactions taken (YES) or not (NOT) into account:

- Influence of Thermics on the Metallurgy: YES
- Influence of the Metallurgy on Thermics: NOT
- Influence of Thermics on Mechanics: YES
- Influence of Mechanics on Thermics: NOT
- Influence of the Metallurgy on Mechanics: YES
- Influence of Mechanics on the Metallurgy: NOT

3.4.2 Standard diagram of a command file *Code_Aster*

To summarize, here great stages of a calculation of an operation of welding in *Code_Aster* :

- 1) One carries out a thermal calculation which makes it possible to obtain the field of temperature in each node of the grid.
- 2) **If the material considered sudden of the metallurgical transformations** : one realizes in post treatment of thermal calculation, the metallurgical calculation which makes it possible to obtain the proportion of the various metallurgical phases (and possibly associated hardness) in each node of the grid.
- 3) From the field of temperature and possibly of the metallurgical phases, one carries out mechanical calculation by choosing a model of behavior which takes into account possibly the various possible effects of the metallurgical transformations. One thus obtains the internal variable and deformation, stress fields in each point of Gauss.

3.4.3 Restrictions of *Code_Aster* [5]

- **Thermal calculation**
 - ◆ The resolution of the equation of heat in pointer by the order `THER_NON_LINE_MO` [U4.53.03] (useful to fix the source of heat of a thermal calculation non stationary 3D) is available only in the case of a rectilinear way of the source of heat, and not in the case of an axisymmetric way, as during the welding of cylindrical conduits for example.
 - ◆ It is currently impossible to define a function of more than two variables with *Code_Aster*, whereas the "classical" sources of heat (Gaussian, double ellipsoid, source CIN) are voluminal or surface densities flux, function of space and time. If the source is function of time (has minimum, except if calculation is carried out in pointer), there remains nothing any more but one parameter of space available.
- **Metallurgical calculation**
 - ◆ The phenomenon of income (which has in particular as a consequence a reduction in the elastic limit) of the rough phases of hardening is not taken into account. One can possibly circumvent this problem. If the number of phases formed with cooling makes it possible to leave metallurgical internal variables "free", one can then assign with these internal variables proportions of returned phases and to model the kinetics of income by introducing a fictitious TRC.
- **Mechanical calculation**
 - ◆ It would be interesting to develop, for a material comprising only one metallurgical phase, the models equivalent to `META_XXX_XXX` (several phases). That currently obliges to carry out a false metallurgical calculation to profit from these laws. That can pose in 3D big problems of memory size and computing time, for little which one uses for example a model with kinematic

work hardening (one stores a tensor like internal variable for each step of calculation and each phase).

4 Methodology for simulation

The experience feedbacks quoted in this part result primarily from the three following studies:

- A piping in 316L chamfered welded by process TIG [2], with filler on the thirteen ways (card CEA/EDF/FRAMATOME 3488); the first 2 master keys of this example constitute a CAS-test *Code_Aster* [V7.42.100]);
- A plate chamfered in 316L welded by process TIG [4], with filler on the two ways of welding (card CEA/EDF 2425); the various command files attached to this study are stored in the base of studies of *Code_Aster* (SERVICE/BDD Studies);
- A plate in 316L not chamfered, with creation of a line of fusion by process TIG [3], but without filler (thesis INSA de Lyon of L. Depradeux supported in 2004).

By preoccupation with a simplicity thereafter, we will name them card 3488, card 2425 and thesis L.D 2004.

4.1 Type of modeling: 2D or 3D?

In any rigour, the process of welding is strictly three-dimensional, the contribution of heat and possibly of matter being mobile and often constant speed. The fields of temperatures and mechanics generated are thus three-dimensional and transitory.

It is thus preferable to carry out a three-dimensional transitory analysis.

However, this choice not being always possible because of complexity, of time calculation and the memory size required by calculations 3D, one often has resorts to a modeling 2D in digital simulation of welding (in particular for multirun welding with a large number of master keys).

Case of a modeling 2D

- In the majority of the cases, simulations 2D consider a transverse section, perpendicular to the projection of the torch of welding. These simulations are carried out with the assumption of the plane deformations;
- Calculations axisymmetric 2D are also adopted for the case of the welding of cylindrical conduits.
 - ◆ **The weak point of two preceding modelings, it is that one neglects the effect speed of welding and that it is supposed that the cord (or heat) is deposited (E) simultaneously over the entire length of the part to weld.**
- Other choices, less classical, are also possible: one can to choose for example to net section longitudinal (in direction of welding) or, if it is considered that the temperatures are constant in the thickness, it can choose to net the average plan of the plate. These simulations are then carried out with the assumption of the plane constraints.

Experience feedback

- Card 3488: The calculation of the chamfered tube is carried out into axisymmetric. Comparisons between this axisymmetric approach 2D and an approach 3D were carried out in [1] and show the good representativeness of the approach 2D, even if this one does not take account of the effects speed.
 - ◆ Thesis L.D 2004: On the not chamfered plate, several modelings are tested:
 - ◆ Calculation complete thermomechanical 3D;
 - ◆ Calculation 2D in deformation planes where one models a section perpendicular to the projection of the torch;

- Calculation 2D in constraint planes where one models the average plan of the plate.

One notes, **in this case**, that calculation 2D in plane deformation does not reproduce well the results got on calculation 3D, in term of displacements and residual stresses, except for these last in the central zone of the plate. As for calculation 2D in plane constraint, it gives results very close in residual stresses to calculation 3D.

4.2 Grid

General advices

- Like any digital study, it is always difficult to precisely give values on the density of the grid; that depends much on the physical problem considered. In the case of welding, the grid must be sufficiently fine around the source of heat (weld beads and molten zone) to correctly apprehend the high thermal gradients and mechanical in this zone.
- In the case of a quasi-stationary thermal modeling in pointer (cf § 3.3.2), the speed of calculations authorizes a more important density of grid, in particular goshawks of the source.
- In the case of welding on steels with metallurgical transformations of phases, it is necessary to net in a sufficiently fine way the ZAT. This is all the more important as maximum constraints is generally reached in periphery of ZAT, in partially austenitized zone. The density of grid in this zone is thus paramount. Simulations of welding on a steel which presents transformations of phases thus require a priori bulkier grids of many elements compared to simulations of welding on steels without transformations (with identical study).
- For mechanical calculations 3D, it is very important of déraffiner as much as possible the mechanical grid when one moves away from the welded zone. Indeed, the strong non-linearity of the problem (and times computings which goes with) and the transitory aspect (requiring many steps of time) limit in practice the number of nodes of the model.
- As for any problem, it is necessary to envisage as of the stage of grid the groups intended to receive the boundary conditions thermal and mechanical (way of the source, heat-transferring surface...), as well as the zones intended for postprocessing. This is all the more true for the thermal grid where the loading (heat source) and the boundary conditions (convection and radiation) move as the demounting of the cords.
- For the melted zone, it is often difficult to represent it because, in the absence of macrography, its form is unknown.

Experience feedback

- Card 3488: The weld beads can be represented geometrically and with a grid in way more or less complex. There are 3 possible choices, while going from most complicated towards simplest:
 - ◆ One can choose to respect at the same time the volume and the form of the master key. The shape of the cords being curved, one will have to net surfaces on curved board, therefore to use finite elements at least of degree 2;
 - ◆ One respects only the volume of the master key;
 - ◆ The volume of the master key as well as possible is respected.

Comparisons were made in [2] with these three possibilities. It proves that the results of mechanical calculations differ very little from one grid to another (with thermics equivalent). In conclusion, a curved grid does not bring anything significant to the level of the results compared to a polygonal grid. It is important on the other hand to roughly respect the volume of the cords deposited.

4.3 Thermal calculation

The critical point for the thermal part relates to the modeling of the contribution of heat.

4.3.1 Introduction

In *Code_Aster*, the calculation of the thermal evolution is carried out by the nonlinear resolution of the equation of heat (operator `THER_NON_LINE` [R5.02.02]) in the volume of the part, being given an initial condition and boundary conditions thermal on the borders. The resolution is transitory, the source of heat moves on the grid.

The diffusion of heat is treated by an enthalpic formulation, which is the integral of the specific heat on the temperature $\beta(T) = \int_0^T \rho C_p(u) du$. One can thus provide, that is to say conductivity and the specific heat ρC_p according to the temperature, that is to say, and it is preferable (cf notices below), conductivity and the enthalpy according to the temperature.

Notice on the choice of an enthalpic formulation

- At the melting point, the heat capacity (which is energy required to raise the temperature of the body) undergoes a discontinuity which results in the latent heat of fusion, which represents energy required to cross the temperature of phase shift. In the case of a mixture of component (it is the case of alloys), fusion is spread out between the temperatures of liquidus and solidus T_l and T_s . A "enthalpic" formulation of the equation of heat is useful for the taking into account of the phenomena of latent heat of phase shift. Indeed this formulation avoids "missing" the transformation, which is likely to arrive for the formulation in capacity if the steps of time are sufficiently small.

4.3.2 Management of the matter addition (weld beads)

Description of the various methods

There exist several methods to take into account, in the transitory thermal model, the successive matter addition at the time of the various passes of welding:

- The first method consists in considering one model (within the meaning of *Code_Aster* defined by the order `AFPE_MODELE`) containing all the passes and "artificially to disable" the cords not yet deposited in their imposing worthless thermal conductivity ($10^{-5} W/m^{\circ}C$ in practice).
- The second method consists in encasing the thermal models (within the meaning of *Code_Aster*): a total grid of all the cords is used, but the thermal model is affected only on the part of the grid corresponding to the metal already deposited (at the time of the stage `AFPE_MODELE`). The cords not yet deposited are not included in the model. In this case, it is necessary to have as many thermal models there are cords deposited. The various models are encased one in another, i.e. the thermal model I contains the master keys of 1 with I and the thermal model $I+1$ contains the master keys 1 with I and passes it $I+1$. This method is cleaner than the preceding one insofar as the elements not deposited do not disturb the calculation of the master key in progress, since they are not included in the model. On the other hand, this poses a problem at the time of the sequence of thermal calculations, the fields of temperature of the model I not being defined in all the nodes of the model corresponding to the following master key $I+1$. It is thus necessary to carry out a prolongation of the computed fields from one model to another. With this intention, one proceeds in 4 stages:
 - ◆ One starts by creating a field of temperature to ambient (T_{20}) on all the grid by the order `CREA_CHAMP` (operation 'AFPE'),

- ◆ One extends the first field of temperature calculated to master key I (sequence number 1) while supplementing by $T20$ on the new meshes (CREA_CHAMP operations 'EXTR' then 'ASSE'),
 - ◆ One stores this field in a new structure of data of the type `evol_ther` by order CREA_RESU,
- ⇒ one makes a loop on the remaining sequence numbers and one repeats operations 2 and 3 for each sequence number by enriching the structure of data created into 3 (keyword reuse of CREA_RESU).
- Lastly, the third method consists, on only one thermal model (within the meaning of *Code_Aster*), to duplicate the nodes with the interface of each cord, which it is necessary to provide in the stage of construction of the grid. At the time of the assignment of the thermal loading (AFFE_CHAR_THER), one affects only the part of the model which corresponds to metal already present. Thus, the cords not deposited do not see the loading, and the unfolding of the nodes prevents the transfer of heat to the interface of the cords not deposited (a temperature equal to ambient is applied in the cords not yet deposited). At the time of the addition of a new cord, one resticks the nodes corresponding by applying the equality of the temperatures to the nodes duplicated by the order LIAISON_GROUP. This method is certainly most reliable but the construction of the grid becomes tiresome if the number of master keys is large.

Experience feedback

- The advantage of the first method (only one model and almost worthless conductivity for the cord not yet deposited) is its simplicity of implementation. On the other hand, it can lead to digital oscillations of the temperature due to the discontinuity of conductivity to the interfaces between the cords, as noted in card 3488 [2]. Nevertheless, this method is often selected because of its simplicity.
- The three methods were tested on plate 2425 [4] and were compared with experimental measurements of temperature. Three calculations lead to results virtually identical to the points of measurements.

4.3.3 Modeling of the source of heat

The truly complete modeling of the thermal problem would require the taking into account of the transfers of heat electro-thermo-fluids in the electric arc, with taking into account of the electromagnetic phenomena, and the modeling of the movements convectifs in the bath melted, in interaction with the plasma of cover, and the transfers of heat in the solid part. Although an abundant literature exists with regard to the taking into account of the modeling of the arc and the bath of fusion in simulation, we will place ourselves thereafter from a point of view of modeling with an industrial computer code, which does not make it possible to model the phenomena present in the arc and the molten bath. Those are replaced by the definition of a source of heat of adequate form. Only the conduction of heat is thus modelled, this is why he will not be alluded to the modeling of the arc and the bath thereafter.

Description of the two possible methods

- The first method consists with **to impose cycles of temperature** with the matter which one deposits. These imposed temperatures can be applied either to the only cord deposited, or on the cord unit deposited more molten zone.
 - ◆ By reason of simplicity, the function imposed temperature T^{imp} is chosen, generally, constant spaces some but variable in time, that is to say $T^{imp} = T^{imp}(x, y, z; t) = T^{imp}(t)$;
 - ◆ Moreover, one often imposes this temperature only on the cord deposited: indeed, the forms and sizes of molten zones are seldom known, and even if they are it, that makes tiresome the construction of the grid, especially if the number of cords is high;

- ◆ The method in temperature is advised in the case of modelings 2D or when no data is available on the parameters of welding. The function $T^{imp}(t)$ often has the following form:

$$T^{imp}(t) = \begin{cases} \frac{T^{max}}{t_1} t + T^{ini} & \text{si } t \leq t_1 \\ T^{max} & \text{si } t_1 \leq t \leq t_2 \\ \text{éventuellement, } \frac{-(T^{max} - T^{min})}{t_3 - t_2} (t - t_2) + T^{max} & \text{si } t_1 \leq t \leq t_3 \end{cases}$$

One prescribes a rise of the initial temperature T^{ini} at the melting point or a possibly higher temperature T^{max} from one duration t_1 (the rise in prescribed temperature can be linear or not linear, exponential for example), then a maintenance at this temperature for one length of time $(t_2 - t_1)$, and finally possibly, one can prescribe the beginning of cooling until the temperature T^{min} . Parameters (t_1, t_2, t_3, T^{min}) can be identified so temperature measurements exist;

- ◆ The continuation of cooling is carried out with exchanges by convection and radiation.
- The second method consists with **to impose a surface heat flow (J/sm^2) or voluminal (J/sm^3)** with the weld bead modelled.
 - ◆ It is preferentially used when the energy of welding delivered is known: it is the case for welding the arc, for which one can consider power delivered UI (with U the tension and I intensity of the current). Of this delivered power, only a fraction ηUI penetrate indeed in the part and takes part in the heating and the fusion of materials. For the process TIG, for example, the parameter η is about 0.6 to 0.9;
 - ◆ It is then possible to distribute this power, on the surface or volume (or both), on the grid. The distribution of this heat flow perhaps extremely simple (constant spaces some in the added metal), or more elaborate (model double-ellipsoid with Gaussian distribution worked out by J. Goldak). The chock of the parameters of the source of heat selected requires temperature measurements.

Thereafter, we detail the approach to in the case of follow a modeling by heat flow, by distinguishing simulations 3D and 2D. It is supposed that there exist available data in temperature.

Case of a modeling 3D with heat flow

- We give below some possible forms for the space representation of voluminal or surface flows:
 - ◆ Example of a voluminal, constant flow following y and z and variable in the direction of welding, here x .

$$Q^V = Q^V(x, y, z; t) = Q^V(x; t) = \begin{cases} \frac{Q^{max}}{L/2} x & \text{si } 0 \leq x \leq \frac{L}{2} \\ -\frac{Q^{max}}{L/2} (x - L) & \text{si } \frac{L}{2} \leq x \leq L \end{cases}$$
 - ◆ Example of a surface flow $Q^S = Q^S(x, y; t)$ cylindrical at circular base of ray R and of maximum intensity Q^{max} .
- When temperature measurements are available, the parameters of this contribution of heat (sizes, values of maximum power injected) can be fixed so as to as well as possible reproduce, by calculation, the measured thermal cycles.

- This stage of chock can be carried out easily and with weak computing times via a quasi-stationary calculation in pointer (`THER_NON_LINE_MO`). That supposes that the way of the source is rectilinear uniform, at constant speed. In this case, case it is supposed that a permanent mode is established, and the equation of the heat written in this reference mark becomes independent of time. One thus obtains the field of temperature in this reference mark (function of space only). One can possibly recover temporal dimension by a change of variable ($X = x - V.t$). One can thus quickly (only one step of time) identify the parameters of the source, which are then re-used in the case of transitory calculation.
- Once the identification carried out and if the power of the process of welding is known, one will be able to deduce the value from it from the parameter η in the output capacity (in order to check the coherence of the value obtained compared to the process). Indeed, the integral of the voluminal density (respectively surface) of heat flow on selected volume (respectively selected surface) must be equal to the output capacity, that is to say

$$\int_V Q^V(x, y, z; t) dv = \eta UI \quad \text{et} \quad \int_S Q^S(x, y, z; t) ds = \eta UI$$

In the two examples presented above, that gives:

- ◆ Example of voluminal flow: $S \int_0^L Q^V(x; t) dx = S * \frac{L}{2} * Q^{max} = \eta UI$ where S is the surface of the cord deposited perpendicular to the direction of welding.
- ◆ Example of surface flow: $\int_S Q^S(x, y, z; t) ds = \pi * R^2 * Q^{max} = \eta UI$.
- The heat flow being identified spatially, it is now necessary to implement the displacement of this source on the grid for transitory thermal calculation. One thus defines a function in the direction of welding, here x , and of time by the operator `DEFI_NAPPE`: a flow function of time is applied successively to the meshes located under the way of the torch of welding, while considering a rise with maximum value, followed of a descent to zero. The descent of flow on a mesh corresponds to the rise of flow on the following adjacent mesh. Thus the sources "are lit" successively along the axis of welding at the time of the passage of the torch, which corresponds to a source of heat of constant intensity which travels in space along the axis of welding.

Case of a modeling 2D with heat flow

- In the case of a modeling in 2D, the approach is different because it is necessary to choose a flow (voluminal or surface) which is variable in time and this in order to take into account, in calculation 2D, the approach and the distance of the torch. For the space distribution this flow, one often chooses a constant flow in space. A surface example of flow is given below:

$$Q_r = Q_r(x, y, z; t) = Q_r(x; t) = \begin{cases} \frac{Q^{max}}{t_1} t & \text{si } t \leq t_1 \\ Q^{max} & \text{si } t_1 \leq t \leq t_2 \\ -Q^{max} \frac{(t-t_2)}{(t_3-t_2)} & \text{si } t_2 \leq t \leq t_3 \end{cases}$$

- There still, it will be necessary to identify, starting from temperature measurements, the parameters of selected flow (in our example, the moments t_1 , t_2 and t_3 as well as the value Q^{max}).
- If one knows the power delivered by the process, one can also deduce the parameter η from it. That gives for our example:

$$\int_t \left[\int_S Q_r(t) ds \right] = S \int_t Q_r(t) dt = \frac{\eta UI}{V} \Leftrightarrow \int_t Q_r(t) dt = \frac{\eta UI}{SV}$$

what makes:

$$\int_t Q_r(t) dt = Q^{max} * \frac{1}{2} (t_3 + t_2 - t_1) = \frac{\eta UI}{SV}$$

where V is the known speed of welding and S the surface of the cord deposited known. To refine the identification of the parameters of the source, one can use the parameter η found by a quasi-stationary calculation 3D in pointer.

Experience feedback

- Thesis INSA L.D 2004:
 - ◆ For transitory modeling 3D of the plate, several forms of surface flows were tested: triangular in the direction of welding, cylindrical at circular and Gaussian base. For these three flows, the distribution in temperature proved about identical.
 - ◆ For modeling 2D (deformation planes), three representations were tested: temperature imposed, surface flow and voluminal flow with identification of the parameters to measures. Only modeling with imposed temperature led the fusion of the added metal. With a voluminal flow, the molten zone was not reproduced.
- Card 3488: The approach in imposed temperature was used on the axisymmetric calculation of the tube. The results of this simulation show that calculations over-estimate the molten zone and maximum thermal cycles. The approach in imposed temperature is thus too energy and it is the approach in flow which is advised for this study.

4.3.4 Boundary conditions thermal with the environment

The boundary conditions thermal are modelled by convectifs exchanges and radiative of the part welded with the environment, which are written:

$$-\lambda \frac{\partial T}{\partial n} = h(T - T_{air}) + \varepsilon \sigma (T^4 - T_{air}^4)$$

where n is the external normal, h the coefficient of convectif exchange, σ the constant of Stefan-Boltzmann and ε the emissivity of material.

Remarks

- In the case of the welding of relatively thick parts, the values taken for the coefficient of exchange and emissivity have often only one influence secondary on thermal calculations: indeed, the heat flow exchanged with the ambient air during the heating and with cooling is very weak, compared to the heat flow by conduction in the part coming from the contribution of heat.
- In the immediate vicinity of the source, the flow emitted by radiation is considerable in reality, but the corresponding unknown factors can be integrated in the definition of the size and the distribution of the source of heat.
- The thermal problem is thus brought back generally to a purely conductive problem and not taken into account of the radiative exchanges and convectifs with the environment is not essential.

4.3.5 Thermophysical characteristics

The thermophysical properties intervening in the equation of heat are function of the temperature. It is thermal conductivity $\lambda(T)$ and of the specific heat ρC_p or of the enthalpy.

Remarks

- With regard to thermal conductivity, it is sometimes of use artificially to increase it for the higher temperatures at the melting point, in order to "take into account" the phenomena convectifs inside the bath, and to homogenize the temperature of this one. In the literature, conductivity is thus increased by a factor 2.10 or 100 according to the authors (it is what is made in tube 3488 with a factor 100). In practice, it is often reasonable to take a constant conductivity starting from the melting point, and it is estimated that it is not necessary to increase it artificially, being given that unknown factors relating to the bath of fusion (phenomena convectifs, etc...) are included in the definition of an ad hoc source of heat.
- During welding, the latent heat of fusion (cf notices paragraph 3.3.1) is low compared to the contribution of heat coming from the process, and it is not inevitably useful to take it into account. Moreover, this latent heat of fusion can also be included implicitly in the definition of the contribution of heat.

4.4 Metallurgical calculation

The critical point for the metallurgical part concerns, primarily, the knowledge of experimental data in order to identify the metallurgical models of behavior correctly.

4.4.1 Introduction

In this part, one is interested only in standard material steel, in particular the 16MND5, which can comprise five different metallurgical phases: ferrite, pearlite, the bainite, martensite, known as cold phase or α , and austenite, known as hot phase or γ .

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

The metallurgical involved phases thus depend on the temperature and the speed of temperature. The calculation of these phases is carried out in postprocessing of a mechanical calculation, by the order `CALC_META`. It is necessary to specify in this order the initial metallurgical state.

4.4.2 Models of behavior to the heating and cooling

Currently in *Code_Aster*, for materials steel type, there exists one model of behavior making it possible to calculate, with each step of time, the proportions of the various phases. Nevertheless, this model is different with the heating and cooling. One will find in [R4.04.01] the detailed expression of the kinetics to the heating and cooling.

4.4.3 Thermal interaction => Métallurgique

As we already specified before, there is no coupling between calculations thermics and metallurgical. However, the thermophysical properties (conductivity, specific heat or enthalpy) of the material point depend on the proportions of the various involved phases: if this is in general not too prejudicial with respect to the mechanical predictions, that can be the being for a fine forecast of the final metallurgy (but it is not, in general, the objective of a digital simulation of welding).

4.5 Mechanical calculation

The critical points for the mechanical part relate to the choice of the law of behavior and the identification of the parameters of this law.

4.5.1 Principle of mechanical calculation

Mechanical calculation is carried out by resolution of the equilibrium equations (operator `STAT_NON_LINE`), by taking account of the dependence of the mechanical properties with respect to the temperature and, possibly of the proportions of the metallurgical phases.

4.5.2 Management of the matter addition (weld beads)

In mechanics, there exist two methods to manage the matter addition, equivalent in the principle to those of thermics.

- One can consider only one mechanical model comprising all the cords, where nodes with the interface between cords are duplicated. At the time of the addition of a new cord, one assigns conditions to the interface relating to the increment of displacements (`LIAISON_DDL`). Just like in thermics, this method is certainly most reliable but the construction of the grid becomes tiresome if the number of master keys is high. One does not have back from experiment **recent** on this method.
- The method most usually used in mechanics is that where one has only one mechanical model for all the passes, the elements not yet present being disabled artificially by assignment of a Young modulus "quasi-no one" ($E=10^{-11} \cdot E(20^\circ C)$ in practice)). The value of modulus Young to be affected in metal not deposited results from a compromise: if the value is too high, of the constraints will be generated in metal not yet deposited, but if it is too weak, that can involve problems of convergence.

4.5.3 Law of behavior

In *Code_Aster*, there exist various laws of behavior to describe the nonlinear behavior of a material (work hardenings isotropic, kinematic, mixed, viscous effect,...). The user will find in the document [U4.51.11] the inventory of these models. Being given that these models are not specific to only simulations of welding, we will not describe them.

Notice

Nevertheless, we can quote the mechanical models with effect of structure transformations, which were developed for steels, the such 16MND5 and especially within the framework of the welding activities.

These models, which are described in detail in the documents [R4.04.02] and [R4.04.03], make it possible to model the following phenomena: plastic behavior or viscous behavior, linear isotropic work hardening or not linear or linear kinematic work hardening, plasticity of transformation, restoration of metallurgical work hardening of origin, restoration of work hardening of viscous origin. One can carry out a calculation in small deformations but also in great deformations, that is to say with the option `PETIT_REAC`, that is to say with the option `SIMO_MIEHE` (the models with kinematic work hardening do not exist with `SIMO_MIEHE`).

The two important matters on the level of the choice of the law of behavior relate to:

- Does one have to take into account the viscous effects because of the high temperatures generated during welding?

- Which type of work hardening does one have to consider (isotropic, kinematic or mixed)? This question is important in welding because this process implies cycles of traction and compression;

The viscous effects are often neglected because primarily of the lack of experimental data. A plastic model can then be sufficient if its identification is carried out starting from tests where the rate loading is close to that met in the studied structure [6]. If not, it is preferable to take a viscous model, especially if one wishes to simulate a loading of type detensioning.

For the type of work hardening, one noted in [3], [4] and [6] that a model with isotropic work hardening leads in general to a final level of constraint very high (compared to measurements). The final level of constraints maximum will be all the more high as the cycles of plasticization in traction and compression will be numerous. This is why the higher the number of master keys modelled is, the more the residual stresses envisaged by a modeling with isotropic work hardening will be high. One can attenuate this result by using an isotropic work hardening with restoration of viscous origin, which will compensate for the effect of isotropic work hardening. On the contrary, a model with kinematic work hardening tends to underestimate the residual stresses. The real behavior of material is often a combination of two work hardenings.

4.5.4 Notice on the great deformations

The taking into account of the great deformations is in general not essential for a simulation of welding on thick structures. On the other hand, the II structures are mean (strong distortions), it is necessary to take them into account.

In *Code_Aster*, there exist two possibilities to take account of the great deformations in the operator `STAT_NON_LINE` :

- The option `PETIT_REAC` adapted when rotations are small;
- The option `SIMO_MIEHE` for an exact formulation of the great deformations, but restricted with the models with isotropic work hardening.

4.5.5 Boundary conditions

Experience feedback

- Card 3488: The axisymmetric modeling of welding on the tube implicitly wrongly supposes that welding simultaneously takes place on all the circumference of the tube, therefore that the temperature rises everywhere in the chamfer. In reality, the source of heat progresses towards part of structure remained cold, which attaches obligatorily the welded zone. The part, on the level of the source of heat, cannot thus dilate freely. This effect of autobridage must grow blurred when diffuse heat and disappear during the phase from cooling. To cure this problem, one can force an axial fastening on the tube, only in the phase of heating. One thus prevents the tube from freely dilating with the heating, on the other hand it is free to become deformed with cooling.

4.6 Computing time

It is noted (in version STA9), through various conducted studies of welding these last years, that the essence of time calculation is consumed in mechanical calculation. To give an order of magnitude, we give two examples below:

- Case test HTNA100A which considers a chamfered tube welded on the two ways with process TIG (card known as 3488):
 - ◆ Many nodes = 3632
 - ◆ Modeling: axisymmetric

- ◆ Time CPU of thermal calculation = 307s
- ◆ Time CPU of metallurgical calculation = 25s
- ◆ Time CPU of mechanical calculation = 5169s

- Study on a chamfered plate welded on the two ways with process TIG (card known as 2425)
 - ◆ Many nodes = 11600
 - ◆ Modeling: 3D
 - ◆ Time CPU of thermal calculation = 951s
 - ◆ Time CPU of mechanical calculation = 64601s

Remarks

- Possible metallurgical calculation does not cost anything in time calculation because it is only a question of integrating the models of behavior; there are no equilibrium equations to solve.
- Mechanical time could be certainly improved if one considered (at the time of the resolution of the equilibrium equations mechanical by the operator `STAT_NON_LINE`), in the phase of prediction, dependence of the YOUNG modulus and perhaps of the thermal coefficient of expansion, with respect to the temperature. Currently, only is taken into account, in the second member, the thermal deformation (makes the derivative of it).
- The mechanical part being a strongly nonlinear problem, it is often necessary to use linear research in the module `STAT_NON_LINE` in order to facilitate convergence. Moreover, one adapted step division of time according to the change of the temperatures makes it possible to facilitate convergence.