Inductive FEA - Benchmark optimization

Feigenblum José*[1], Mocellin Yann[1], Perrier Damien[1], Ernst Roland[2]
[1]ROCTOOL, Savoie Technolac, BP 341, Modul R, 34 Allée du lac d'Aiguebelette, 73375 Le Bourget du Lac – France
[2]Laboratoire SIMAP, Bâtiment EPM, Domaine Universitaire, 1340 rue de la piscine, 38400 St Martin d'Hères – France
*Corresponding author: feigenblum@roctool.com

Abstract: In this paper, after a brief presentation of our company, we will detail our technology and the importance of the simulation step. In the same time, we will describe different levels of FEA we have followed and we will conclude on the best balance, for our industrial target, between complexity of models and accuracy of results.

Keywords:
Induction heating, plastic process

1. Introduction

Roctool developed processes to allow fast heat cycling in plastic and composite sector. It is in this frame that the use of induction it is so imposed. Indeed, the CageSystem® makes it possible to heat only the moulding surface of tools, in general several steel tons, to allow a quick cooling then.
Our business model, based on licensing out, impose us, for want of to propose processes turn key, to play the role of support for our customers on always different subjects. Our action, with the aid of Comsol, of simulation of complex physical phenomena, allows, by defining and optimizing, the dimensions of tool; inductor and its source of power associated, to deliver to our customers the parameters of design and realization for a process optimized in energy with a distribution of temperature on the surface of the tools, most realistic possible.

2. The Cage System® technology

In fact, an inductor all around the tool creates a magnetic field and therefore two electrical loops of "induced current" in both part of the mould.
Current passes into a very thin layer (which is the electromagnetic skin depth) all around the mould. Because we want to heat only the tooling surface, we use non-magnetic material for all the exterior sides where currents pass (fig. 1 & 2).
At the tooling surface, we need a material with high electrical resistivity to allow an important Joule effect. Moreover, the material has to get some properties making it possible to achieve an important induction output. This property is the relative magnetic permeability μ_r. Higher this value is, more important the induction output on the moulding surface is. As a result, we can heat much more with an equivalent power.

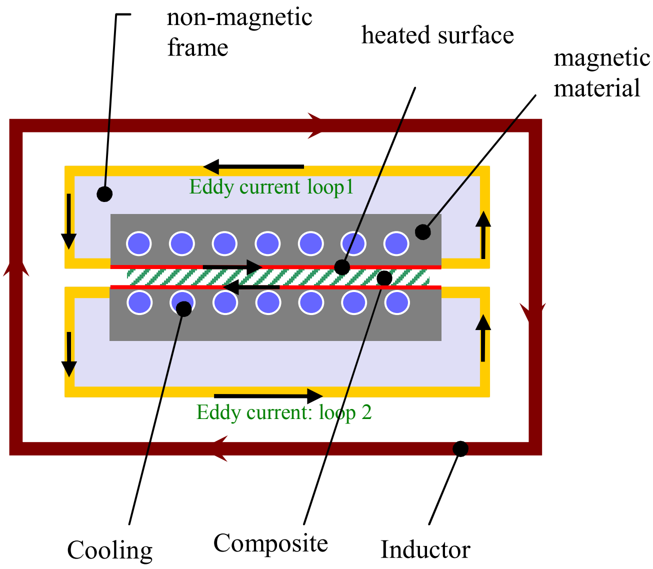

fig.1: Cage System® principle

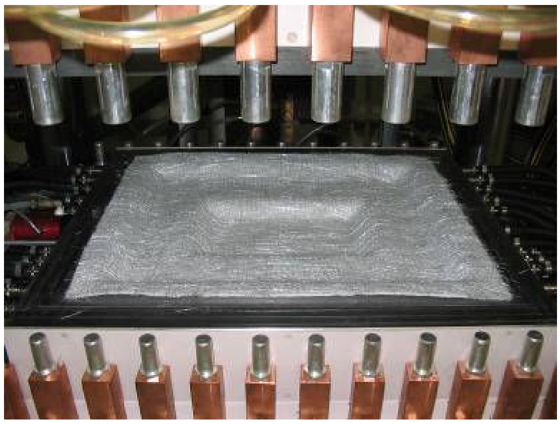
fig.2: Cage System®

Hence, Cage System® makes it possible to decrease a lot the energy consumption compared to classical process which need to heat the whole mould and not only a surface.
The induction phenomenon is complex since it's strongly linked with mould and mould surroundings. Moulding surface shape can influence magnetic field way and as consequence, induced current way. As a result we could have a temperature heating difference according to a local

point on the moulding surface. Today with 3D modeling, simulation time is longer than before. However, we lose much less time during trials than before where we needed to create several moulds to manage to get good surface heating quality. Being better with simulation, we influence the earliest possible the project development, gaining time and saving money finally.

3. Study Case

3.1 The process

This tool of projected surface ~0.5mx0.5m must allow the realization of an epoxy resin part reinforced by a carbon fibre fabric (fig.3). This box with a bottom on two levels is interesting, because it represents at the same time a case rather representative of part which one can find in automotive industry, but also a case of study, for our process, interesting because successions of convex and concave zones, in fact, although the geometry is elementary, a model difficult to apprehend intuitively.

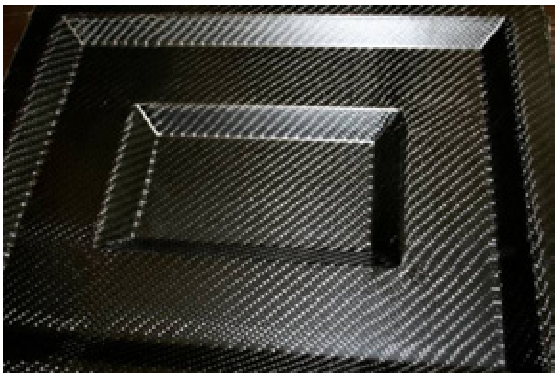

fig.3: Composite part

In opposition, with a traditional process of thermoregulation (T_{cst}~100°C) imposing a curing time for the resin of ~10’, it will be proposed a cycle time starting from 50°C until 140°C in 60’’ making it possible to reduce cross-linking time to 2’. It will be accepted a distribution of temperature of +/- 10°C on the surface of the tools, to guarantee a good reticulation of the resin and to thus obtain the mechanical properties of the composite. This tool will be connected to an inductive generator (100kw), working in a given frequency range (30 to 50kHz). Analytically, it was evaluated an inductor of 12 wires, positioned all around the tools with 5mm of the tools. The wires are mainly copper tubes of diameter 20mm, spaced 39mm between them.

3.2 Use of Comsol Multiphysics

It is first of all carried out a first simplified CAD model to only allow the FEA of the phase of heating initially and phase of cooling in the second time.

In the light of the computation results, it is carried out a final CAD model, too complex to be modeled, to be sent in machining (fig.4). During this comparative analysis, we will concentrate only on the phase of heating, obtained by a multiphysics analysis between the EM *equation (ACDC Module; Quasi-statics; Magnetic; Time Harmonic ; Linear)* and TH equation *(Comsol Multiphysics; Heat Transfer; Conduction; Transient Analysis; linear)*. We will use a *direct linear system solver (UMFPACK)*. Thanks to the mode *time harmonic*, one imposes the frequency according to the range of the generator used thereafter. However, there is no strong relation between the frequency and the quality of heating, or the output, in the range of the generators used (10-30 kHz or 30-50 kHz).

The configuration of the work station used is a station 64 bits with 16 Go of RAM, making it possible to work in configuration client/server on several stations at the same time.

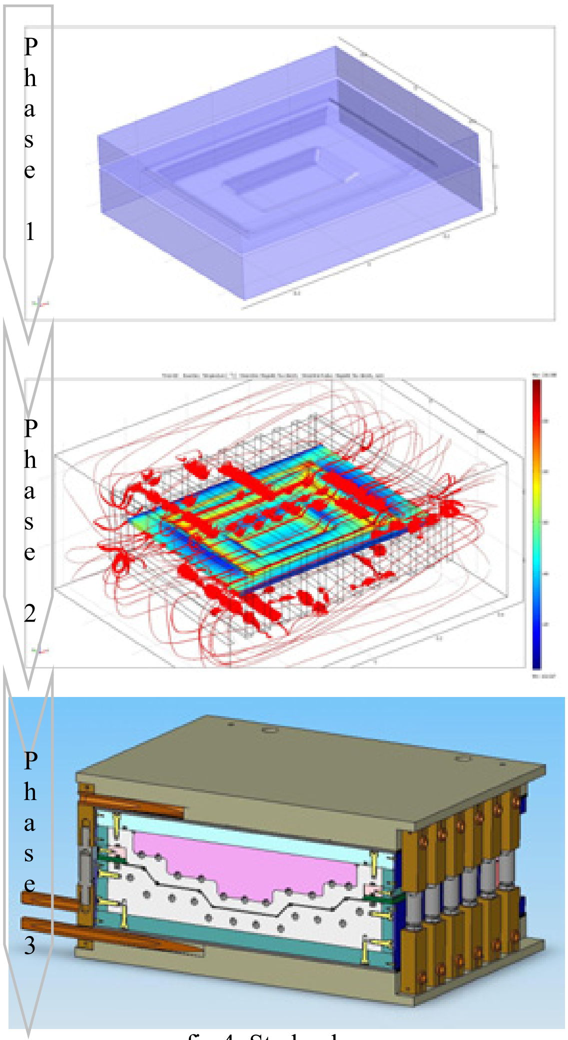

fig.4: Study phases

3.3 Modeling in boundaries impedance

In front of thin electromagnetic skin depth of various materials used (at 25kHz, δ=0.2mm for steel and δ=0.4mm for copper), it will be used the boundaries impedances to model only the inductive phenomenon at the boundaries of the mould and in the air and thus to limit the number of *dof* by unselecting '*active in this domain*' the interiors of moulds. Our simulations residents in the study of large and complex geometries (up to 1m²), opposed to skin effect (lower than the millimetre) and air gap in order to the millimetre.

Induction Currents (emqa); Boundary Settings; Conditions; Impedance Boundary Condition; Material Properties (σ, μr).

Modeling will be made in two stages on a given geometry, in weak coupling, the first by studying the distribution of the magnetic field (*magnetic flow density - B_emqa*), only in the air around the tool, and the distribution of the induced currents (*surface current density - Js_emqa*) for electromagnetic (EM) and its dual for the thermal (TH) part, the source term resulting from the EM being injected on the surface of the tool (*Heat Transfer by Conduction (ht); Boundary Settings ; Boundary condition : Heat flux ; Inward heat flux ; q0=Qsav_emqa*) to treat the thermal only inside the tool (fig.5).

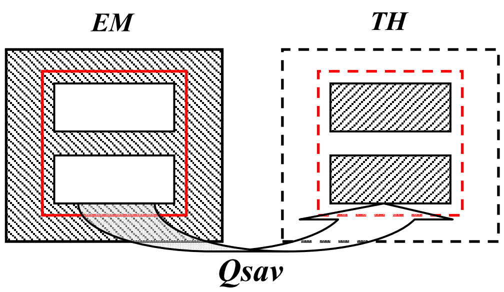

fig.5: Use of boundaries impedance

Concerning the external layer of shielding out of copper, he was studied two configurations. The first lies in the application of a source term on the external surface of this layer of copper (5mm thick), the second consists in neglecting, thermally the thickness of copper to apply a source term, resulting from a calculation in impedance realized to a copper surface, but directly applied to the steel mould (fig.6). The main objective is to reduce the size of the mesh, while not modeling, thermally, the incidence of the layer of copper.

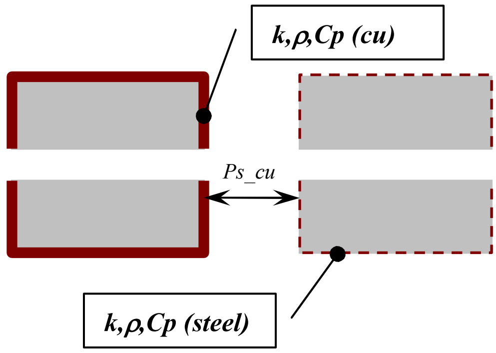

fig.6: Surface representation

There is no important difference on the level of temperature reached, at the same time on the layer of copper and on the remainder of the mould, however, the quality of the mesh (obligatorily more refined in the layer of copper) as well as the thermal role of diffuser of copper, make that the configuration of the study of the layer of copper in its thickness is smoothed (fig.7). However the interest is not sufficient, the objective being the study of the moulding zone of steel, and the increase in the computing time (~3 times) make that the second configuration will be retained (fig.8).

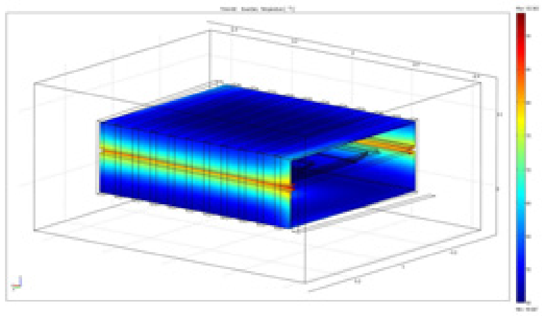

fig.7: Thickness configuration

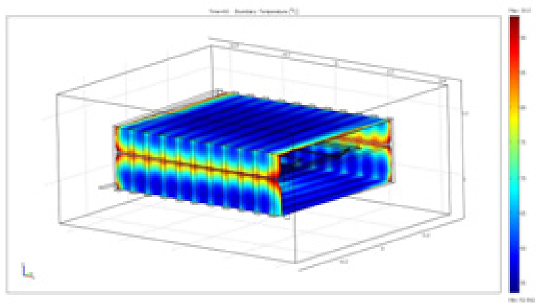

fig.8: Surface configuration

3.4 Limit of Q_{sav}

As explained above, the source term, resulting from EM calculation is applied to the surface of the tool.
However, under certain "coarse" conditions of mesh, the source term resulting from Comsol gives negative values, or positive but very high (fig.9).

Although the mode in *Model Settings; Geometry Shape* is forced in *Linear*, to remove all *inverted mesh*, we cannot be sure estimate of the source term under these conditions.

*Qsav=0.5*real(Jsx*conj(Ex)+…)*
and *Ex_emqa=-jomega_emqa*Ax*

Indeed, the currents of surface being normalized, the problem is at the level of the expression of E and implicitly of A.

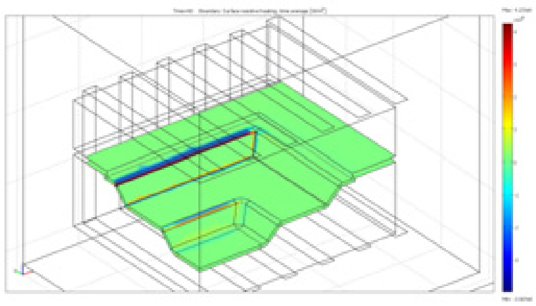

fig.9: Q_{sav} representation

Thus, we rebuilt a term source, an expression of the surface power density, dedicated specifically to materials used, here definite like:

$$P_s = Js.Js^*/2.\delta.\sigma$$

*Ps_steel=(normJs)²*alpha_steel*
and *alpha_steel= 1/(2*delta_steel*sig_steel)*

The expression of the source term, under these conditions allows, some is the quality of the mesh, to give a coherent interpretation of heating to the surface of the tool (fig.10), even if the interest to optimize the mesh remains, to evaluate in detail the physical phenomena.

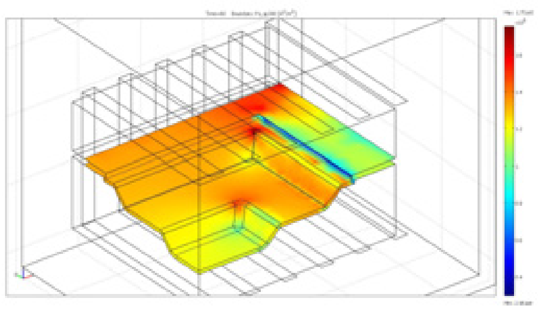

fig.10: P_s representation

3.5 Effect of free convection

Concerning the boundary conditions on the thermal part, considering the levels of heating on the tool; ~60°C on external surfaces out of copper and ~150°C on moulding surfaces, it is not necessary to integrate an effect of free convection. It is then imposed a thermal insulation on all surfaces of the mould.

3.6 Bands representation of the inductor

In optics to make calculation compatible with our configurations of work station, it is systematically sought simplifications (symmetry, elementary geometries…), but the risk is to move away from the real phenomenon and to distort the analysis.
The first operation, carried out using the drawing tool of Comsol, is to represent the inductor in the form of elementary bands, where the current will be dominating, while imposing a constant surface density of current on the surface of the inductor (fig.11). Indeed, knowing the real distribution of the currents in our inductors of cylindrical wire cross-section, a simplification towards a surface representation is allowed.

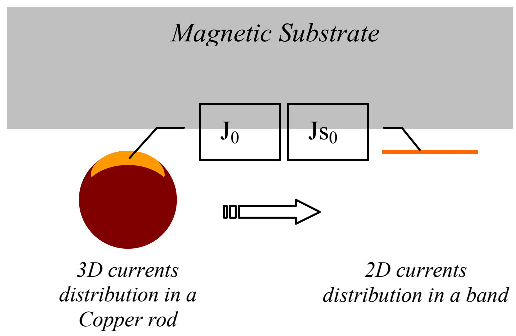

fig.11: Band representation

From the helicity of the inductive coil, the value of J_s, will be imposed, respectively on components X, Y and Z, in order to obtain a constant current density along the course of the inductor (fig.12).

Induction currents (emqa); Boundary settings; Boundary conditions; Surface currents; Surface current density: J_{s0}.

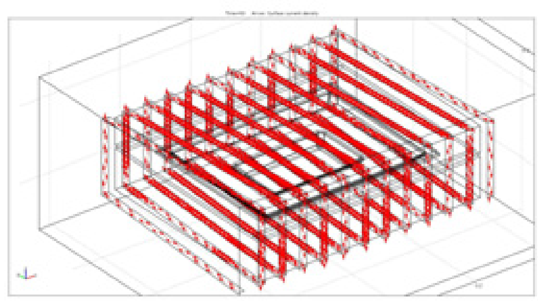

fig.12: Surface current density

3.7 Results

We will concentrate on the thermal analysis of the zone grinding out of steel to be able to evaluate and compare the various configurations

There still, the bad distribution of heating obtained after this first stage of is not the object of the study, the objective being contrary, to determine the potential zones of under heating or overheating to apply various solutions in order to improve the distribution of temperature on the tool, either by an EM device or a TH device. Below, one finds the distribution of temperature on the moulding surface of the upper part of the tool, this succession of radii concave and convex finds itself in an identical way on moulding surface of the lower part of the tool.
Thus, as one could await it, the convex zones are generally overheated, compared to the plane zones of reference and contrary, the concave zones are under heated compared to the plane zones.
In our activity, it is important to evaluate these differences in temperatures finely, to be able to adjust the solution suggested. For example, for a zone of overheating, it will be proposed to position, taking into consideration this zone, a channel of water with a thermal role of regulation, it will be then important to evaluate the level of temperature to be recovered to define precisely, the localization, the dimension, the flow and the temperature of water in this channel.
Obviously the parameters of geometrical definition of the channel will be important, contrary to those parameterizing the flow, because machining carried out, it will not be possible any more to change these parameters.
In an identical way, for certain zones of overheating, it can be proposed to modify material of the mould, locally, by welding or an insert for example. It will be then, in this case, selected a material with lower electromagnetic properties in order to reduce the effect of heating locally. With this intention, it will be important to know precisely, at the same time the data of various materials used, but also the difference in temperature to be recovered.
While considering, that with a 3D effect, the convex or concave zones, respectively perpendicular to the magnetic field or to the currents will not have the same behavior.
First of all, heating seems symmetrical on the surface of the tool, validating the positioning of the coil around the tool.
Using a *Linear* mode for EM and TH equations, a *normal* mode for the *global mesh size* and forced mesh size on some surfaces:
- 10mm on the inductor and the copper frame
- 5mm on the moulding surface in steel

We acquire then (fig.13):

⇨ 1 150 000 elements; ~725.000 *dof* for EM calculation (21' calculation time); ~135.000 *dof* for TH calculation (2' calculation time)

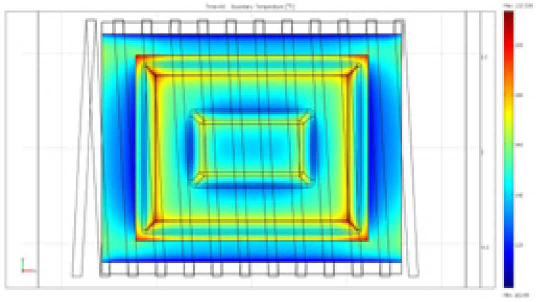

fig.13: Thermal cartography

On the moulding surface (fig.14):

⇨ T_{min} =113°C and T_{max}=213°C

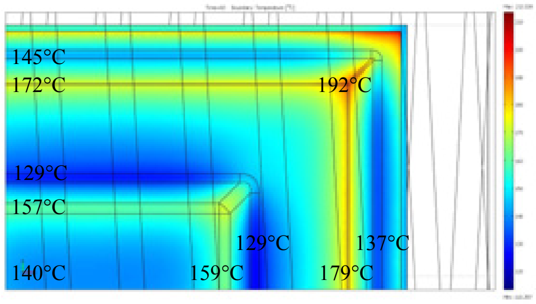

fig.14: Thermal cartography

In optics to dimension the associated generator, as it is difficult to be based on the value of density of current imposed on the surface of the inductor, we calculate in *postprocessing* and using the mode *Boundary Integration*, surface power densities *Ps_steel* and *Ps_cu* respectively for steel and copper. We apply then a coefficient yield, obtained empirically, to consider the size of the generator sufficient in order to obtain the time of heating estimated with the temperature targeted.
Obviously, the distribution of temperature obtained is heterogeneous and the composite would not make it possible to transform, but before proposing solutions allowing a rebalancing of the temperature, validate if the model obtained is right, or, so of other modes of simulations degraded, or contrary more complex are relevant.

4 Benchmark analysis

4.1 Interest of the quadratic mode vs linear one

Associated with an identical mesh, it is already relevant to carry out a comparative study between the linear mode and quadratic.
But indeed, in both cases, the number of *dof* will be significantly different. The interest will lie in the comparison between a *Linear* model refined and optimized in mesh, and a *Quadratic* model with the mesh inherent in the size of the work station.

Using a *Quadratic* mode for EM and TH equations, a *normal* mode for the *global mesh size* and a free mesh size on all surfaces, we acquire then:

- ⇨ 235 000 elements; ~785.000 *dof* for EM calculation (2h15' calculation time); ~195.000 *dof* for TH calculation (5' calculation time)

On the moulding surface (fig.15):

- ⇨ T_{min} =112°C and T_{max}=216°C

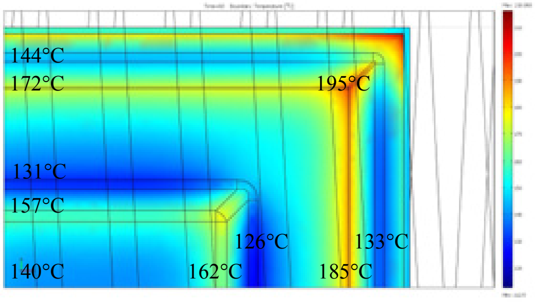

fig.15: Thermal cartography

Several points are to be raised, first of all, the results are not significantly different, and moreover, in the direction of the currents, the results are similar. However, in the direction of the magnetic field, the results are appreciably different.
The zones of overheating are slightly higher than the *Linear* mode (on average, from 3 to 5°C) whereas the zones of under heating are they slightly lower compared with the *Linear* mode (on average, from 3 to 5°C).
One can thus conclude, on the fact that a calculation carried out in *Linear* mode, with a refined mesh, will make it possible to have a correct interpretation of the results, while optimizing the computing time. The ultimate objective remaining to have the finest mesh possible, to be able to treat it with the *Quadratic* mode.

4.2 Use of symmetry

Thereafter, always in optics to reduce the number of elements significantly, as the geometry allows it in this present case, and as the result seems symmetrical, it is proposed of realized a study on a symmetry ¼ of the mould, which forces to represent the inductor in the form of parallel bands (fig.16), moving away however from the initial helicity of the inductor.
However, while being careful on the interpretation of the magnetic field creates by this inductor, an undeniable profit on the number of elements is to be noted.

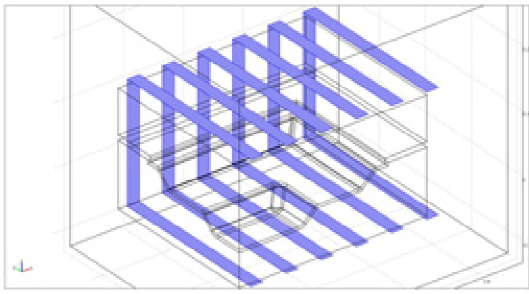

fig.16: Symmetry representation

With number of *dof* equivalent, one can obviously refine the mesh on the zones of strong curves like within the air-gap.
Following the study of the relative relevance of the *Quadratic* mode in our case, it will be used a *Linear* mode, with identical conditions of parameter settings. Only characteristic, the face of symmetry parallel with the currents will be defined like *Electric Insulation*, thus forcing the currents with beings parallel with the face of symmetry.

Induction Currents (emqa); Physics ; Boundary Settings; Conditions : Electric Insulation

The face of symmetry parallel with the magnetic field, following the example others external faces of the volume of air surrounding the mould, will be defined like magnetic insulation.

Induction Currents (emqa); Physics ; Boundary Settings; Conditions : Magnetic Insulation

Using a *Linear* mode for EM and TH equations, a *normal* mode for the *global mesh size* and forced mesh size on some surfaces:
- 20mm on the inductor and the copper frame
- 5mm on the moulding surface in steel
- 1mm on the curved zones of the tool

We acquire then:

- ⇨ 915 000 elements; ~530.000 *dof* for EM calculation (78'' calculation time); ~115.000 *dof* for TH calculation (60'' calculation time)

On the moulding surface (fig.17):

- ⇨ T_{min} =112°C and T_{max}=210°C

The results there still are largely identical to the results obtained within the framework of a study of the complete mould in mode *Linear*, the difference relating to the fact of forcing the currents and the magnetic field following directions X and Y, does not seem to bring notable differences.

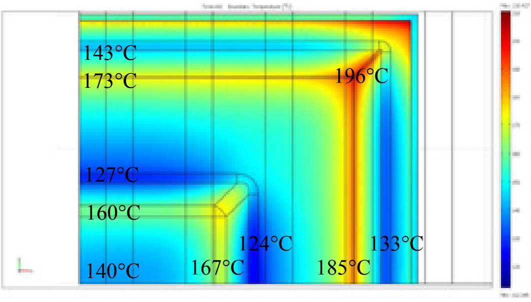

fig.17: Thermal cartography

By comparing these results with the *Quadratic* mode on the complete mould, an agreement even nearer is to be noted. This reveals, while remaining careful on other geometries, it brings a great facility of construction of the model with the parallel bands. The limit will be can be reached in the case of inductor with a more marked step of helicity.

4.3 Interest of the strong coupling

Modeling in symmetry ¼ in *Linear* mode being validated, we can push the analysis on an easily exploitable model, because inexpensive in computing times.
It appears interesting to evaluate, for example, the effect of the increase of the electrical resistivity with the temperature, to observe a possible increasing of the hot spots. Thus, it is proposed to analyze the relevance of our initial modeling, with properties EM and TH of materials defined as constants (available data classically in the literature at RT). However, for this study, and materials used, we pushed our analysis (fig.18).
For EM equations properties will be applied on boundaries whereas TH properties will be applied on domains. The condition of relative permeability will be fixed, because this data is very difficult to obtain, moreover we are very far from the Curie point, therefore far from a possible variation of this value. The two equations will be calculated in strong coupling. We will interpolate these data like lines defined by these two points of passage.

	@ RT	***@ 100°C***
Electrical resistivity ρ_e *µΩ.cm*	26	31
Relative permeability μ_r	50	50
Thermal conductivity k *W/m.K*	40	44
Specific heat C_p *J/Kg.K*	450	517
Density ρ *Kg/m³*	7850	7810

fig.18: Steel properties *f*(T)

Using a *Linear* mode for EM and TH equations, a *normal* mode for the *global mesh size* and forced mesh size on some surfaces:
- 20mm on the inductor and the copper frame
- 5mm on the moulding surface in steel
- 2mm on the curved zones of the tool

We aquire then :
⇨ 390 000 elements; ~270.000 *dof* for both calculation EM et TH; and ~35’ for calculation time

On the moulding surface (fig.19):
⇨ T_{min} =113°C and T_{max}=213°C

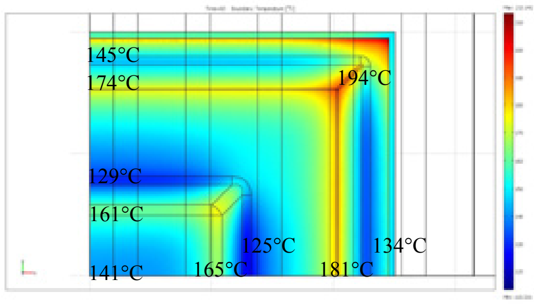

fig.19: Thermal cartography

We do not observe a notable difference, this being able to be explained various manners. In first, the temperatures being low, the variations are low In second, if the source term seems to increase with heating, the thermal term of thermal conductivity, also increases to him, this balance gets a solution then identical to us to the preceding ones.

5. Conclusions

These different methods of modeling are worth being once approached at least, however, with the goal to define an internal protocol of study for our company, we notice the possibility of using a ‘shaded’ mode with symmetry or a simplified representation of the coil. The idea will be to make converge different parameters like the frequency, the positioning of the coil, material selection …on a simple model, but correct, for after validate our model with an optimized configuration. It will be advisable to remain careful, these rules not adapting systematically to all the geometries (size, form…) or with all the processes (heating up to 400°C, materials with thick skin depth…).
Indeed, for amongst other things, to control a zone of overheating, it will be proposed to integrate by welding a non-magnetic material cord in order to limit the source term locally.
The interpretation so much from an EM point of view, with the boundary impedance to simulate the skin depth about 3mm in this case, so much thermal with a strongly voluminal source term, recomputed like a surface power density, will have to be another approach, finer, requiring a heavier model then because implying a size of mesh close to the surface at least of the size of the skin depth.
Lastly, like ultimate approach, it will be interesting to carry out a more realistic model of the inductor and flow of the currents, by imposing a voltage at

the boundaries in entry of the inductor defined by its most real possible geometry. A critical analysis of the representation of the inductor in band with an imposed Js will be possible.
It will be used in same time the *infinite elements* in boundary conditions, instead of use of *magnetic insulation*, to optimize the volume of air surrounding the tool in order to validate the relevance of this parameter while reducing the number of mesh in this volume.

6. References

[1] J. Feigenblum, A. Guichard: **Method of heating materials in order to produce objects and device for implementing said method**, *ROCTOOL Patent N° WO2005094127 A1, 18-03-2004*.
[2] J. Feigenblum, A. Guichard: **Device for transforming materials using induction heating,** *ROCTOOL Patent N° WO2007031660 A1, 12-09-2005*.
[3] J. Feigenblum: **3D inductive phenomena,** Comsol Conference 2006