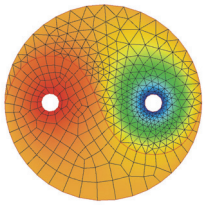
Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE

Informatyka w Technologii Materiałów

Vol. 10, 2010, No. 4



A COUPLED MULTI-PHYSICS MODEL FOR INDUCTION HEAT TREATMENT PROCESSES

DAVID CARDINAUX, FRANÇOIS BAY, YVAN CHASTEL*

MINES ParisTech, CEMEF - Centre de Mise en Forme des Matériaux,
CNRS UMR 7635, 06904 Sophia Antipolis Cedex, France
**Corresponding author: yvan.chastel@mines-paristech.fr*

Abstract

Several multi-physics problems are coupled in induction heat treatment processes. This makes them often difficult to control and understand. For instance, anticipations or minimizing distortions generated by such a process usually may require long and costly try-outs. A specific computational tool has been developed to help designing and optimizing this class of heat treatment operations. The tool is based on a multi-physics model which couples electromagnetic equations, heat transfer, mechanical response of the material, and metallurgical phase changes. This paper gives a short presentation of this tool. Emphasis is placed on analyzing which phenomena have to be taken into account. Simulations of the induction heating of a crankshaft are also presented.

Key words: multi-physics coupling, electromagnetism, metallurgy, finite elements, heat transfer, solid mechanics

1. INDUCTION HEAT TREATMENT PROCESSSES

The mechanical behaviour of a manufactured part strongly depends on the thermal, mechanical and metallurgical cycles which it has undergone during production. Industry takes advantage of this interdependence to control structural properties of manufactured products, and to provide components with enhanced characteristics. For example, local heat treatment operations are used to create gradients of mechanical properties throughout a workpiece, which can then meet simultaneously various resistance criteria such as wear or endurance durability.

Different heat treatment techniques are available. A heat treatment process based on local induction heating followed by massive quenching in water, enables to obtain local hardening of a specified zone in the workpiece. The depth of the affected zone can be predefined and controlled with the process parameters (Rudnev et al., 2003). Mechanical properties of the component as a whole can be considerably improved without any other manipulation.

The induction heat treatment process typically takes place in two stages. The first one is the induction heating of the workpiece to obtain austenite in desired areas. The second step of the heat treatment process is the cooling of the part. The Thermal Affected Zone (TAZ) is controlled during the first step. The second one consists usually in quenching the workpiece, either by spraying water or by total immersion into a water tank. Only the austenite area produced during induction heating undergoes significant changes, namely phase changes.

We shall focus here on a finite element modelling tool developed for local quenching after induction heating processes. The modelling of such a multi-physics coupled process requires to deal explicitly with electromagnetic, thermal, mechanical

 ISSN 1641-8581

and metallurgical phenomena, as well as their mutual interactions during the heating and quenching stages.

2. COUPLING ELECTROMAGNETISM WITH HEAT TRANSFER AND SOLID MECHANICS

A first step in the modelling of the heating stage for induction heating processes is the development a coupling procedure between electromagnetism and heat transfer. Our model thus couples a solving procedure for Maxwell equations (Gie & Sarmant, 1985) and a finite element tool for solving the heat transfer equation. In a second stage, this procedure can be coupled with a solver for mechanical equilibrium equations, and a constitutive law for modelling mechanical behaviour (Chenot & Bay, 2005). The next and last stage deals with the metallurgical couplings and will be introduced in the following section.

In the end, the most important point in such a coupled model is the determination of the coupling procedures between electromagnetism and heat transfer, mechanics and heat transfer, metallurgy and heat transfer, mechanics and metallurgy, electromagnetism and mechanics. All these equations and laws may be coupled but some couplings may be neglected (figure 1).

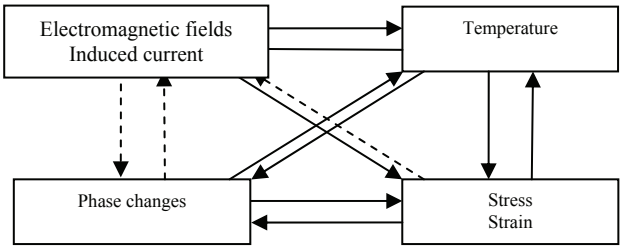


Fig. 1. *Coupled physics in quenching after induction heating processes. Dashed lines represent neglected couplings*

Let us provide some details about the electromagnetic model (Bay et al., 2002). The model is based on the Maxwell equations, neglecting the displacement currents in the Maxwell-Ampere equation (magneto-quasi-static approximation). This is a common approximation for modelling such processes in which the frequency remains between low- and medium- frequencies. We thus get:

$$\begin{aligned} curl(E) &= -\frac{\partial B}{\partial t} \\ curl(H) &= J \\ div(B) &= 0 \end{aligned} \qquad (1)$$

where H denotes the magnetic field, B the magnetic induction, E the electric field and J the electric current density.

We also have the following relations which for the intrinsic material properties:

$$\begin{aligned} B &= \mu(\|H\|, T)H \\ J &= \sigma E \end{aligned} \qquad (2)$$

where μ denotes the magnetic permeability, and σ the electrical conductivity. They all depend on temperature and the magnetic permeability μ depends also on H.

A suitable formulation for solving the Maxwell equations is the (A, V) formulation (Bossavit, 1993) - defining a vector potential A such that :

$$B = curl(A) \qquad (3)$$

Using this expression leads us to:

$$E = -\frac{\partial A}{\partial t} - grad(V) \qquad (4)$$

where V denotes an electric scalar potential.

We finally get an equation where the unknown is the vector potential A field:

$$\sigma \frac{\partial A}{\partial t} + curl(\frac{1}{\mu})curl(A) = -\sigma\, grad(V) \qquad (5)$$

In order to ensure solution uniqueness, we have to introduce an additional equation. The most usual condition is known as the Coulomb gauge and writes:

$$div(A) = 0 \qquad (6)$$

Space discretisation is then carried out using a global finite element approach where the workpiece, the inductors and surrounding air are meshed. We use edge finite elements (figure 2) supported by a tetrahedron (Nédélec, 1986).

Space discretisation leads to a classical finite element set of equations.:

$$[\mathrm{C}]\left\{\frac{\partial A(t)}{\partial t}\right\} + [\mathrm{K}]\{A(t)\} = \{\mathrm{B}(t)\} \qquad (7)$$

Using the harmonic approximation, we then get the following complex system:

$$[\mathrm{i}\varpi[\mathbf{C}] + [\mathbf{K}]]\{A\} = \{\mathbf{B}\} \qquad (8)$$

where ω (= 2* π * f) denotes the angular frequency of the magnetic field.

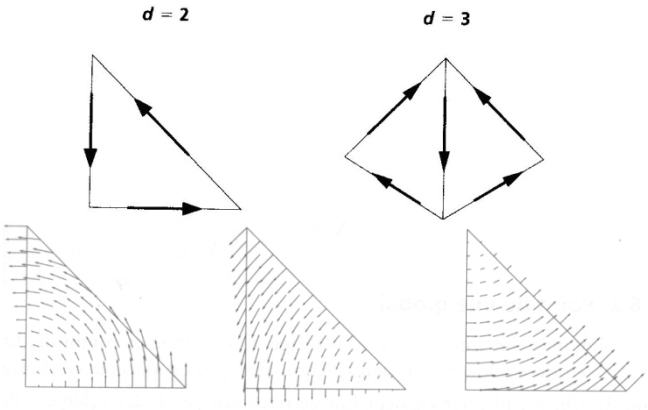


Fig. 2. a) 2D or 3D edge elements; b) Edge element shape functions for 2D edge elements

Regarding heat transfer coupling, temperature evolution in the work piece is governed by the classical heat transfer equation:

$$\rho C \frac{\partial T}{\partial t} - div(kgradT) = Q_{em} \qquad (9)$$

where ρ denotes the material density, C and k respectively the specific heat and thermal conductivity, which are all temperature dependent. Q_{em} denotes the local heat rate, generated by the eddy currents, and averaged over one period:

$$Q_{em} = \frac{1}{T}\int_0^T \sigma \left|\frac{\partial \mathrm{A}}{\partial t}\right|^2 \qquad (10)$$

Space discretisation is based on the use of tetrahedral P1 elements, for which the tetrahedral geometrical support is the same as the one used for the edge elements in electromagnetism.

3. MODELLING METALLURGICAL TRANSFORMATIONS AND RELATED EFFECTS

From a thermodynamic point of view, equilibrium is not reached during heating and quenching since constituents of a steel grade will evolve according to solid-solid phase change kinetics. Phase changes are classically modelled thanks to the well known Johnson-Mehl-Avrami equation (Johnson & Mehl, 1939; Avrami, 1939; 1940; 1941) for diffusive changes (austenite, ferrite, pearlite and bainite) (equation 11), and Koistinen and Marburger equation (1959) for the generation of martensite (equation 12):

$$y = y_{max}\left[1 - exp\left(-bt^n\right)\right] \qquad (11)$$

$$y = y_{max}\left(1 - exp\left[-A_M\left(M_S - T\right)\right]\right) \qquad (12)$$

where y denotes the growing phase rate, y_{max} is the maximum rate that can be reached, t is time, T is temperature, b and n are Avrami parameters depending on temperature, A_M a material constant, and M_S the martensite start temperature.

Parameters b and n in equation 11 are obtained from isothermal data derived from TTT (Time-Temperature Transformation) or CCT (Continuous Cooling Transformation) diagrams. In practice, during heating or quenching, calculations have to be performed along non-isothermal temperature paths. Such a problem can only be solved with a specific numerical procedure. We have decided here to decompose the process time into elementary time steps – which may be the same as the ones used for thermo-mechanical calculations. At a given time step, the temperature is provided by the complete model, and the metallurgical evolution over the time step has to be estimated. The method relies on the calculation of a "fictitious time" which is defined as the time needed to reach the same metallurgical state but as if the temperature had been this temperature since the beginning of the process. This "fictitious time" is then used for updating the progression of the phase change over the time increment, by using TTT diagrams for instance (Aliaga, 2000).

When using induction, high temperatures can quickly be reached. During such rapid heating and over the time spent at high temperature, several metallurgical phenomena can be triggered: not only the transformation into austenite, but also the homogenization of austenite by diffusion of Carbon and austenite grain growth if the temperature is high enough (Niclas, 1998).

As a first approach, the current model only deals with the kinetics of austenite development using a Johnson-Mehl-Avrami formalism, and does not describe chemical diffusions at any scale and grain structure evolutions. According to the literature review, these latter evolutions can modify slightly the metallurgical kinetics which then take place during quenching, and we plan to integrate them in future models.

As mentioned in figure 1, different couplings are related to metallurgical evolutions and have to be discussed.

Phase changes induce the production or the dissipation of heat. A source term expressed as enthalpies of phase changes need to be added in the heat transfer equation.

A constitutive law such as a standard power law or a more advanced elastic-viscoplastic law can be

used for each phase, and homogenization rules can be used to derive the global mechanical response. As a first approximation, Taylor rule, also known as mixture rule applied to mechanical behaviour, can be applied. In the case of metallurgical transformations, several specific mechanical effects should also be included in the model:

– during a phase change, the material contracts or dilates, and a spherical strain rate tensor relationship is added ;
– transformation-induced plasticity is an anisotropic phenomenon which is well-known but remains difficult to measure (Denis, 1986). In our approach, it is meant to describe the effect of the microstructure orientation on the flow under a load. An additional deviatoric strain rate term is then added in the total strain rate expression, and it is related to the stress deviator part according to an appropriate law. The related material parameters need to be determined from tests using dilatometry measurements coupled with mechanical tests.

Conversely, the effects of accumulated deformation and of a given stress state on the kinetics of phase change (both diffusive and displacive phenomena) can be significant. They can be expressed as shifts in TTT or CCT diagrams, that is to say modifications of the transformation times, or start temperatures.

4. EXAMPLE OF A NUMERICAL SIMULATION

We present here an academic example which only aims at demonstrating the capability of the numerical tool presented hereabove. It is a schematic case of an induction heat treatment for an automotive crankshaft (figure 3). The goal is here to demonstrate that numerical coupling between modules dealing with different physics is possible in the environment of a metal forming code, and to show examples of output which could be used later on for validations in the future.

Data for a made-up steel grade is used for the TTT information as input of the simulation.

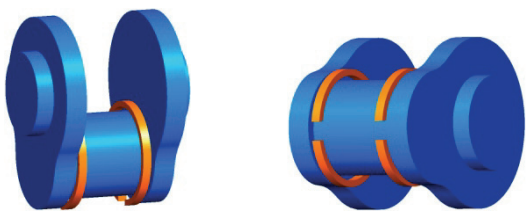


Fig. 3. *Induction heating of a crankshaft with two coils.*

The crankshaft is surrounded by two coils which aim at heating up the area located close to them in order to austenitise the material.

A global finite element mesh encompassing the crankshaft and the inductors has been created. The electromagnetic computations are carried out on this global finite element mesh, while the heat transfer, mechanics and metallurgical computations are carried out only on the crankshaft.

Results of temperature fields and austenite volume fraction are presented respectively in figures 4 and 5. As it can be seen, heating and metallurgical transformations are located in the areas of the crankshaft close to the inductors.

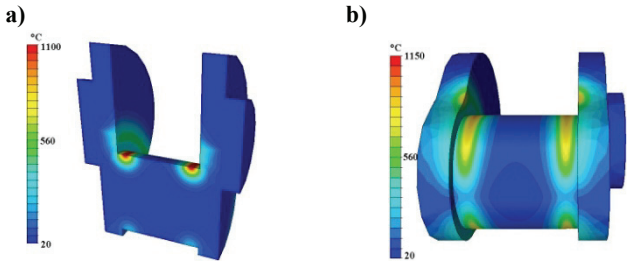


Fig. 4. *Temperature field in the crankshaft after 15s heating in a section a); near the gap in the coils b).*

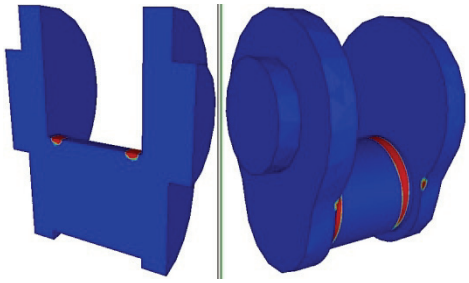


Fig. 5. *Volume fraction of austenite after induction heating*

Figure 6 shows the predicted evolution of the volume fractions of the different phases at a material point close to a coil. First, some austenite transforms into ferrite. The kinetics then slows down before other transformations start. This behaviour is due to the material data which is used. Then bainite and very little pearlite are formed.

These results of such simulations can then be transformed into hardness maps. We have presented here an academic example, but, when using appropriate material and process data for an industrial case, this tool could thus be used to optimise process design, and hardness distributions in heat treatment applications.

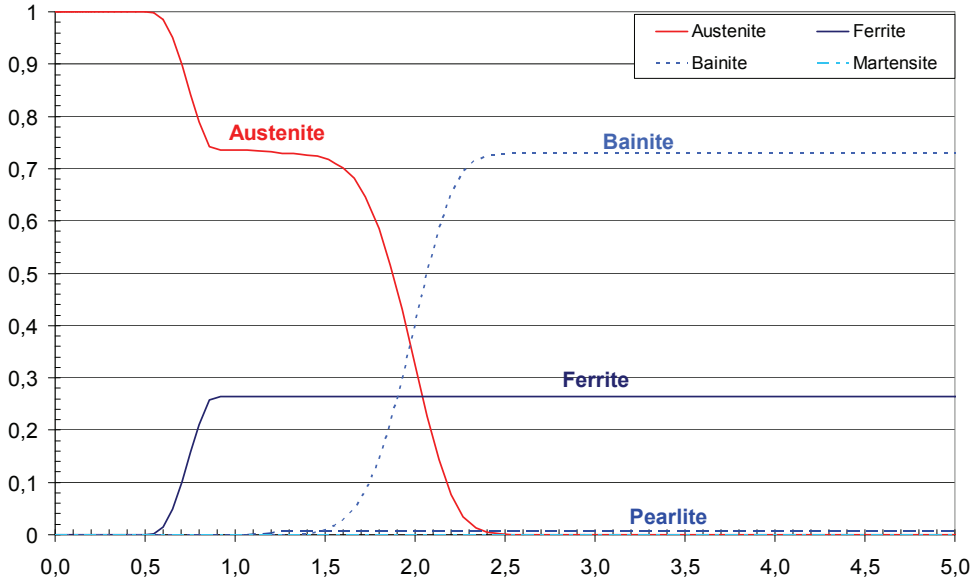


Fig. 6. *Evolution of volume fractions at a material point close to a coil as a function of time during quenching*

5. CONCLUSION

The main issues which arise when dealing with the modelling of an induction heating process have been reviewed. The couplings between multiphysics problems, particularly the electromagnetic couplings are emphasized.

In our opinion, future developments in that field need to be focused on the following topics:

– reducing computational time, through intensive use of parallel strategies, development of more efficient solvers for the linear systems arising from harmonic approximation;
– development of specific optimisation approaches to improve process design;
– advanced metallurgical models for non equilibrium phase change kinetics, and integration of other major evolutions related to chemical diffusions, grain growth and tempering.

One should also stress the need for efficient experimental and analysis protocols to obtain all material and physical parameters which are used in the different models. The lack of material data remains one important limitation for the widespread use of such numerical models to optimize industrial applications.

REFERENCES

Aliaga, C., 2000, *Simulation numérique par éléments finis en 3D du comportement thermomécanique au cours du traitement thermique d'aciers: application à la trempe de pièces forgées ou coulées,* PhD Thesis, ENSMP.

Avrami, M., 1939, Kinetics of phase change I: general theory, *J. Chem. Phys*., 7, 1103-1112.

Avrami, M., 1940, Kinetics of phase change II: transformation-time relations for random distribution nuclei, *J. Chem. Phys*., 8, 212-224.

Avrami, M., 1941, Kinetics of phase change III: Granulation, phase change and microstructure, *J. Chem. Phys*., 9, 177-184.

Bay, F., Labbé, V., Favennec, Y., Chenot, J.-L., 2002, A numerical model for induction heating processes coupling electromagnetism and thermomechanics, *International Journal for Numerical Methods in Engineering*, 58, 839-867.

Bossavit, A., 1993, Electromagnétisme en vue de la modélisation, *Mathématiques et applications*, 14, Springer-Verlag, Paris, France.

Chenot, J. L., Bay F., 2005, Modeling of metal forming processes and multi-physics coupling, *COMPLAS VIII*, *International Conference on Computational Plasticity*, Barcelona.

Denis, S., Simon, A., 1986, Discussion on the role of transformation plasticity in the calculation of quench stresses, *Conference proceedings of Int. Conf. Residual Stresses*, Garmish, 1-9.

Gie, H., Sarmant, J. P., 1985, Electromagnétisme, 1-2, *Collection des Sciences Physiques, Technique et Documentation*, Lavoisier.

Johnson, W.A., Mehl, R.F., 1939, Reaction kinetics in processes of nucleation and growth, *Trans AIME,* 135, 416-458.

Koistinen, D.P., Marburger, R.E., 1959, A general equation prescribing extent of the austenite-martensite transformation in pure iron-carbon alloys and plain carbon steels, *Acta Metallurgica*, 7, 59-60.

Nédélec, J. C., 1986, A new family of mixed finite elements in R^3, *Numer. Math.,* 50, 57-81.

Niclas, A., 1998, *Prise en compte des gradients de propriétés liés au traitement thermique dans le dimensionnement des pièces mécaniques*, PhD Thesis, ENSAM Paris.

Rudnev, V., Loveless, D., Cook, R., Black, M., 2003, *Handbook of induction heating*, Marcel Dekker, New York.

WIELOFIZYCZNY MODEL OBRÓBKI CIEPLNEJ Z NAGRZEWANIEM INDUKCYJNYM

Streszczenie

Obróbka cieplna z nagrzewaniem indukcyjnym obejmuje szereg zjawisk fizycznych. W konsekwencji ten proces jest trudny do sterowania i zrozumienia. Przykładowo, przewidywanie i minimalizacja zniekształcenia wyrobu wywołanego nagrzewaniem indukcyjnym wymaga wielu kosztownych prób. Opracowano dedykowane narzędzie numeryczne dla wspomagania projektowania tego typu operacji obróbki cieplnej. Narzędzie opiera się na wielo fizycznym modelu, który łączy równania elektromagnetyczne, transportu ciepła, mechanicznej odpowiedzi materiału i metalurgicznego opisu przemian fazowych. W artykule opisano podstawy modelu. Nacisk położono na ocenę, które mają najistotniejsze znaczenie i powinny być uwzględnione w analizie. Zaprezentowano wyniki symulacji nagrzewania indukcyjnego wału korbowego.

Received: October 11, 2010
Received in a revised form: November 11, 2010
Accepted: November 29, 2010