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# Multiphysical-Multiscale FEM Simulation of Contour Induction Hardening on Aeronautical Gears

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## Abstract

Since many years, induction hardening has been successfully applied for the heat treatment of components, mainly in the aeronautical and automotive sectors, because of its peculiar advantages like high quality and repeatability of process and its easy automation. A multi-scale multiphysical finite element (FE) analysis is presented in this paper for the prediction of microstructural evolution during induction hardening processes. An ad hoc code has been developed in order to calculate the metallurgical phase changes that occur during heating and cooling steps. This routine has been coupled with commercial FEM codes able to solve the coupled electromagnetic and thermal problem that typically describes the induction heating processes. During the heating, the magnetic field generated by the coil induces currents in the workpiece and as consequence the heating of conductive material by Joule effect. In induction hardening of steels, an external layer of the piece is heated up to the austenitization temperature, then it is cooled down to obtain a layer of martensite. In thermo-metallurgical model, material properties depend on the temperature distribution but also on the microstructure since the material is a mixture of different phases. From the solution of the coupled steady-state, at a given frequency, electromagnetic and transient thermal problem, temperature distribution as well as heating and cooling rates are used for the evaluation of the existing metallurgical phases at every time step. The effect of latent heat of solid-solid phase transformations has been also considered. The model developed has been applied on a real complex case, e.g. an aeronautical spur gear, in order to predict the phase transformation during the whole process. The numerical results will be verified through experimental validation.

**Key words :** Induction hardening, Phase transformation, Coupled problems

## Introduction

Heat treatments are used in order to improve the mechanical properties of steel parts. In the case here presented, superficial heat treatments permit to modify only the superficial layer of a work-piece, maintaining unchanged the core of the material. Nowadays Contour Induction Hardening (CIH) process is increasingly applied instead of carburizing process, due to its repeatability and easy automation.

During induction hardening, the magnetic field generated by a coil induces current in the work-piece, which is heated by Joule effect. During the process, solid-solid phase transformations occur in the material. These transformations depend on the thermal history, i.e. on the evolution of temperature distribution during the time.

Due to its multiphysical nature, simulation tools become essential for the prediction of phase transformations.

Many studies have been carried out in the field of heating by induction [1, 2] and for some specific cases of induction hardening [3, 4], but the multiphysical simulation of all the phenomena that occur during the whole process is still an open task.

## Electromagnetic Formulation

The mathematical analysis of coupled electromagnetic and thermal problem has been carried out by solving Maxwell and Fourier equations. The computation of magnetic flux density and induced current density is obtained by solving a time-harmonic eddy-current problem at a prescribed frequency. The numerical solution of the EM problem has been carried out by means of the well-known Magnetic Vector Potential formulation where the Coulomb gauge has been imposed in order to guarantee the uniqueness of magnetic vector potential  $\mathbf{A}$ :

$$\begin{cases} \nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) + \sigma(j\omega \mathbf{A} + \nabla V) = 0 \\ \nabla \cdot \sigma(j\omega \mathbf{A} + \nabla V) = 0 \end{cases}$$

In which  $\sigma$  is the electrical conductivity,  $V$  the electric scalar potential and  $\omega$  the angular frequency.

When the current density distribution is known in the conductive body, the distribution of power densities by Joule effect can be evaluated as follow:

$$w_p = \rho |J|^2 = \rho \omega^2 |A|^2$$

where  $\rho$  is the electrical resistivity.

### Thermo-Metallurgical Formulation

The nodal power densities calculated in the EM step for each time step are used as the internal heat sources in a coupled thermo-metallurgical model.

In the thermo-metallurgical model the material can be described as a mixture of different phases, each one with different physical properties. The global material properties can be estimated through a linear rule of mixture:

$$P(T, \xi_k) = \sum_{k=1}^N P_k(T) \xi_k$$

where  $P_k(T)$  is the value of the physical property, temperature dependent and  $\xi_k$  is the volume fraction of the k-th phase. During phase transformations latent heat is absorbed or released by the body and this effect must be included in the calculations for an accurate estimation of temperature distribution. The temperature distribution within the workpiece is determined by the modified heat conduction equation:

$$\nabla(\lambda \nabla T) + w_p + \sum_{k=1}^N \Delta H_k \frac{d\xi_k}{dt} = \gamma C_p \frac{dT}{dt}$$

where  $\Delta H_k$  is the enthalpy change due to phase transformation.

The thermal exchange by convection and radiation have been taken into account during the heating stage on the external surfaces of contact between the treated body and the air:

$$\Phi(T_S, T_\infty) = h(T_S - T_\infty) + k_B \varepsilon (T_S^4 - T_\infty^4)$$

where  $h$  is the coefficient of heat exchange by convection,  $k_B$  the Stephan-Boltzmann constant and  $\varepsilon$  the emissivity of the surface. During the induction heating process the initial microstructure (generally made of pearlite, ferrite and carbides) changes when austenitization temperatures are reached: below the Ac1 temperature, the microstructure is composed by ferrite and pearlite, between Ac1 and Ac3 it is a mixture of ferrite, pearlite and austenite and above Ac3 the microstructure is typically inhomogeneous austenite. These temperatures are affected by the chemical composition, heating rate and also by microstructure. The kinetics of transformation during high heating rate processes can be calculated through the use of Continuous Heating Transformation (CHT) Diagrams, which provide an indication of the transformation temperatures at different heating rates. In this study, the CHT diagram has been derived from the literature and the austenite transformation kinetic has been treated by using a linear interpolation.

During quenching several types of microstructures are generated by the decomposition of austenite (pearlite, ferrite, bainite and martensite), depending on the cooling rate.

The microstructure can be evaluated starting from the thermal history using Isothermal (IT) diagrams. These diagrams can be drawn through a numerical method developed by Kirkaldy and reviewed by Victor Li [5]. The numerical method is based upon Zener and Hillert formulas which are derived from kinetic-chemical equations. Once the IT diagram has been calculated, an analytical procedure has been developed for the calculation of microstructure evolution during quenching. Considering isothermal conditions, the kinetics of diffusional transformation can be expressed through the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation:

$$\xi_k = 1 - \exp(-b_k t^{n_k})$$

where  $\xi_k$  is the total amount of transformed phase,  $t$  is the time,  $b_k$  and  $n_k$  coefficients directly deduced from IT diagram. Diffusive transformations always require an incubation time before starting and this can be explained through Scheil's additivity rule:

$$S = \sum_{i=1}^n \frac{\Delta t_i}{\tau_s(t_i)} = 1$$

in which  $\tau_s(t_i)$  is the incubation time at a current temperature and  $\Delta t_i$  is the time increment.

Transformation begins when Scheil's sum is equal to unity. During quenching the material is never subjected to isothermal conditions and also sometimes the austenite is not the only metallurgical phase existing in the material. To solve this problem the thermal history during the quenching needs to be discretized into isothermal steps. The effective elapsed time must be corrected, because of the different kinetics of transformation that occur during each step and can be calculated as the sum of the time step and a fictitious time evaluated from the IT diagrams[6]:

$$t_k^* = \left[ \frac{-\ln(-\xi_{k-1})}{b_k} \right]^{\frac{1}{n_k}}$$

where  $\xi_{k-1}$  is the transformed phase in the previous step. Once the fictitious time is known a fictitious volume fraction  $\xi_i^*$  can be calculated through the JMAK equation:

$$\xi_k^* = 1 - \exp[-b_k(t_k^* + \Delta t)^{n_k}]$$

Hence the practical transformed volume fraction is:

$$\xi_k = (\xi_{k-1}^A - \xi_{k-1})\xi_{max}$$

in which  $\xi_{k-1}^A$  and  $\xi_{k-1}$  are respectively the austenite volume fraction and the transformed phase in the previous step and  $\xi_{max}$  is the maximum possible transformed fraction. The equation considers that a part of the whole microstructure may not transform because it has been already transformed or it was not austenitized. This is the case of coexistence of different phases due to a partial austenitization that occurs where Ac3 temperature has not been reached. A different formulation is used to model the martensitic transformation that describes this process as a diffusionless (or displacive) transformation. The martensite volume fraction is generally evaluated through the Koistinen-Marburger (KM) model [7], but it tends to underestimate the transformed part in low-alloy steels. In this model, the martensite volume fraction has been calculated through a semi-empirical model proposed by Lee [8]:

$$\xi_M = \xi_A \cdot \{1 - \exp[-K_{LV}(M_S - T)^{n_{LV}}]\}$$

in which  $\xi_M$  is the total amount of martensite,  $\xi_A$  the volume of parent phase,  $K_{LV}$  and  $n_{LV}$  are two coefficients dependent by the chemical composition

### 3D FEM model and Results

In this study the numerical simulation have been divided in two main steps: the first one is the electromagnetic and thermal coupled calculation solved by means of the commercial FEM software Flux 3D and the second one is a thermo-metallurgical simulation developed in Comsol with ad hoc MATLAB sub-routine for the evaluation phase transformations kinetics.

The developed model has been applied to a 56-teeth, 2.5 mm modulus spur gear made of AISI 4340, a low alloy steel used in the aeronautical sector due to its mechanical properties and high hardenability.

Only a part of the entire geometry of the gear, drawn with CAE packages, has been modeled in order to exploit the symmetries of the model and reduce drastically the number of degrees of freedom of the problem. Current in the coil is generated by the voltage drop assigned between the radial-symmetrical faces of the coil. Non-linear behavior of thermal and magnetic properties of material has been considered. For this specific type of gear, the process starts with a long lasting low-power preheating at MF (10 kHz) followed by 10 second dwell time in order to reach a uniform temperature on the gear tooth (c.a. 280°C). Then, a high-power high-frequency shot (185 kHz – 0.23 s) is applied. The tests have been carried out with an industrial induction hardening machine fed by two IGBT converters (10 kHz – 600 kW and 150-250 kHz - 350 kW). The frequency cannot be tuned because the capacitor bank is not modifiable and, as consequence, resonance frequency depends only upon the inductor-load system. At the end of the high frequency heating stage the gear is moved down in the shower. The spray quenching consists of 30 second of 12% aqueous polyalkylenglycole (PAG) solution. During quenching the Heat Convection Coefficient, which controls the cooling rate, is not constant but varies significantly with the temperature.

The results obtained from the simulation have been validated through experimental tests and compared in Fig.1, in which the martensite distribution along the tooth profile and along the vertical section of the root is shown. These results show a very good accordance between the experiments and numerical models.

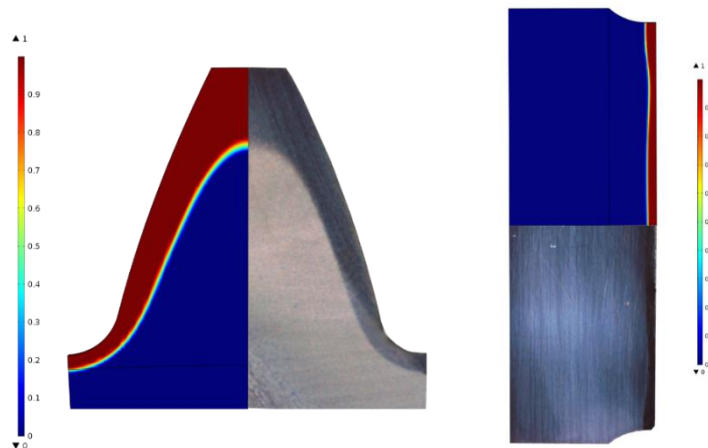


Fig. 1: Comparison between experimental martensite distribution on the top face of the tooth (etching Nital 3%) and the temperature distribution evaluated with the numerical method

### Conclusions

A FEM based mathematical method has been developed in order to predict the phase transformations kinetics during the whole process of induction hardening. In particular:

- A non-linear magnetic behavior has been considered for the given steel, taking into account both magnetic saturation and Curie temperature.
- Both heating and quenching process have been simulated, calculating the complete thermal history and the microstructure at every time step that discretizes the process time.
- Different physical models have been weakly coupled in order to properly take into account the mutual dependences of material properties.

Through experimental procedure on a complex shape geometry the model implemented has been validated, showing a great accordance between the results.

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