Numerical Simulation of Solid-Solid Phase Transformations During Induction Hardening Process

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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.

***Index Terms*—Eddy currents, Materials science and technology, Heat treatment, Numerical simulation**

I. Introduction

HEAT TREATMENTS have traditionally been used in order to improve the mechanical properties of steel parts. During the process, phase transformations occur due to the temperature variations induced by Joule effect or by the cooling shower. Each metallurgical phase has different physical properties and thus, mathematical modeling of phase transformations is necessary to accurately analyze the heating and quenching process.

In this study a model for the evaluation of solid-solid phase transformations during induction hardening has been developed.

II. Computational Model

In this study, numerical simulations have been developed considering two separated steps. In the first one the induced power densities and the temperature field have been calculated with a magneto-thermal simulation using the commercial FEM software Flux 2D. In the second step thermo-metallurgical simulations have been developed in Comsol with user-subroutine written for the description of phase transformations kinetics. The model has been applied to an induction hardening process of an AISI4340 billet, heated by a single turn coil.

A. Electromagnetic-Thermal Formulation

The electromagnetic-thermal coupled problem has been solved by means of vector potential formulation, applied to a 2D-axisymmetric model.

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \vec{A}\right) + \sigma\left(j\omega\vec{A} + \nabla V\right) = 0 \qquad (1)$$

$$w_p = \rho\left|\vec{J}\right|^2 = \rho\omega^2\left|\vec{A}\right|^2 \qquad (2)$$

in which μ is the magnetic permeability, $\vec{A}$ the magnetic vector potential, V is the electric scalar potential and $\vec{J}$ the current density.

Material properties have been considered as temperature dependent and the magnetic permeability is also affected by the magnitude of the magnetic field [1] as described in Table I.

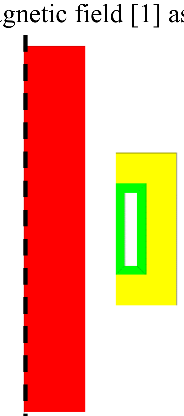

Fig. 1. Geometry of the model. Billet (red), coil (green) and flux concentrator (yellow)

TABLE I
RELATIVE MAGNETIC PERMEABILITY PARAMETERS

Parameter	Value
Initial Permeability	600
Saturation Value	1.8 [T]
Knee adjustment coefficient	0.5
Curie Temperature	785 °C
Temperature Constant	40 °C

B. Phase Transformation Formulation

The temperature distribution within the workpiece can be determined by the heat conduction equation:

$$\nabla(\lambda \nabla T) + w_p + \sum_{k=1}^{N} \Delta H_k \frac{d\xi_k}{dT} = \rho C_p \frac{dT}{dt} \qquad (3)$$

where ΔH_k is the enthalpy change due to phase tranformation, ρ the density and C_p the specific heat, λ the thermal conductivity and w_p the heat sources due to Joule effect.

During phase transformations latent heat is absorbed or released by the body and this effect must be included in the Fourier's equation.

In thermo-metallurgical simulations the material can be seen as a mixture of different phases, each one with different physical properties. The global material's properties can be extimeted through a linear rule of mixture:

$$P(T, \xi_k) = \sum_{k=1}^{N} P_k \xi_k \qquad (4)$$

where P_k is the value of a physical property and ξ_k is the volume fraction of the k-th phase.

During the quenching the steel microstructure changes due to the phase transformations. This type of transformations can be predicted by the use of IT (Isothermal Transormation) Diagrams, that describe the evolution of the microstructure during the time at a fixed temperature. These diagrams can be extimated through a model proposed by Kirkaldy [2] and modified by Victor Li [3].

Considering isothermal conditions the kinetics of diffusional transformation can be expressed through the Johnson-Mehl-Avrami-Kolmogorov (JMAK) Equation:

$$\xi_k = 1 - \exp(-b_k t^{n_k}) \qquad (5)$$

where ξ_k is the total ammount of transformed phase, t is the time, b_k and n_k coefficients directly deduced from IT diagram.

During quenching the material is never in isothermal conditions and also sometimes the austenite is not the only one metallurgical phase existing in the material. The thermal history during the quenching is discretized into isothermal steps. The effective time must be corrected, becouse 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:

$$t = \Delta t_i + \tau = \left(-\frac{\ln\left(1 - \xi_k(t)\right)}{b_k}\right)^{\frac{1}{n_k}} \qquad (6)$$

The JMAK equation is modified as follow:

$$\xi_k = \xi_k^0 + (\xi_k^{max} - \xi_k^0)[1 - \exp(-b_k t^{n_k})] \qquad (7)$$

where ξ_k^0 and ξ_k^{max} are the initial and the maximum volume fraction.

The isothermal transformation law can be applied to non-isothermal case through the use of the Scheil's Additivity Rule:

$$S = \sum_{i=1}^{n} \frac{\Delta t_i}{\tau_s(t_i)} \qquad (8)$$

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

The martensite volume fraction is generally evaluated through the Koistinen-Marburger (KM) model [4], but it tends to underextimate the transformed part in low-alloy steels.

The martensite volume fraction have been calculated through a semi-empirical model proposed by Lee [5]:

$$V_M = V_A \cdot \{1 - \exp[-K_{LV}(M_S - T)^{n_{LV}}]\} \qquad (9)$$

in which V_M is the total ammount of martensite, V_A the volume of parent phase and K_{LV} and n_{LV} are two coefficients dependent by the chemical composition.

III. Results

The test process has been carried out using a single turn coil fed by a current of 4300 A at 10 kHz for 1 s of heating on a simple cylindrical steel billet. At the end of heating, the billet has been quenched for 30 s, simulating the effect of a shower. Convective heat transfer coefficient has been considered as temperature dependent on the boundary surface between air and billet.

In Fig.2 the temperature profile at the end of heating and the volume fraction of martensite at the end of quenching are shown.

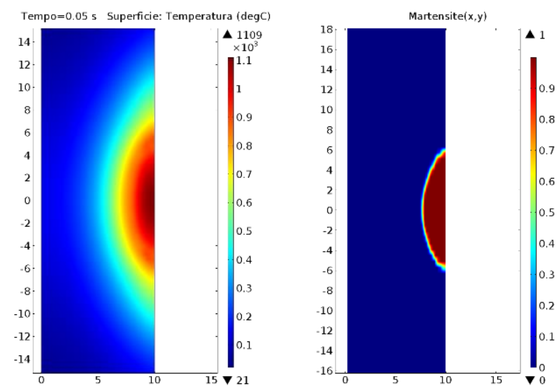

Fig. 2. Temperature distribution at the end of heating (left) and martensite volume fraction at the end of quenching

IV. References

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