ELECTROMAGNETIC PROCESSING OF METAL AS COUPLING OF MULTI-PHYSICS PHENOMENA

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Abstract. Effective numerical models of induction heat treatment are developed. They include two-dimensional modeling of coupling electromagnetic and temperature fields in cylindrical systems for processing of tubes and rolls. Also thermal tension during heating and cooling of tubes and rolls are simulated. These data allow defining structure, hardness, the size of grain and other properties of the tubes and rolls. They allow optimizing design and a choice of equipment, a heat treatment mode for the purpose of achievement of the maximum quality and minimization of energy consumption. The developed two-dimensional models were used not only for the design of induction heat treatment systems of tubes and rolls, but also for a digital control of these complexes.

1 INTRODUCTION

The aim of induction hardening is to increase the hardness of the boundary layers of a workpiece by rapid heating and subsequent quenching. This heat treatment leads to a change in the microstructure, which produces the desired hardening effect.

In the case of induction heating, a current in the induction coil induces eddy currents inside the workpiece. Eddy currents lead to an increase of the temperature in the boundary layers of the workpiece due to Joule and Skin effects. After that the current is switched off and the workpiece is quenched by spray-water cooling.

In spite of the fact that induction hardening has successfully been applied in industry for many years, there is a growing demand in industry for a more precise process control. This circumstance is linked with the growing complexity of the quenched components, reduction of the workpiece thickness due to modern weight requirements, etc. Using of computer simulation is a powerful and necessary approach for solving these problems. From the physical point of view the induction hardening is a very complicated process (Figure 1). We should include all the significant phenomena in the mathematical description to achieve an acceptable calculation result. Moreover, it is very important to understand that all phisical phenomena are linked with each other.

It is obvious that induction hardening mathematical description should include the electromagnetic, thermal and phase transformations phenomena. But the resulting workpiece properties are strongly depend on stress-strain state (residual stress) due to summation stress effect with the external load. Moreover, stress is an additional driving force for the phase transformation (Figure 1). That's why it is desirable to describe this phenomenon too.

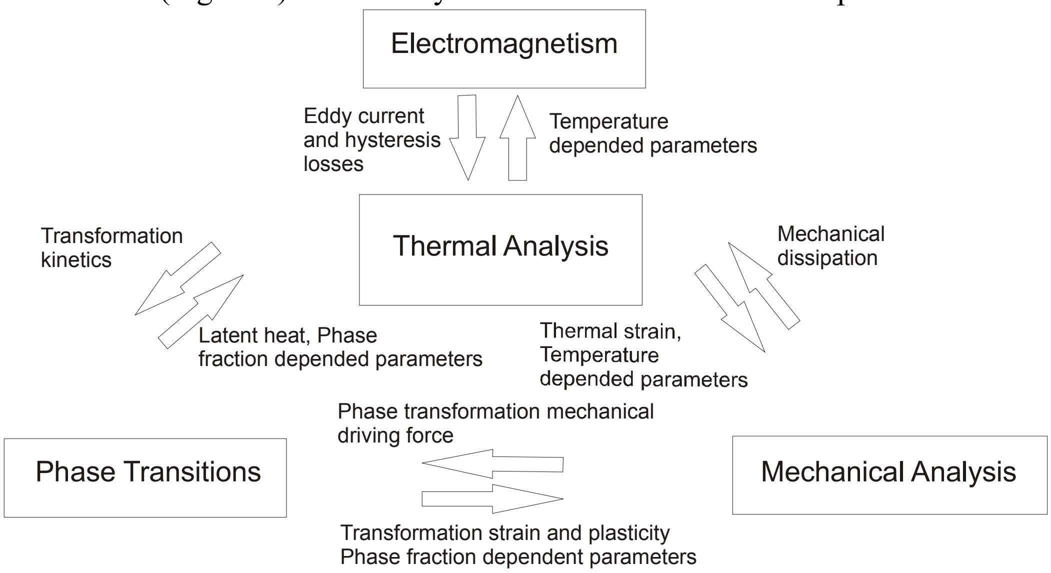


Figure 1. Heat treatment physical phenomena

2 ELECTROMAGNETIC AND THERMAL ANALYSIS

A simulation of the induction heating process includes a computation of electromagnetic and temperature fields. In the case of ferrous steel heating, some features should be taken into account because of very strong non-linearity in the system.

Codes for the simulation of induction heating should provide the capability to solve the tightly coupled (inter-related) computations of electromagnetic and heat transfer phenomena. In order to create this feature, a special computational algorithm has been developed [1]. This algorithm is based on jointly solving a system of two non-linear differential equations, which describe the electromagnetic and temperature fields, and provides a reliable coupling of both phenomena.

Electromagnetic field in the workpiece can be described by the following equation

$$rot(\rho \, rot H) = -\mu\mu_0 \frac{\partial H}{\partial t}, \qquad (1)$$

where:

H is the strength of magnetic field, ρ is the electrical resistivity of metals, μ is the relative magnetic permeability, μ_0 is the permeability of free space. The electrical resistivity of a metal is temperature dependent. In addition, the relative magnetic permeability is a function of two parameters: magnetic field intensity and temperature.

It is important to note that common approach of using the first harmonic for the computation of the electromagnetic field in induction heating systems can result in a low accuracy in the ferrous workpiece heating analysis. For more accurate computations, equation (1) should be used for the simulation of a non-sinusoidal distribution of the electromagnetic field in a workpiece. Very strong dependence of magnetic permeability on temperature is very important for the simulation induction heating.

Accurate data of this dependence are not readily available, though in many cases it could be approximated as follows:

$$\mu(T,H) = 1 + (\mu - 1) \times \left[1 - \left(\frac{T}{T_c} \right)^n \right], \quad T \langle T_c \tag{2}$$

$$\mu(T,H) = 1, \qquad T \geq T_c$$

where:

T_c - temperature of Curie, n - index.

The most reliable data that is supported by experimental investigations correlate with an index n between 4 and 6.

The transient heat transfer process in a steel tubes and rolls can be described by the nonlinear Fourier equation:

$$C_V \frac{\partial T}{\partial t} = div(\lambda gradT) + w, \tag{3}$$

where:

T is the temperature, C_V is the volume specific heat, λ is thermal conductivity of the metal, and w is the heat source density that is generated in the case of induction heating process. The thermal conductivity and specific heat of metal are each functions of temperature.

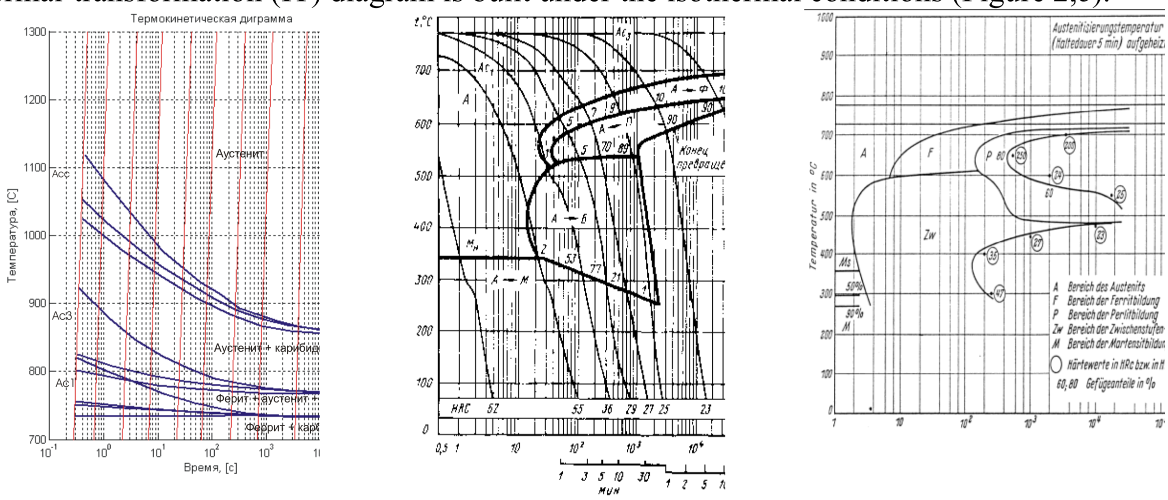
The coupling algorithm jointly solves the system of two non-linear differential equations for the electromagnetic (1) and temperature fields (3) with either the Finite Element Method (FEM) or the Finite Difference Method (FDM). The algorithm calls for an iterative process consisting of an electromagnetic computation and followed by a re-calculation of the heat sources in order to make an updated heat transfer computation. This assumes that temperature variations are not significant in each time step that the material properties remain approximately the same, and the temperature fields can be computed without correcting the heat sources. The temperature distribution within the workpiece, obtained from the time-stepped heat transfer computation, is used to update the values of specific heat and thermal conductivity in each time step. As soon as the heat source variations become significant (due to the variations of electrical conductivity; magnetic permeability, change of the current in the inductors, etc.) the convergence condition will no longer be satisfied and a re-calculation of the electromagnetic field and heat sources will take place.

In general case all the coefficients in (3) are depended on temperature. This circumstance leads to a non-linearity thermal analyses problem which should be solved by using one of the iteration numerical methods.

Moreover, these coefficients are depended on instant phase mixture during the process of heating or cooling of the workpiece. Thus, it is desirable to use the temperature dependencies of the thermal coefficients for all the possible phases in coupling with additivity concept, which allow us to calculate the mean coefficient quantity. The experimental data for the thermal properties of each phase are absent in available reference-literature, but the modern state of computational material science allows us to use specialized for this purposes software like JMatPro [2].

3 PHASE TRANSITIONS

Time-temperature-transformation (TTT) diagrams (Figure 2) are used for the description of experimental research in steel phase transformations. Continuous-cooling-transformation (CCT) diagram is built under the continuous cooling (or heating) conditions (Figure 2,*a*, 2,*b*). Isothermal-transformation (IT) diagram is built under the isothermal conditions (Figure 2,*c*).



a) b) c)

Figure 2. Examples of typical TTT-diagrams

a – CCT diagram of heating; b – CCT digram of cooling; c – IT diagram of cooling

Nowadays the experimental diagrams using is wide spread for the induction heat treatment process analysis and development. Most of the calculation approaches based on the combination of Scheil rule for the continuous conditions analysis and Avrami-type kinetics parametric equation [3]. In this case the model is based on the IT diagrams only. But there are several problems for this approach:

- Scarce phase solubility data – necessity of thermodynamics using for the correct calculation of the ferrite, pearlite transformation. Moreover, the maximum volume fraction of bainite is complicated for calculation [4].
- Lack of the grain size kinetics influence information.

- Absence of the mechanical driving force influence information.
- TTT diagrams do not reflect a simultaneous phase transformation.

Thus, for solving these problems it would be suitable to develop a mathematical model which allows us to calculate of cooling or heating diagram for arbitrary steel, taking into account composition, microstructure and stress-strain station. It is possible to use a modern computational material science for these purposes [5]. These theories based on combination of thermodynamics and kinetics and could be used for the calculation of:

- Incubation time for the certain phase.
- Nucleation rate and the type of grain geometry.
- Growth mechanism and rate.
- Ac3, Ac1, Ms points.

Usually these calculations are used in combination with thermodynamics theory and CALPHAD method [6]. There are several program tools which implements this method (MTDATA, ThermoCalc, etc).

4 MECHANICAL ANALYSIS

It is very important to analyze the residual stress because it is an additional component of loading during the exploitation of the part. Moreover, it is important to evaluate stresses during the induction heating technological process to avoid cracks and large deformations.

The classification of the stresses based on the scale of continuity is shown on Figure 3:

- Stresses of type *I* vary continuously over large distances (σ_{Macro}).
- Type *II* (intergranular stresses) vary over the grain scale (σ_{II}).
- Type *III* – atomic scale (σ_{III}).

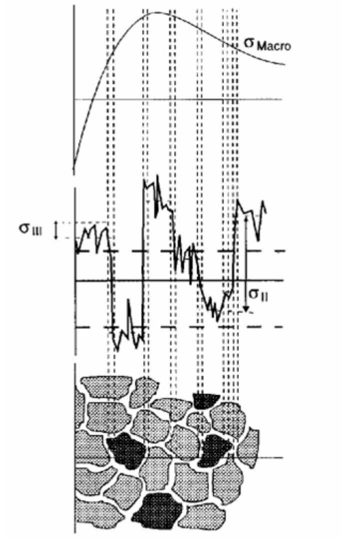


Figure 3. Stress classification

We concentrate on analysis of type *I* stresses because their importance and direct influence on exploitation part properties.

On the other hand the classification based on causes of stress is needed for the development of the valid mathematical model of stress-strain state. This type of classification could be done by the Figure 1. In compliance with it, there are three main sources of the residual stresses:

- Thermal stresses.
- Misfits in different phases density and their thermal expansion coefficients.
- Transformation induced plasticity (TRIP).

All of this sources cause the residual stress. One of the main problems in induction heating simulation by the general-purpose FEM programs is adequately calculation of the residual stress. It is necessary to calculate phase transformation phenomenon for TRIP and phase transformation stresses analysis.

It is obvious that elastic solution of this problem is being of no favor because all of the interesting effects are linked with the plasticity. In case of the plasticity calculation it is necessary to determine the yield criterion. It is good idea to use von Mises criterion for the steels [7]. Besides that, we need to determine the type of hardening. Kinematic hardening is taking place during the cycle loading only. Moreover it is complicated to determine phenomenological coefficients for this type of hardening. We use the isotropic hardening rule.

Thus, we have a mathematical description based on von Mises criterion and isotropic hardening rule. For solving this problem it is possible to use J_2-plasticity model [8]. This algorithm does not require a difference approximation of partial differentials in tangential matrix. This circumstance reduces a computational complexity.

5 CONCLUSIONS

The effectiveness of induction heat treatment computation is related to the numerical methods which are used. In the most practical cases it is impossible to use a “general” method for all the phenomenon description. We have shown that it could be combination based on FEM, thermodynamic analysis, etc. It is convenient and appropriate to use individual approach for all the physical phenomena in induction heat treatment process.

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