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Numerical optimisation for induction heat treatment processes

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A B S T R A C T

This paper aims at introducing new approaches for designing and optimising induction heat treatment processes. Although the final objectives of induction heating processes may deal with some specific mechanical or metallurgical properties for manufactured parts, we shall primarily focus here on achieving an accurate control of temperature distribution and evolution in the Heat Affected Zone (HAZ). This objective can be formalised as a classical optimisation problem: we seek to minimise a cost function which measures the difference between computed and goal temperatures – along with some constraints on process parameters. We deal here with both zero-order algorithms – using a method based on Efficient Global Optimization algorithm which is an optimisation procedure assisted by a meta model – as well as first-order algorithms. These algorithms have been coupled with 2-D and 3-D finite element models developed in our laboratory; this model is based on a coupling procedure between Maxwell equations and heat transfer models, and has been extended to mechanical and metallurgical computations.

1. Introduction

Induction heating processes aim at enforcing some specific properties for heated or heat treated manufactured parts. They have become quite popular these last years in industry – the main reasons for this being their fast heating rate, good reproducibility and low energy consumption [1].

They are however quite difficult to design and control as they involve many coupled multi-physics problems – as shown in Fig. 1.

A global model for such a process thus requires considering electromagnetic, thermal, mechanical and metallurgical phenomena – as well as their mutual interactions during the whole process: heating and quenching.

Energy gets transferred – through electromagnetic means – from a coil through which runs an alternative current to an electrically conductive workpiece. Currents induced in the conductive part then heat the workpiece thanks to the Joule effect. In the manufacturing field, industrial applications range from pre-heating operations – taking place before forming at rather low frequencies (50–5000 Hz) – to heat treatment applications for which frequencies usually range between 10^4 and 10^6 Hz in order to heat locally the surface thanks to the skin effect [2].

Industrial use of induction heating processes aims at achieving various objectives like reaching prescribed temperatures, achieving specific hardness levels, getting a specific metallurgy. Up to now, design and set-up of induction heating processes still relies mostly on trial-and-error procedures.

The aim of this paper is to move forward in the field of numerical design and optimization of induction heating processes – as a numerical optimisation procedure can be a powerful tool for industrial applications.

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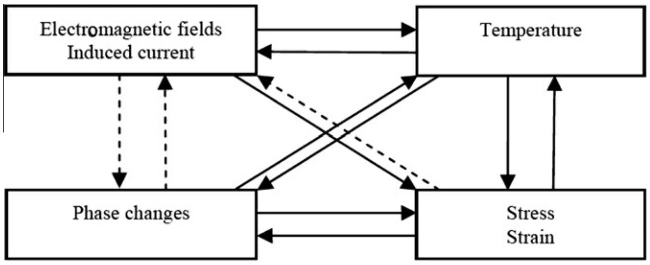

Fig. 1. Coupled physics in quenching after induction heating processes. Dashed lines representing neglected coupling [26,27].

An efficient optimisation approach needs to rely both on:

– an accurate predictive numerical model
– robust optimisation algorithms

These procedures can of course lead to high computational times – incompatible with an industrial use.

We shall thus focus on objectives related to temperature distribution and evolution – either in the global workpiece or in a localised area – most of the time close to the surface when dealing with heat treatment processes.

This implies first the use of direct coupled electromagnetic/heat transfer models. Most models rely either on the finite element method [3–5] or mixed finite element and boundary element approaches [6–8]. In this paper, we shall use 2-D and 3-D models developed in our laboratory [9]; based on a global finite element approach which is better suited for parallel computing and a full time integration approach which is valid when considering linear magnetic materials, but can lead to large errors when dealing with highly ferromagnetic materials [3,10].

Globally speaking, optimisation algorithms may be of two kinds – either zero-order or first-order algorithms. First-order algorithms have proved their efficiency for induction heating processes [11]. However, zero-order algorithms – such as evolution strategy algorithms - are better at reaching global minimal values for cost functions.

Some optimization models [12–14] dealing with coupled magneto-thermal problems can be found in the literature. Models presented in [12,13] use the harmonic approximation and assume electromagnetic and heat conduction problems to be uncoupled. The same approach can also be found in the control of ultrasound surgery [15,16]. In [12], the optimization procedure is based on a zero order method, but the approach used leads to a high computational cost.

In our opinion, efficient optimisation procedures for induction heating will have to rely on the coupling between efficient zero-order approaches and first-order approaches. Zero-order approaches have the main advantage of enabling a global search of optimal parameters non-dependent on a set of initial parameters, while first-order approaches can be used to refine locally the search for optimized parameters once the set of initial parameters has been determined – using a zero-order approach. Furthermore, in order to be efficient, these procedures will have to rely on an efficient direct numerical model.

We shall thus introduce in Section 2 the main features of the direct numerical models we have developed in 2-D and 3-D. Section 3 is devoted to the optimisation problem – minimising a cost function which measures the difference between computed and optimal temperatures – along with some constraints on process parameters – as well as the different optimisation algorithms we have used and developed: on one hand, an approach based on the coupling of a gradient approach with a sensitivity computation through an adjoint approach, and on the other hand a method based on Efficient Global Optimization algorithm developed by Jones which is an optimisation procedure assisted by a meta model. Results will then be presented and discussed in Section 4.

2. The direct numerical model

We introduce here the various equations on which the model relies, as well as the numerical methods used in order to model induction heating processes.

2.1. The electromagnetic model

2.1.1. The Maxwell equations

The electromagnetic model is classically based on the set of Maxwell equations. This system is based on the four following equations:

Magnetic flux equation

$$\vec{\nabla} \cdot \vec{B} = 0. \tag{1}$$

Maxwell–Gauss equation

$$\vec{\nabla} \cdot \vec{E} = 0. \tag{2}$$