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An axisymmetrical non-linear finite element model for induction heating in injection molding tools

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ABSTRACT

To analyze the heating and cooling phase of an induction heated injection molding tool accurately, the temperature dependent magnetic properties, namely the non-linear B-H curves, need to be accounted for in an induction heating simulation. Hence, a finite element model has been developed, including the non-linear temperature dependent magnetic data described by a three-parameter modified Fröhlich equation fitted to the magnetic saturation curve, and solved with an iterative procedure. The numerical calculations are compared with experiments conducted with two types of induction coils, built in to the injection molding tool. The model shows very good agreement with the experimental temperature measurements. It is also shown that the non-linearity can be used without the temperature dependency in some cases, and a proposed method is presented of how to estimate an effective linear permeability to use with simulation codes not able to utilize a non-linear solver.

1. Introduction

Induction heating is well known in processes like surface hardening, annealing, preheating for hot forging of billets as well as melting and welding of metals. In recent years induction heating has been employed for injection molding tools for different reasons. Using a very rapid heating in the cavity surface of the mold is typically desired due to micro- or nanostructures on the surface, the part is long and having thin features, or a good surface finish is required. Since injection pressure levels are decreased with higher mold temperatures, it is also possible to mold large parts on smaller machines than normally if applying induction heating. Another use is to avoid weld lines, hence improving the mechanical properties of injection molded parts. Elevating the mold temperature above the no flow temperature will help ensuring complete filling of the cavity, but will lead to a longer cooling time, hence cycle time, if the mold is heated in a conventional way. Placing an induction coil near the cavity surface can increase the temperature very fast to reach the no flow temperatures, which will prevent the frozen layer to develop during filling.

Induction heating in injection molding is typically based on two different principles either using an external inductor or an internal inductor. The external inductor is typically placed on a moving arm, which heats up the mold surface when the mold is open. The inductor coil can be wrapped around features [1–3], or be a flat coil, not necessarily circular, placed above a flat mold surface with e.g. micro/nano features [4,5]. The internal inductor is integrated in the mold, and different types exist, such as placing a coil with a flux concentrator beneath the mold surface [6].

As mentioned, induction heating for heat treatment, melting and welding of metals has been used for a long time, and also simulation of the induction heating process in those applications has been addressed in the literature; see [7,8] for references. More recently, the topic of simulating induction heating in injection molding tools has been introduced in several papers, which are typically dealing with the simulation of the induction heating itself [1,2,4,5,9–12,6], while the effect of fluid flow is emulated by assuming an equivalent thermal boundary condition [13,14]. In these papers, the magnetic properties are assumed linear, that is a linear relation between the magnetic field and flux. Recently, simulation of coupled induction heating and fluid flow has been conducted [3,15,4], in which the electromagnetic analysis and the mold filling simulation are coupled by imposing either an average constant thermal boundary condition or the actual transient thermal field from the induction simulation to the fluid flow simulation. This is done by mapping the thermal field from the electromagnetic solution to the flow solver to include the effect of the induction heating during filling of the cavity. Imposing the mapped actual transient thermal field was found to give the most realistic results. The work done in Refs. [3,15,4] also assume linear magnetic data, similarly to the previously mentioned papers.

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The magnetic materials that have been used in this work include magnetic tool steels, which had their B-H relation (describing the relation between magnetic flux density, B, and magnetic field, H) and its dependence on temperature (in the range of the injection molding process 25–350 °C) characterized by the authors in [16]. Due to the fact that the magnetic properties depend on temperature, and are non-linear (stemming from magnetic saturation) a lot of data is required to analyze the influence of induction heating applied to injection molding tools. Furthermore, the heat arising from the induction is mainly due to Eddy currents, which can be realistically estimated from the linear magnetic properties (e.g. constant permeability), but since the magnetic permeability is non-linear and temperature dependent, a study on these effects are needed.

In this work a finite element model has been developed with a proposal on how to include the non-linear temperature dependent magnetic data characterized in [16] by using a three-parameter modified Fröhlich equation fitted to the B-H data, and solved with an iterative procedure. The numerical calculations are compared to experiments conducted with two types of induction coils built in to the injection molding tool. A traditional ferrite core with copper windings and a flat core made of Somaloy with copper windings, are investigated.

2. Theoretical background

2.1. Governing equations

The electromagnetic part of induction heating is controlled by Maxwell's equations, which here are presented in terms of free charges and currents:

$$\nabla \cdot \mathbf{D} = \rho_f \quad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (3)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \quad (4)$$

where $\mathbf{D}$ is the electric flux density, $\mathbf{B}$ is the magnetic flux density, $\mathbf{E}$ is the electric field, $\mathbf{H}$ is the magnetic field, $\mathbf{J}_f$ is the free current density, ρ_f is the free charge density, t is the time. Relating $\mathbf{D}$ and $\mathbf{H}$ in terms of $\mathbf{E}$ and $\mathbf{B}$ depends on the material, and for linear media it can be related through the following constitutive relations:

$$\mathbf{D} = \varepsilon \mathbf{E} = \varepsilon_0 \varepsilon_r \mathbf{E} \quad (5)$$

$$\mathbf{H} = \frac{1}{\mu}\mathbf{B} = \frac{1}{\mu_0 \mu_r}\mathbf{B} \quad (6)$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m is the vacuum permittivity, ε_r is the relative permittivity, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum permeability, and μ_r is the relative permeability. Furthermore the current density and electric field can be related by the well-known Ohm's law:

$$\mathbf{J} = \sigma \mathbf{E} \quad (7)$$

where σ is the electrical conductivity. The displacement current, the last term in Eq. (4), will be ignored and the assumption that a time-harmonic varying source current density will result in a sinusoidally varying magnetic field will be made. Combining Maxwell's Eqs. (1)–(4) with the constitutive Eq. (5)–(7), the following complex diffusion equation can be derived:

$$\frac{1}{\mu}\nabla^2 \overline{\mathbf{A}} + i\omega\sigma\overline{\mathbf{A}} = -\overline{\mathbf{J}}_s \quad (8)$$

where $\overline{\mathbf{A}}$ is the magnetic vector potential related to the magnetic flux by $\mathbf{B} = \nabla \times \mathbf{A}$, $\overline{\mathbf{J}}_s$ is the source current density in the coil, $\omega = 2\pi f$ is the angular frequency (and f the frequency), and the overbar is denoting the peak value or the amplitude. From Eq. (8) it is possible to derive certain other quantities, such as the magnetic flux density $\mathbf{B}$ or the magnetic field $\mathbf{H}$, but for the case of induction heating it is the time average Joule heat density that comes from the induced Eddy currents which is of interest and can be derived from Eq. (8) as:

$$\overline{\mathbf{J}}_e = -i\omega\sigma\overline{\mathbf{A}} \quad (9)$$

And the Joule heating is found using Joules law:

$$\dot{Q} = \frac{1}{2\sigma}|\overline{\mathbf{J}}_e|^2 \quad (10)$$

For the calculations of the temperature distribution from the induction, the transient heat conduction equation is solved

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + \dot{Q} \quad (11)$$

where T is the temperature, ρ is the density, c_p is the specific heat capacity, k is the thermal conductivity and $\dot{Q}$ is the heat source from Eq. (10). The thermal conductivity is assumed not to vary as a function of temperature.

2.2. Non-linearity

2.2.1. Fröhlich and the modified representation

The B-H curves (sometimes called anhysteresis curves) express the non-linear behavior of the magnetic material, and they can be used to describe the relation between the magnetic field and the flux density in a material. This relation can be used in an FEM simulation code that assumes the electrical currents and the magnetic fields are varying sinusoidally, hereby using the complex formulation. It can in this respect be convenient to have an analytical expression for the anhysteresis curve, also in connection with iterative methods [17]. Most commonly used is the Fröhlich approximation:

$$B = \frac{H}{\alpha + \beta|H|} \quad (12)$$

where α and β are two material fitted constants (which can be temperature dependent). The equation has two limitations with respect to this work, firstly it does not yield a relative permeability of 1 at high fields, but it rather yields 0, so an extra term $\mu_0 H$ should be added. Furthermore, it does not correctly describe the transition from the high permeability at low magnetic fields to the saturation (the knee area). This can be remedied by adding a term that is proportional to the square root of the magnetic field, so the Fröhlich equation becomes a three-parameter equation [18]:

$$B = \frac{H}{\alpha + \beta|H| + \gamma\sqrt{|H|}} + \mu_0 H \quad (13)$$

The three parameters in the modified Fröhlich equation, can be seen in Figs. 14–21 for all the measured materials from [16]. They all represent the measured B-H curves and have been fitted in a least square sense. The fitting of the modified Fröhlich and the original Fröhlich equations can be seen in Fig. 1, and it shows a better fitting with the modified Fröhlich equation as expected. Further explanation of this is given in Section 3.

A simulation code can then utilize the three parameters of α, β, γ, with a coupling to a heat transfer analysis. In [17] a procedure for utilizing the parameters from the Fröhlich equation was presented. The non-linear material is approximated with a fictitious linear material that has a constant relative permeability, which is unknown, called μ_r^f where f denotes the fictitious material. The linear fictitious material should have the same average heat