Modeling induction heater temperature distribution in polymeric material

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Abstract: An induction heating system has a number of inherent benefits compared to traditional heating systems due to a non-contact heating process. The main interesting area of the induction heating process is the efficiency of the usage of energy, choice of the plate material and different coil configurations based on application. Correctly designed, manufactured and maintained induction coils are critical to the overall efficiency of induction heating solutions. The paper describes how the induction heating system in plastic injection molding is designed. The use of numerical simulation in order to get the optimum design of the induction coil is shown. The purpose of this work is to consider various coil configurations used in the induction heating process, which is widely used in plastic molding. Correctly designed, manufactured and maintained induction coils are critical to the overall efficiency of induction heating solutions. The results of calculation are in the numerical model.

1. Introduction

The induction method of heating is widely used in numerous technological processes for hot forming, surface hardening, annealing, etc. It is extremely effective because of its contactless energy transfer, unlimited power densities and controlled temperature field in the work piece. However, high potential of induction heating can be fully realized on the basis of numerical simulation only.

Induction heating is a part of electromagnetic and thermal physics, which are strongly coupled because of temperature dependent properties of the working material. Induction heating is a process which is used to bond, harden or soften metals or other conductive materials [5]. For many modern manufacturing processes, induction heating offers an attractive combination of speed, consistency and control. The choice of the induction method of heating is determined by such factors as design features of the product and the conditions of its operation, the technological properties of the processed material, as well as a number of economic factors.

2. Optimal coil design for high frequency induction heating

Coil design is one of the most important aspects of an induction system. A heat generation rate in induction heating depends on the several independent parameters such as power
supplied, induction heating time, work piece geometry, material properties, work piece positioning in the coil, coil structure geometry, the number of turnings in the coil, as well as induction power supply frequency (Figure 1).

A well-designed coil maintains the proper heating pattern and maximizes the efficiency of the induction heating power supply. An inductor coil for high frequency induction heating is often referred to as heating coils and it can be made in a large variety of types and styles, which depends on the shape of the polymer surface to be heated.

The shape of the work coil is varied according to the geometry of working surface and the size of the work coil is governed by the length of the work piece. Basic points to consider for efficient working of induction heating process are as follows [6]:

1. The work coil for induction hardening is made in a wide variety of styles, shapes and sizes. Depending upon the natures of the work piece, the styles of the work coil are changed.
2. The inductor coil itself is only a part of the generator output system and success is directly dependent on the proper design of the inductors (work coils).
3. The same principles of design must be applied to the leads, which connect the coil to the output terminals of the generator or remote heating station [7].

The following factors have been considered for construction of the heating coil, required for the induction heating system [8]:

- **Type of wire:** there may be solid wire or multi stranded litz wire. At high frequency, the skin effect loss will be more in case of solid wire. Thus for an energy efficient induction cooker, the heating coil may be made of multi stranded litz wire.

- **Work piece shape:** It governs the important factor for the design of the induction coil because the shape of the induction coil depends on the shape of the work piece.

- **Shape of wire:** It can be round or rectangular cross sectional wire or it may be a foil coil. In a round cross-sectional wire, the current flows uniformly through the whole cross section. But in case of a rectangular or foil coil, current density is more at the corner or edge section.

![Figure 1. Typical arrangement of an induction heating system in a longitudinal flux configuration: (a) general view and (b) top view](image)

Although all induction heating applications share the main fundamental principle, they have differential characteristics that have to be addressed through the technologies involved in each design. Industrial applications require usually higher output powers and higher reliability, constraining the power converter topology selection. Besides, since they have intensive industrial usage, assembly-line readiness and an improved interface and communications are required.
3. Induction heating in plastics production.
Plastic reflow involves using induction heating in processes where plastics change their state from solid to liquid one. One common use for this application is press fitting a metal part into a plastic part. The metal is heated using induction to a temperature greater than that of the plastic reflow. In some cases the metal may be pressed into the plastic before heating occurs; or the metal may be heated before being pressed into the plastic, causing the plastic to reflow as the part is pressed in (also known as heat staking). Induction heating can also be used in plastic injection molding machines. Induction heating improves energy efficiency for injection and extrusion processes. Heat is directly generated in the barrel of the machine, reducing warm-up time and energy consumption. Induction heating provides the precise heat control to ensure a consistent result with high quality results.

The design of the plastic injection molding machine is schematically represented in Figure 2. Polymer materials (7) fall into the plasticizing cylinder (2) from the hopper (3) and are distributed along the length of the screw (6). The engine (1) causes rotation of the auger. The heating barrel and screw is produced with the inductor (4). Then, the polymer material is poured into a mold of the stamping device through the nozzle (5). The control system is implemented using a work station (8) [2].

![Diagram of induction heating system for plastics](image)

Figure 2. Diagram of induction heating system for plastics

For the successful implementation of induction heating, it is necessary to conduct a preliminary study of the processes by the methods of physical and mathematical modeling. To provide a complete picture of the changing nature of distribution density current and power in the plasticizing cylinder and the screw in the heating process and the possibility of the analytical description of the distribution function of the internal heat sources require a consistent solution of the electromagnetic and thermal problems [3]. Therefore, the electromagnetic problem can be formulated as quasi-stationary. All this allows creating a mathematical model partly independent of the procedure for electromagnetic and thermal fields’ calculation. (Figure 3).
Figure 3. Electro-thermal model. 1 – insulation of the coils of the inductor, 2 – the inductor, 3 – the wall of the plasticizing cylinder, 4 – the layer polymeric material, 5 – the screw

These models give a comprehensive characteristic of the induction device from the point of view of energy consumption from an external power source and its release in the download [4].

In figure 3, q1 is the heat flow from the wall of the plasticizing cylinder into the environment. q2 - heat flow from the wall of the plasticizing cylinder in the resin material; q3 is the heat flow from the auger in the polymeric material; h1 is the radius of the auger; h2 – the thickness of the layer of the polymeric material, h3 – the thickness of the wall of the plasticizing cylinder.

In a general case, the induction heating process is described by a nonlinear equation of Maxwell for an electromagnetic field with appropriate boundary conditions [5, 6]. The next step is to develop a mathematical model of thermal processes in a complex, physically heterogeneous medium. The distribution pattern and the density of the power of internal heat sources are defined by the solution of the electromagnetic problem [7].

4. Method of parameters optimization of induction heater

The arrangement of the inductors is an important step during the design phase of an injection mold since it is not possible to make a post correction by the existing mold. Because of the complex thermal processes during the injection cycle, it is a must to use a suitable simulation program for calculating the temperature distribution (heating and cooling phase). Based on the results of the calculation, it is possible to optimize the inductor arrangement and the cooling channel layout, as well as to avoid other failures. [8].

Frequency, except in specified circumstances, determines the choice of the power source and other equipment in the induction heating system, i.e. determines the cost of the entire installation. In this regard, first of all, the frequency can be considered as an optimized parameter. The optimization problem is as follows: for the given geometric parameters and electro physical characteristics of the plasticizing cylinder and the screw, it is required to find the frequency of the power source, which will allow one to engage the screw in the heating process.

In practical situations, the frequency range is specified as a series of discretely spaced intervals, or a set of discrete frequencies, due to the limited capacity of frequency converters [9]. Consequently, the frequency of the current becomes a problem of choosing its optimal value. The optimization criteria is the depth of penetration and the electrical efficiency of the inductor. The frequency in our system was varied in the range of 50 – 10000 Hz. To analyze
the effect of frequency on electrical parameters of the inductor and to choose the optimal parameters, let us use analytical dependences, presented in the monograph [3].

Therefore, the mathematical formulation of the problem is reduced to a system of linear differential equations of transient heat conduction. For a complete physical certainty, the general system of equations is complemented by empirical dependencies of specific heat capacity, viscosity, thermal conductivity, heat transfer and other quantities of temperature.

The calculation of the thermal field is carried out using the finite element method. An analytical solution can be obtained, but subject to considerable simplifications and low accuracy [10]. Calculation of electrothermal models (Figure 3) implemented the finite element method by using packages ELCUT and FEMLAB, which take into account the specifics of the task.

Next step is to define the conditions of heat transfer and heating time. The simulation of the electromagnetic problem (Figures 4-5) demonstrated that heating of the polymer material is maximum at the surface of the cylinder and decreases with the penetration depth.

The calculation results of the electrothermal model indicated the temperature distribution in the polymer material in its section during induction heating, which is shown in Figure 6.

5. Frequency dependence of the material electrical properties
The choice of frequency also depends on the electrical properties of polymer materials and cylinder sizes. The minimum wall thickness is determined by requirements of mechanical strength of the structure, operating at high pressure. Besides, an increase in the wall thickness leads to an increase in weight and size. In this regard, it becomes unnecessary to vary the wall thickness of the tube in order to obtain the desired power distribution. To ensure maximum efficiency is possible by appropriate selection of the frequency of the current of the inductor.
Figure 5. The current density distribution over the cross section

The choice of frequency is quite complicated and depends on the nature of the part and its condition. For bodies of circular cross-section, efficiency usually increases with frequency, tending to the limiting value. For hollow cylinders, there is an optimal frequency at which the efficiency is maximum.

Figure 6. Temperature distribution in the cross section of the polymeric material
Valid area change of the variable parameters is determined by the area of operating frequencies for through-heating of the cylinder wall with predetermined electro-physical characteristics of the material. The dependence of electrical efficiency and power factor on frequency is shown in Figure 7.

![Figure 7. The dependence of $\eta$ and $\cos \varphi$ on frequency](image)

Here one can see that the values of efficiency and the power factor at the frequency of 50 Hz are the most suitable. Therefore, the following energy parameters for the induction system should be selected: frequency $f = 50$ Hz, $\eta = 0.602$, $\cos \varphi = 0.549$.

6. Conclusions

Induction heating is an innovative technology in the field of plastic injection molding. It enables high quality surfaces at low cycle times and saves costs. To tap the full potential of this technology, numerical simulations are necessary in order to get the best inductor shape.

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