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Electrothermal Modelling and Numerical Optimization of Induction System for Disk Heating

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Abstract

Induction heating of the disk shape workpiece is wide spread used in different industrial technologies. Disk shape geometry offers several advantages because of its rotational symmetry. However, uniform heating of disks requires optimal design of the induction coil. The paper presents a modelling concept of the coupled electromagnetic and thermal simulations, which are used for analysis and numerical optimization of the heating systems. Optimization approach, based on genetic algorithms, is applied to reach a uniform steady-state temperature distribution in the disk by parametric optimization of the induction coil shape and its position. Presented examples demonstrate the possibilities of the developed concepts and tools for applied optimization of industrial induction heating systems.

Introduction

A lot of modern technologies require providing different processes running under high temperature conditions. The processes could be oriented to mechanical or metallurgical treatment of products, chemical reactions, crystal growth etc. Induction concept of heating offers many advantages in intensity of the process and its flexibility because of contactless method to transfer the energy. Nevertheless, direct induction heating application is often limited by complicated shape of the workpiece or low electrical conductivity of its material. Indirect induction heating is an alternative approach, which is nowadays applied in many kinds of production lines and installations. In this case the products are put onto the surface of additional body (so called susceptor), which is directly heated by induction. Good thermal contact between the susceptor and the products guaranties effective heating process. Most industrial applications require as uniform as possible temperature distribution in the susceptor or on its surface.

In spite of the fact that the susceptor can be of any shape, the disk body has an advantage because of rotational symmetry. It gives an additional opportunity to equalize the temperature field using rotation of the susceptor. The disk is usually heated by an induction coil of spire shape mounted under the susceptor. In this case the eddy current flow in the disk is of rotational symmetry as well. It is impossible to provide a uniform temperature distribution in the susceptor by optimizing the Joule heat distribution only because the eddy currents have a death point in the centre of the disk. Temperature equalization by thermal conduction is only the process, which can help to overcome this problem.

The temperature distribution in the susceptor, necessary for the technological process, is mainly required in steady-state mode when stable in time temperature field is a result of balance between the Joule heat and the thermal losses from the disk surface. By this reason the heating system should be optimized for the steady-state mode first of all. Taking into account that experimental search for best configuration is extremely time and cost intensive, numerical optimization based on mathematical modeling of the heating process is only the way to successful design of installations.

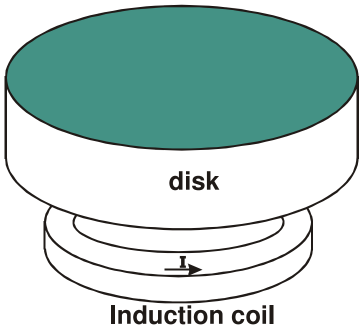

Fig. 1. Schematic view of induction system for the disk heating

1. Induction system for disk heating

Induction system used for the disk heating consists of one or more induction coils and the heated disk as it is schematically shown in Fig. 1. Pancake induction coil of one or several water-cooled windings is located under the susceptor so that the eddy currents are induced in the plan of the disk. Neglecting spire effects of the induction coil, such concept of induction heating provides a rotational symmetry of electromagnetic as well as thermal processes in the system. In this case two-dimensional (2D) analysis describes the behaviour of the system in a proper way.

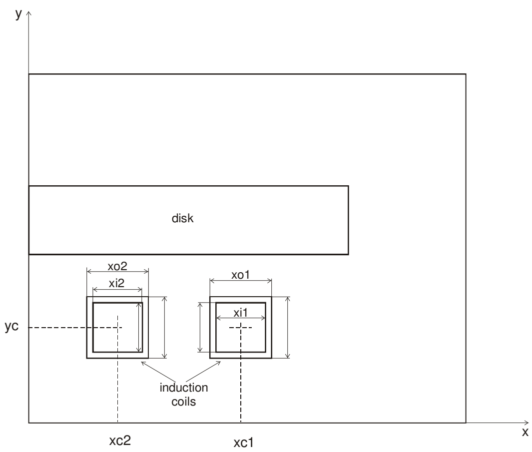

Fig. 2. 2D cross-section of the system

One sketch of 2D cross-section of the disk heating system is shown in Fig. 2. Left border of the system is the axis of rotational symmetry. Massive susceptor is located above the induction coil, which is represented by two windings made of rectangular shape copper tubes. Geometry and positions of the windings are described by parameters, which can be easy changed during optimization.

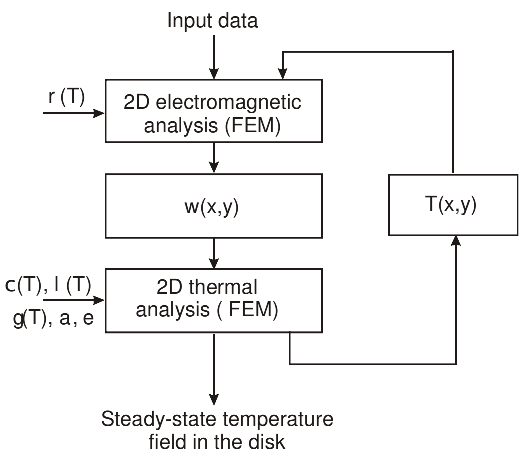

Fig. 3. Structure of the coupled electro-thermal model

2. Numerical model

Mathematical model of the disk heating system has been created for investigation as well as for numerical optimization of the system design. Structure of the model is shown in Fig. 3. Generally induction heating consists of at least two main physical processes, which have to taken into consideration in simulation: electromagnetic and thermal. Electromagnetic field is initiated by high frequency current, loaded to the induction coil. This field penetrates to the susceptor material and induces eddy currents in it. The induced currents generate the Joule heat in the

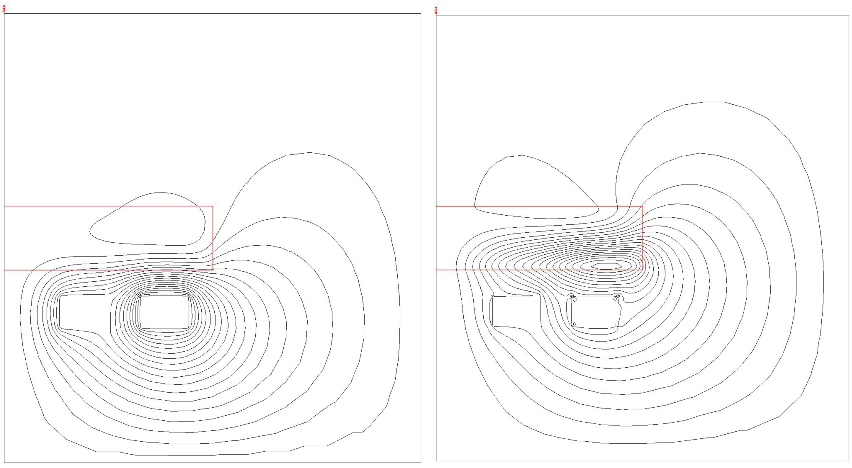

Fig. 4. Real and imaginary magnetic flux lines

susceptor. Distribution of the heat sources depends on applied frequency, electro-physical properties of the susceptor material, geometry of the workpiece and design of the induction coil. Electro-physical properties of conductive materials (like specific resistance) significantly depend on temperature. This dependence has to be taken into account in electromagnetic analysis. The Joule heat, generated by magnetic field, initiates the growing up temperature in the susceptor. However the thermal process also forms temperature distribution in the susceptor by thermal conduction in the workpiece material and thermal losses from its surface. Thermo-physical properties as well as thermal losses depend on temperature also. Well pronounced non-linear behaviour of the simulated system requires organizing a coupled model based on numerical techniques [1]. The Finite Element Model developed in the work has been built using the commercial package ANSYS for both electromagnetic and thermal analysis [2]. Coupling is organized in an iterative loop where the Joule heat from electromagnetic analysis is used for thermal calculation and the received temperature distribution is taken to correct the disk specific resistance for electromagnetic calculation at next iteration. Convergence of the iterative loop depends on the process non-linearity. Typically it is enough to make 4-5 iterations.

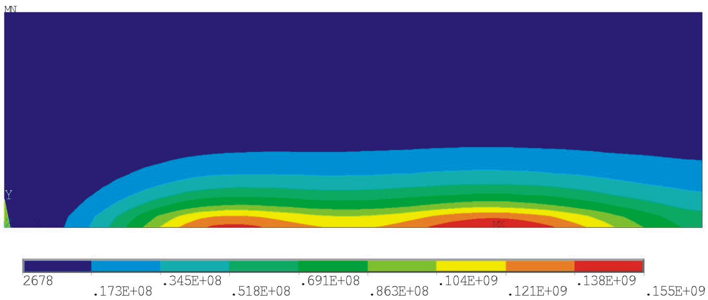

Fig. 5. Joule heat distribution in the disk

Operating of the created model can be demonstrated on one example, where the conductive disk with diameter of 130 mm and height of 20 mm is heated by two windings induction coil with at frequency of 65 kHz. The current value was chosen to provide the average temperature level in the susceptor of 1200 °C.

Electromagnetic coupling of induction coil with the disk is visualized in Fig. 4, where real and imaginary magnetic flux lines are shown. Joule heat distribution in Fig. 5 shows that heat sources

Fig. 6. Temperature field in the disk

are concentrated at the bottom of the susceptor and they have a death zone at the axis of rotational symmetry. Steady-state temperature field (see Fig. 6) is formed by thermal losses from the disk surface. Heat exchange coefficients and reference temperatures for convection and radiation are taken individually for top, bottom and side surfaces of the disk. The values of the coefficients have been calculated extra to guarantee correct heat exchange conditions. In spite of the death zone in the Joule heat distribution at the disk centre, the temperature field has a minimum at the edge of the disk. It shows that the temperature distribution cannot be estimated by heat sources analysis only. Numerical optimization base on the coupled model is the way to design such kind of induction heating system.

3. Numerical optimization technique

Numerical optimization is a process to search a combination of independent variables, which provides a minimum value of the chosen goal function. A lot of different optimization algorithms are known to search the optimum. Experience of the authors shows that genetic algorithms are the most effective tools for optimization of complicated multi-physical systems like induction heating installations. In spite of bigger amount of necessary goal function calculations, they are very robust and stable in search independently on complicated shape of the goal function [3]. A universal library of optimization programs with different amount of independent variables has been created for optimal design of induction systems.

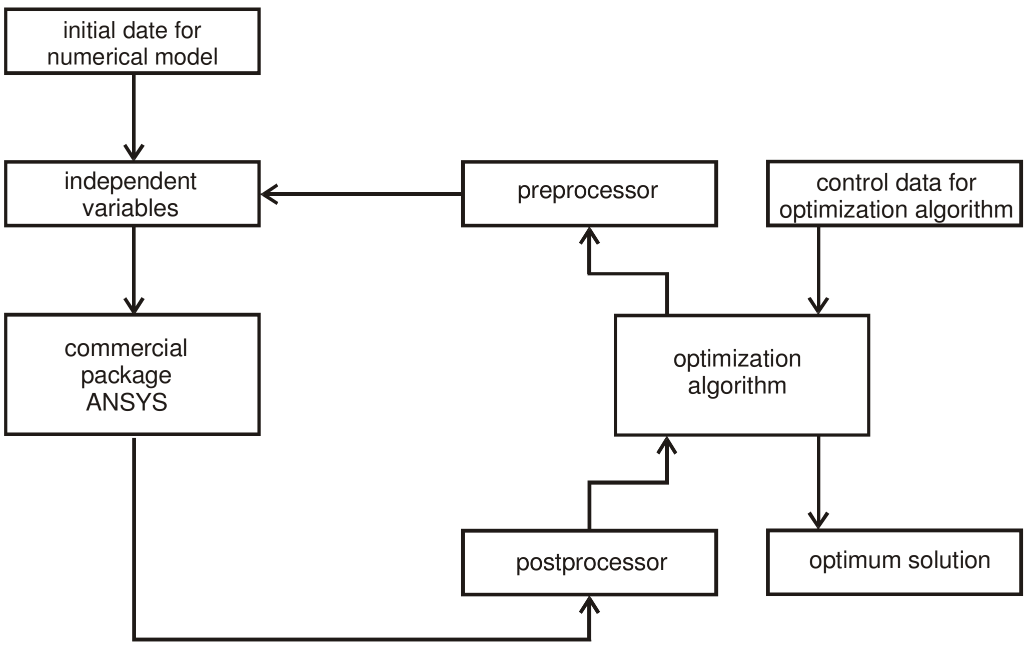

Fig. 7. Structure of the combined optimization procedure

Another important step is to combine the optimisation program with the routine for calculation of goal function. In case of induction heating, the goal function is usually calculated at the end of big program package or even set of different packages. In this case it is impossible to build a complete optimization set as one program. One special approach has been developed to overcome this problem. Optimization search and goal function calculation are running one after another in a loop, where exchange of data is organized via data files (see Fig. 7). Optimization preprocessor transforms the current set of independent variables, created by optimization algorithm, to the input data file for the process model. After the goal function calculation this set of variables is written to the history file together with corresponding value of the goal function. This history file is available for optimization program, which creates a next set of independent variables.

The described approach of optimization together with the coupled electrothermal model of the heating process has been applied for parametrical optimization of induction systems for disk heating.

4. Examples of optimization

First important step to make numerical optimization is to describe the goal function. In case of the disk heating the minimized goal function has been formulated as maximum deviation of temperature in the disk from the prescribed temperature value. The formulation guarantees that the found optimum is all the time located at the required temperature level. To realize this statement, the current of the induction coil must be included to the list of independent variables.

Next step to start optimization is to select the design parameters, which have to be used as independent variables. Geometrical parameters of the induction coil are usually selected for the coil optimal design. Usually they are the size of the induction coil conductor and the position of the coil windings. Field of the search should be defined for each independent variable so that the system geometry will never collapse.

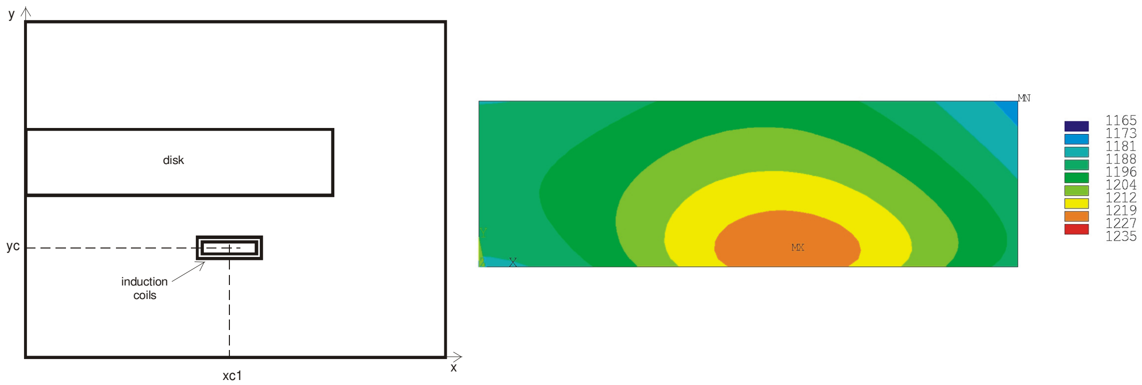

Fig. 8. Single winding induction system and optimal temperature distribution in the disk

First optimization has been done for a system with single winding induction coil (see Fig. 8). Temperature field in the disk is optimized by position of the induction coil winding in both *x* and *y* directions. Induction coil current is included as an independent variable also. The prescribed temperature value of 1200 °C should be reached with minimum deviation. Temperature distribution in the susceptor with the found optimal set of independent variables is presented in Fig. 8 as well. Symmetric deviation of 35 K above and under the prescribed temperature value confirms that the found point is an optimum.

Second example demonstrates the optimization approach for more complicated system consisting of two windings induction coil (see Fig. 9). The windings are connected in series so that they have the same current. Temperature distribution was optimized by the size and the positions of the windings. The optimal temperature field differs qualitatively from previous example. Nevertheless, deviation of temperature from the prescribed value is the same. It shows that in this case the two winding induction coil has no advantages against the single winding coil.

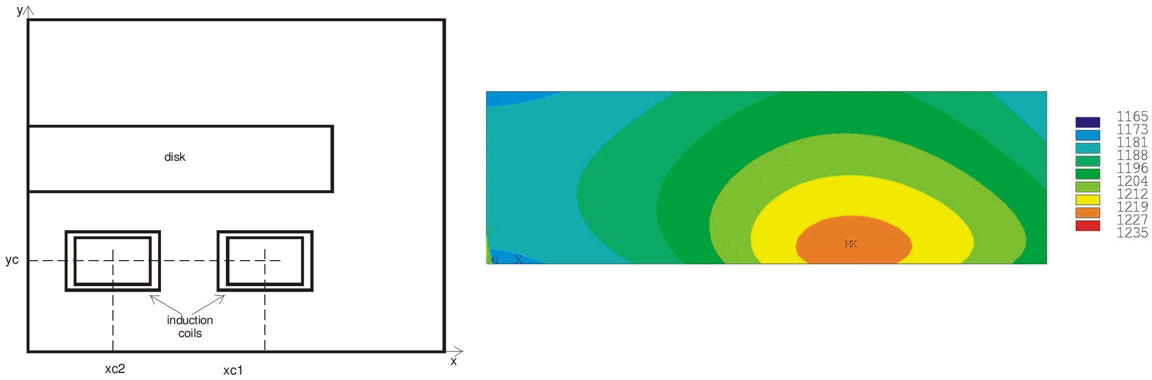

Fig. 9. Two winding induction system and optimal temperature distribution in the disk

The developed concept for numerical modelling and optimization of induction systems for disk heating have been successfully applied for industrial design of optimal induction coils with bigger number of windings for bigger disks. Use of optimal coils improved the temperature uniformity in the susceptor in three times with increasing of the disk lifetime.

Conclusions

One concept of the coupled electromagnetic and thermal modelling of the disk induction heating system is established and can be used for analysis and numerical optimization of the temperature distribution in the disk. The developed process model is combined with optimization search procedure based on genetic algorithm. Two examples demonstrate the results of optimal shape design for different induction coils. The described approach has been successfully used for optimal design of industrial induction coils for bigger disks.

Acknowledgements

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