

Numerical analysis of coupled physics for induction heating of movable workpieces

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Abstract

This paper describes the experience of the authors in numerical modelling of induction heating systems with movable workpieces. Four different numerical approaches have been applied and tested to predict “quasi” steady-state or transient thermal field in the workpieces of different shape and kind of movement. All the approaches have been analysed to prove their advantages and inconveniences to be used in coupled electromagnetic and thermal numerical models of induction heating systems. Each approach is explained by an example from research practice of the authors.

Introduction

Induction method of heating is wide spread 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 workpiece. However, high potential of induction heating can be fully realized on the basis of numerical simulation only. All technological processes used induction method of heating are multiphysical. Heating by induction itself includes electromagnetic and thermal physics, which are strongly coupled because of temperature dependent properties of the workpiece material. That is why all numerical models have iterative or time-step loops where electro- and thermo-physical properties of the heated material are corrected according to actual temperature distribution. In technological processes the induction heating is very often combined with movement of the workpiece. In this case rotation and continuous or step-by-step shifting of the workpiece strongly influence the temperature field. It must be included to the simulation algorithm to provide correct results of modelling.

Basically, movement of the workpiece is of mechanical nature, so it cannot be directly included into electro-thermal analysis used for simulation of induction heating process. This contradiction becomes especially actual, when universal commercial numerical packages are in use.

In most induction heating applications, electromagnetic effect caused because of the workpiece movement plays no role in forming the temperature field. That is why it is normally not necessary to take into account the movement effect in electromagnetic analysis. All approaches to implement the workpiece movement effect, described in the paper, use the thermal analysis.

1. Mass transfer in the thermal analysis directly

The first way to take into consideration the workpiece movement effect is to include the mass transfer component into the thermal analysis directly. It can be applied for induction heating systems with continuous movement of endless workpieces with constant cross-section, which is normal to the direction of the workpiece motion [1]. This approach provides the fastest solution to get so-called “quasi” steady-state temperature distribution in such kind of workpieces.

The mass transfer implementation approach has been applied for numerical modelling of innovative sinter-casting process [2]. A two-dimensional “quasi” steady-state analysis is used to take into consideration the distributed magnetic field created by real induction coil. To avoid any workpiece shape transformations during the simulation, real geometry of bronze was replaced to uniform layer with effective artificial properties. These effective properties must be especially strong temperature dependent to imitate phase transformations in the bronze. Fig. 1 shows the modelling concept for the system with solenoid induction coil to

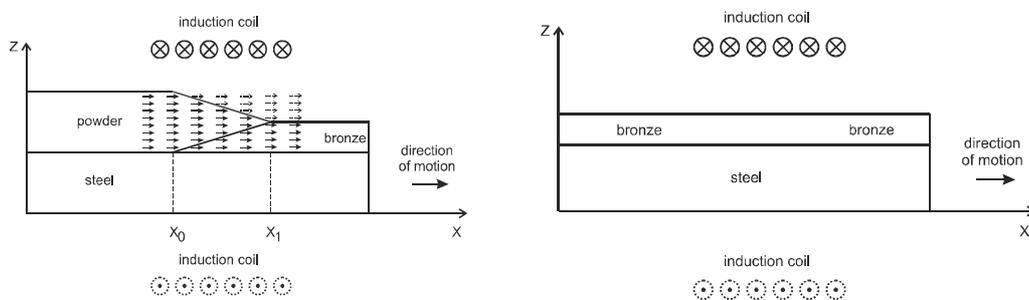


Fig. 1. Real geometry of the multi-layer system and the modelling approach

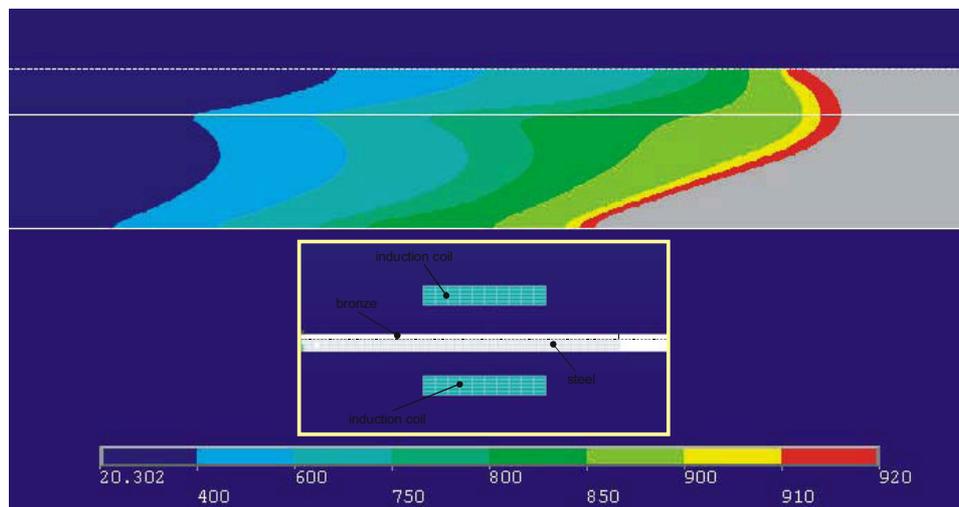


Fig 2. Simulated temperature plot during the sinter-casting process

provide heating in longitudinal magnetic flux from both sides of the workpiece. One example of simulated temperature field in the double-layer workpiece of the sinter-casting system is presented in Fig. 2. Movement of the workpiece, implemented directly as mass transfer, forms the “quasi” steady-state temperature distribution, which was confirmed experimentally.

Nevertheless, two difficulties have been detected using this approach. An iterative loop to correct the temperature dependent material properties is still needed. If the properties depend on temperature very steep, this iterative process is of poor convergence or does not converge at all. The second problem found came from an internal limitation of the commercial package ANSYS used by the authors for this simulation. The ratio between the motion speed and the length of the element in the direction of motion must not exceed a certain value. This limitation allowed modelling the systems with very low speed of the workpiece motion only.

2. External shifting the temperature field

One robust way to implement the workpiece movement is based on shifting the temperature field after each time step outside the thermal analysis.

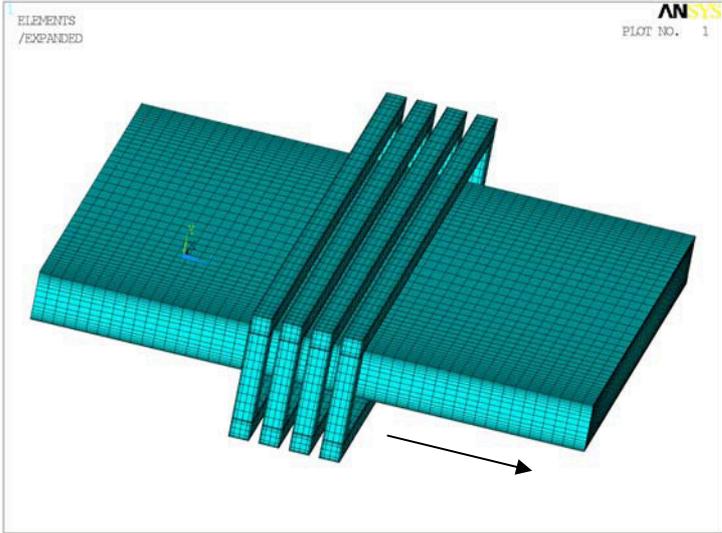


Fig. 3. Numerical system for endless slab heating

“Quasi” steady-state temperature distribution in the workpiece is reached via transient thermal analysis after certain time. This approach can be also applied only for induction heating systems with continuous movement of endless workpieces with constant cross-section normally to the direction of motion. In this case the numerical mesh in the workpiece must be uniform in the direction of motion. Speed of motion is taken into account in the model as the element length divided on

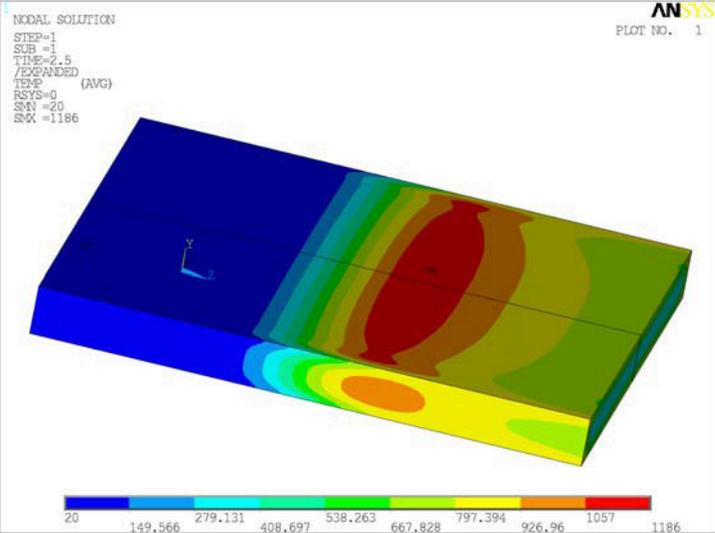


Fig. 4. “Quasi” steady-state temperature field in the steel slab

the chosen time step. The temperature dependent material properties at each time step are corrected according to the temperature distribution in the workpiece at the previous one.

The described approach has been successfully applied to investigate numerically several induction heating systems. One of them is shown in Fig. 3. The endless steel slab is moved through the solenoid induction coil to be heated in longitudinal magnetic flux. Numerical mesh in the slab is uniform in the direction of motion. The result “quasi” steady-state temperature field in the slab (see Fig. 4) is already reached after 35 time steps.

For the tested models the numerical process to reach “quasi” steady-state temperature

field in the workpiece is very robust. Number of necessary time steps does not exceed the number of elements in the direction of the workpiece motion. Computer run time using this approach is comparable with the needed run time in case of direct mass transfer implementation with strong non-linearities.

3. Changing the electromagnetic environment

The described above two approaches to implement the movement of the workpiece to numerical models are valid for simulation of endless workpiece of constant cross-section only. If the workpiece has variable profile or/and it is not endless, changing the electromagnetic environment is the only way to implement the workpiece motion. In this case

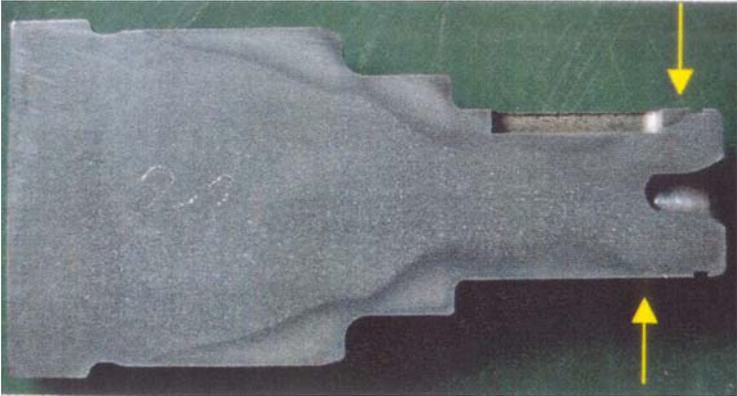


Fig. 5. The steel shaft to be hardened

the thermal process is pure transient without reaching the “quasi” steady-state phase at all. There are no restrictions for numerical mesh in the workpiece using the approach. Time stepping during the heating process can be variable as well. It is the most universal approach and it can be applied for all kind of induction heating systems. However, necessity of changing the system geometry with new numerical meshing increases the

model complexity and the needed run time.

One typical example with changing the electromagnetic environment is simulation of induction heating for hardening of the steel shaft shown in Fig. 5. According to the technology, the single-winding induction coil is moved up during the heating process along

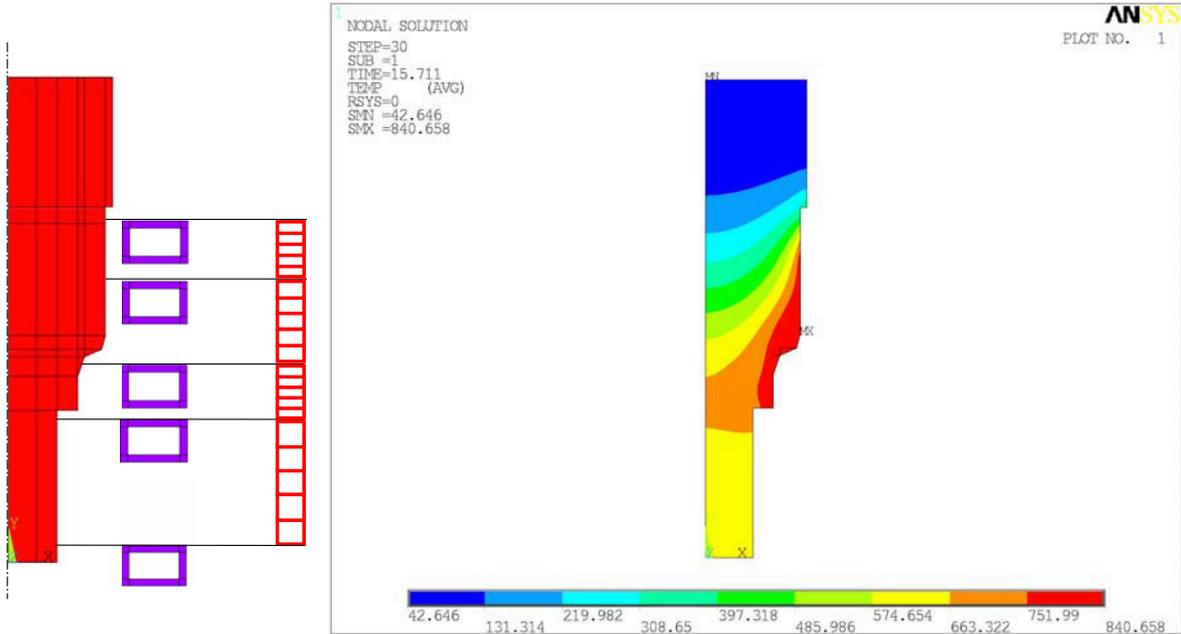


Fig. 6. Configuration of the modelled system (left) and final temperature distribution in the shaft (right)

the vertically positioned shaft as it is shown in Fig. 6 left. Speed of the induction coil motion varies inside the heating cycle. To solve the modelling problem, the electromagnetic analysis has been carried out with new position of the inductor at each time step as well. It required meshing the air between the induction coil and the shaft individually at each time step as well. Numerical mesh in the shaft and in the coil was used without any changes. The numerically simulated temperature distribution in the shaft at the end of the transient heating process is shown in Fig. 6 right. The hardened profile shown in Fig. 5 is in very good coincidence with the predicted final temperature distribution in the shaft.

4. Imitation of the workpiece rotation by anisotropic thermal conductivity

In contrary to all approaches, described above, in some cases of numerical simulation different artificial imitation of the workpiece motion can be very effective. The simulation of the induction heating system for hardening of gear worm [3] can be presented as an impressive example of such artificial approach. It consists of the gear worm and the induction coil with flux concentrator.

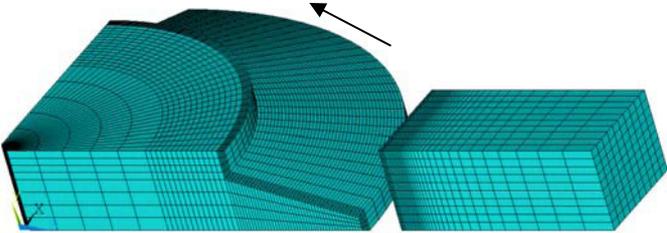


Fig. 7. Numerical model for the gear worm heating system

The induced current in the gear worm flows from gear to gear along the worm axis. To uniform the temperature distribution around the gear, the worm is rotated with relatively high speed. Fig. 7 shows the model of the system, which is by all possible symmetry conditions.

The Joule heat, generated in the gear worm, is concentrated under the inductor only, like it is shown in Fig. 8 left. Thermal unification in the direction of the worm rotation is reached by input of anisotropic thermal conductivity, which is much higher in the direction of rotation. The thermal conductivity in all other directions is real value. The received temperature field in the gear worm at the end of the transient heating is shown in Fig. 8 right. One can observe the temperature distribution, which is absolutely uniform in the direction of rotation. No additional run time is needed to take into account the rotation of the workpiece.

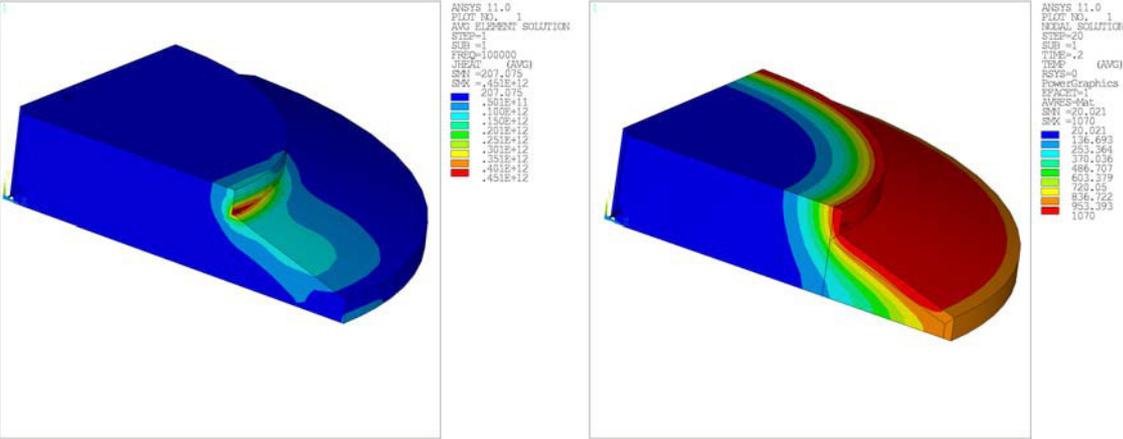


Fig. 8. The Joule heat distribution in the gear worm (left) and the temperature field after imitated rotation (right)

The described approach can be applied when the rotation speed is high enough. At least one cycle of the workpiece rotation should be inside of the simulation time step. This condition is fulfilled in most cases when the temperature unification by rotation is used.

Conclusions

Numerous induction heating applications include the workpiece movement. Numerical simulation of movement effect can be carried out in different ways. Direct mass transfer implementation, external shifting the temperature field, changing the electromagnetic environment approach and imitation of the workpiece rotation by anisotropic thermal conductivity have been successfully tested. Advantages and application areas of each approach have been demonstrated on examples.

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