Modeling of Induction Heating of Steel Billets for DPS Control Design Purposes

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Abstract: This article deals with numerical modeling of modular industrial induction heating of steel billets for hot forming applications using COMSOL Multiphysics. Basic mathematical model based on Finite Element Method is presented. Design of induction heaters is constantly evolving and improving in terms of electrical and thermal efficiency. In recent years there is a trend of modular designed induction heating systems with separated power supply which replaces conventional one coil-one power supply heaters. The primary goal of computer modeling was to investigate the thermal dynamic characteristics in steady-state generated by four-module heater. Obtained results were loaded into MATLAB & Simulink with installed DPS Blockset for purpose of design the progressive control circuit based on distributed parameter systems theory(DPS).

Keywords: induction heating, computer modeling, thermal analysis, DPS control.

1. Introduction

In principle, all real-life systems can be described as distributed parameters systems (DPS) in terms of control, especially heavy industrial devices, such as gas/electrical furnaces, induction heating or continuous casting processes. Simple time-dependent identification may not be sufficient for modern, robust and highly efficient control. Most of the controlled thermal processes are nonlinear, complex and changing in time and space (Hulkó, G. et al., 1998).

Fortunately, for modern design there is no longer necessary to deal with physical identification of process. The computer aided modeling (CAM) software become useful assistant in exploring thermal analysis and dynamics of wide range of applications when using properly. Advanced multi-physical modeling, investigation of time-spatial dynamic characteristics of system and finally the Simulink/DPS Blockset control circuit suited for induction heating are described in this paper.

DPS Blockset Toolbox for MATLAB & Simulink, developed by our institute, is able to virtually control the process of continuous steel casting, the casting form and also the extrusion of plastics (Ondrejkovič, K. et al., 2011), which are properly published. Induction heating of billets for forging industry is result of our searching for new DPS control application in mechanical engineering. It is widely used and therefore there is an ambition to put into practice the distributed parameters based control, well suited for this technology. Also the Roboterm Company – the Czech manufacturer of industrial induction heaters, find our study useful for their products development.

The first step in time-spatial temperature control design based on DPS theory is to obtain dynamic characteristics of the system. In terms of automation, it is a measurement or calculating steady state of the system. In many cases the experimental identification is not realizable because of high dimensionality and complexity of the systems. Physical identification also could be expensive because of financial losses to business resulting from production shut down. Therefore the COMSOL Multiphysics for inspection of dynamic characteristic has been used.

1.1 Induction heating of steel billets

Induction heating is a complicated contactless heating method that combines electrical, magnetic and thermal phenomena. It works on the basis of absorbing energy from magnetic field generated by inductor coil. The heat is generating by eddy currents, which flow through heated billet near its surface and create a Joule heat. Heat intensity and its distribution through the heated billet depend on many factors, such as size and shape of heated material, material properties, current frequency and coil current/power (Rudnev V. et al., 2003, 2010).

The companies offer a portfolio of induction heaters with conventional one-coil design or with modern modular multi-coil concept. The one-coil concept uses one inductor coil with constant current frequency during heating cycle. Optimal frequency and power range are set by operator according to the tables in documentation list and coil power is controlled (or even switched on/off) by PLC depending on measured temperature scanned by pyrometers. Empirical settings of fixed parameters do not correspond with the modern solution of the problem, which shows the latest portfolio of many major companies, such as Inductoheat Inc. They offer modular multi-coil heaters composed of several individually controlled heating modules and each of them can work in wide frequency and power range. It resulted in very efficient heating, accurate temperature profile of heated material and optimal thermal distribution to its core as well. Example of modular multi-coil induction heater by Inductoheat Inc., is shown in Fig.1.

Modular multi-coil concept gives a good opportunity for modern DPS based control design.

Figure 1. Modular concept of induction heater

1.2 Control of Distributed Parameter Systems

In the last decade, great attention has been focused on practical ultilization of theoretical results obtained in the fields of continuous media involving studies of laws of mass movement over complex definition areas. In technical branches it concerns electrotechnics, structural mechanics, acoustic, hydraulics, thermal and nuclear power engineering, automation, biotechnology, etc.

In development of modern technologies, special interest is paid to mass movement control over complex areas as distributed parameter systems (DPS). New approach to modeling, control and design of distributed parameter systems on the basis of lumped-input/distributed-output systems (LDS) was presented to wide engineering community. It is a new idea in control theory, that DPS systems operating in engineering practice can take the structures of LDS systems with proper synthesis (Hulkó, G. et al., 1998).

Distributed parameter systems (DPS) are systems with state/output quantities X(x,t)/Y(x,t) – parameters which are defined as quantity fields or infinite dimensional quantities distributed through geometric space, where x – in general is a vector of the three dimensional Euclidean space. Generally in the control of lumped parameter systems (LPS) the actuator and the controlled plant create a lumped parameter controlled system. In the field of DPS control the actuators together with the controlled plant generally being a distributed-input and distributed-parameter-output system (DDS) create a controlled lumped-input and distributed-parameter-output system (LDS, see Fig. 2).

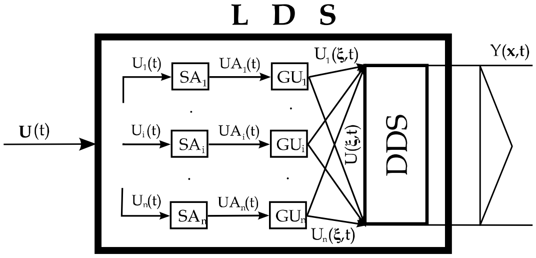

Figure 2. General structure of lumped-input and distributed-parameter-output systems.

LDS	- lumped-input and distributed parameter-output system
$\{SA_i\}_i$	- actuating members of lumped parameter input quantities
$\{GU_i\}_i$	- generators of distributed parameter input quantities
DDS	- distributed-input and distributed parameter-output system
$\mathbf{U}(t) = \{U_i(t)\}_i$	- vector of lumped input quantities of LDS
$\{UA_i(t)\}_i$	- output quantities of lumped parameter actuators

$\{U_i(\xi,t)\}_i$	- distributed parameter output quantities of generators
$U(\xi,t)$	- overall distributed parameter input quantity for DDS
$Y(\mathbf{x},t)=Y(x,y,z,t)$	- distributed parameter output quantity

When distributed quantities are used in discrete form as finite sequences of quantities, the discretization in space domain is usually considered by the computational nodes of the numerical model of the controlled DPS over the complex-shape definition domain in 3D. Schematic of distributed parameter system closed-loop control shows Fig. 4

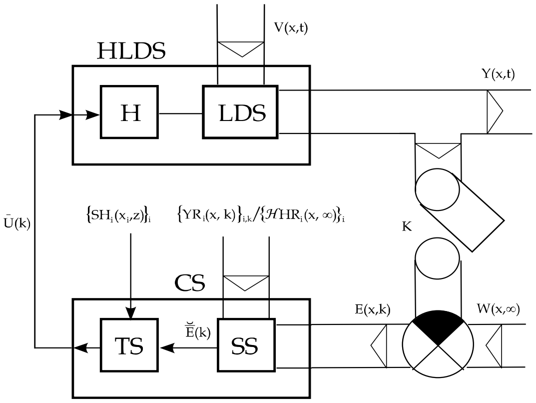

Figure 3. Closed-loop control of a distributed parameter system

HLDS	- LDS - with zero-order hold units
CS	- control synthesis
TS/SS	- time/space control synthesis
K	- time/space sampling
$Y(x,t)/W(x,\infty$	- vector of lumped input quantities of LDS
$\{SH_i(x_i,z)\}_i$	- output quantities of lumped parameter actuators
$\{YR_i(x,k)\}_i$ / $\{\mathcal{H}HR_i(x,\infty)\}_i$	- distributed parameter output quantities of generators
$E(x,k)$	- overall distributed parameter input quantity for DDS
$V(x,t)$	- distributed parameter output quantity
$\breve{E}(k)$	- vector of control errors
$\breve{U}(k)$	- vector of control quantities

. With certain amount of simplification can be said that the main principle of DPS theory in thermal engineering is to investigate both *Time Components of Dynamics* $\{SH_i(x_i,z)\}_i$ (for given i and chosen x_i- variable z) and *Space Components of Dynamics* $\{\mathcal{H}HR_i(x,\infty)\}_i$ (for given i in ∞ – variable x) of the process. These distributions together represents the HLDS dynamics of system in steady-state.

All mathematical descriptions of DPS based control theory is included in DPS Blockset toolbox for MATLAB & Simulink (see <www.dpscontrol.sk> for more information about toolbox and deep theory of DPS) which makes the DPS Blockset a very useful tool for intuitive DPS control design.

2. Modeling of induction heating using COMSOL Multiphysics

At first step, it is necessary to obtain a steady-state temperature profile of billet solved by CAM software using Finite Elment Method. The COMSOL Multiphysics was chosen for this purpose, because of easy implementation of non-linear material properties and very good cooperation with MATLAB & Simulink. The main goal of numerical modeling was to simulate a real application of induction heating in forming technology in purpose of control. Please, note there was no need of absolute precision because of priority of thermal dynamics investigation in steady state.

2.1 Mathematical model description

Magnetic vector potential **A** for axially symmetric cylindrical system can be written as

$$\frac{1}{\mu_0\mu_r}\left(\frac{\partial^2\mathbf{A}}{\partial r^2}+\frac{1}{r}\frac{\partial\mathbf{A}}{\partial r}+\frac{\partial^2\mathbf{A}}{\partial r^2}-\frac{\mathbf{A}}{r^2}\right)=-\mathbf{J}_{source}+i\omega\sigma\mathbf{E}$$

where $\mu_0 = 4\pi\cdot 10^{-7}$ [$\mathrm{H\cdot m^{-1}}$] is permeability of vacuum, μ_r is relative permeability, $J_{source} = -\sigma\nabla\phi$ drive current density in the coil, σ electrical conductivity and $\mathbf{E}$ represents the vector of electric field intensity. Boundary condition is set as a standard Dirichlet boundary condition $\mathbf{A} = 0$, or as a gradient of vector $\mathbf{A}$, which is negligible small in space (Neumann boundary condition *grad***A** = 0). In case of cylinder body heat it is necessary to consider a modified two-dimensional Fourier equation of the heat transfer in axial symmetry form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(T)r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right)=$$
$$= -\,q(T)+c(T)\rho\frac{\partial T}{\partial t}$$

where T is temperature, ρ density of material, c specific heat capacity, λ thermal conductivity coefficient of material and q is the density of heat flow, which is produced by heating of the body due to eddy currents. It should be noted that two variables c and λ are nonlinear functions of temperature dependent and their replacement by a constant value can increase the error of calculation. For most applications in industrial practice, the boundary conditions reflect a heat losses due to convection and radiation. Boundary condition is defined as the relation of

$$-\lambda \,\mathrm{grad}T=\alpha(T-T_0)+k_{SB}\beta(T^4-T_0^4)+q_s$$

where α is a coefficient of heat transfer by convection, $k_{SB} = 5.67\cdot 10^{-8}$ [$\mathrm{W\cdot m^{-2}\cdot K^{-4}}$] is the Stefan-Boltzmann constant, β the emissivity of the material surface and T_0 is the ambient temperature.

2.2 Close look at nonlinear material properties

Material properties of heated steel billets are non-linear temperature dependent, which means they are changing during heating cycle. It is necessary to take it into account in model preparation.

The ability of material to conduct current is specified by electric conductivity σ [$\mathrm{Ohm\cdot m}]^{-1}$. More often it is expressed as reciprocal value to the conductivity, which is called electrical resistivity ρ [Ohm·m]. For most metals, ρ rises with temperature and it affects all important parameters of an induction heating system (heating depth, heat uniformity, coil efficiency, coil impedance).

Relative magnetic permeability μ_r [-] is non dimensional parameter. Relative magnetic permeability μ_r indicates the ability of a metal to conduct the magnetic flux better than a vacuum. It has a great effect on all basic induction heating phenomena and corresponds to the ratio of the magnetic flux density B to magnetic field intensity H (also known as B-H/H-B curve). Based on magnetization ability, all materials can be divided into paramagnetic ($\mu_r > 1$), diamagnetic ($\mu_r < 1$), and ferromagnetic ($\mu_r >> 1$) categories. The temperature at which a ferromagnetic body becomes nonmagnetic is called the Curie temperature T_c ($\mu_r = 1$).

The phenomenon of non uniform current distribution within the billet cross-section is called the „skin effect". The maximum value of current density will be located on the surface of the heated body and the current density will decrease from the body surface toward its center.

In induction heating, all three modes of heat transfer (conduction, convection and radiation) are present. Heat is transferred by conduction from the high temperature regions of the billet toward the low-temperature regions. The basic law that describes heat transfer by conduction is Fourier's law equation, which calculates with thermal conductivity λ [W/(m·°C)]. A material with high λ value will conduct heat faster than a material with low λ value. The thermal conductivity is a nonlinear function of temperature. Heat transfer by convection is carried out by air from the surface of the heated billet to the ambient area. The Newton's law can describe convection heat transfer and calculates with convection surface heat transfer coefficient α [$\mathrm{W/(m^2\cdot °C)}$] which is also temperature dependent. In radiation mode of the heat transfer, the heat may be transferred from the hot billet into surrounding areas. This phenomenon is governed by the Stefan–Boltzmann law of thermal radiation.

2.3 Model preparation

The heating process of large diameter steel billets (above 80mm radius) for forging industry takes about several minutes to achieve an optimal steady state, depending on heated material, production stage cycle and desired temperature profile as well. In our model situation based on real engineering application, the billets are constantly moving through the coil tunnel with velocity of 1cm/s, which means, approximately every 25 seconds the properly heated billet drops out. To simplify a calculation and to reduce solving time, there was considered a moving bar instead of number of separate involving billets. The desired forming temperature of steel billet in the end of inductor should be around 1450K, including the minimal core-to-surface temperature variation. In practice, the forging temperature may vary depending on forming technology and heated material.

The geometry of one copper coil (25x20mm) with 14 turns, kindly provided by Roboterm, represents the one-coil inductor module. It was transformed into 2D axisymmetric space dimension. According to latest trends in multi-coil modular induction heating of billets and DPS control abilities, there is a series of four identical inductor modules. It creates an inductor „tunnel" with total and 55 turns and 3 meters length. Whole indutor is coated by refractory. Fig.4 shows the part of complete model.

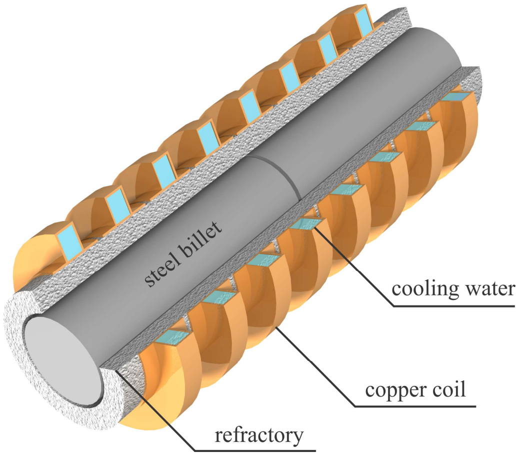

Figure 4. Part detail of complete model

Every module is virtually powered by different currents at the same frequency of 1.5 kHz. The coil currents i_1-i_4 was set to 3.75kA, 3.25kA, 2.5kA and 2kA .

Nonlinear temperature dependency of electrical and thermal steel properties were taken into account and were set up properly as temperature dependent interpolations (Rudnev, V. etal., 2010, Behúlová, M. et al., 2006).

Custom combination of distributed, mapped and free quadratic mesh was applied to achieve good accuracy-to-computing time ratio. Very dense mesh was applied especially to the billet surface and between coils and billet, because of proper calculation of electro-magnetic phenomena.

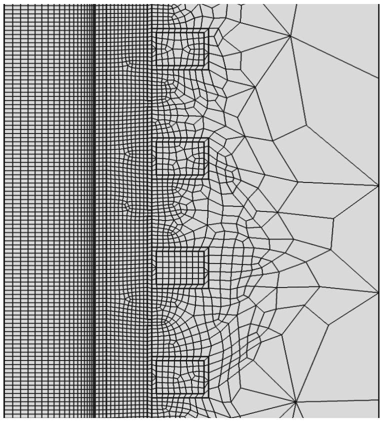

Figure 5. Custom finite element mesh

An induction heating multi-physical module including the translational motion and heat transfer has been used in COMSOL Multiphysics. In this case, the radiation heat-transfer was disabled in this because of very thin layer (about 5mm) of air between billet surface and refractory. The refractory is mainly designed to minimize the heat radiation losses from billets surface, which means, it reflects a significant amount of heat back. The calculation of heat reflections from refractory back to billets surface could be very time consuming.

2.4 Model Solution

Solving time was set up to t=800s , which makes the steady-state clearly visible. The expected forming temperature around 1450K in the end of inductor has been achieved during time of approximately 400s with billet moving velocity of 1cm/s. It meets the requirements of industrial hot forging production. The desired time-dependent temperature distribution in billets through whole inductor length gives a fairly accurate view on induced heat to the surface of billet and to the core as well (see Fig. 6).

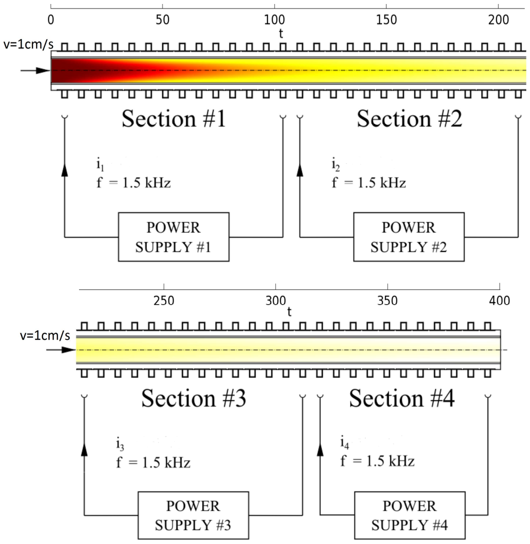

Figure 6. Solved temperature-to-time distribution in billets through whole inductor length

Solved steady state temperature-to-time profile of four-module inductor was measured by 10 virtual probes symmetrically placed on whole length of inductor shown Fig. 7.

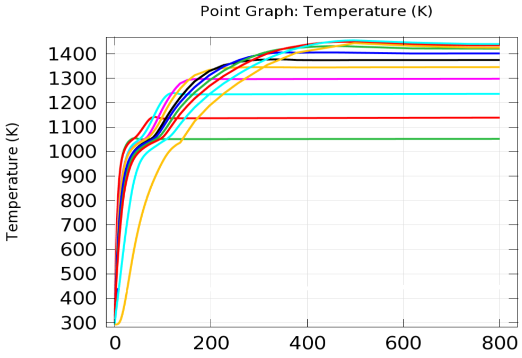

Figure 7. Steady-state temperature-to-time profile

The solved time-spatial distribution of temperature solved by COMSOL, represents both components of dynamics, therefore it was used as steady-state system representation for DPS control circuit design. In other words, in terms of DPS theory, it represents the essential dynamic characteristic of system. It was exported in matrix form from COMSOL and loaded into MATLAB interface for DPS control design purposes.

3. Design of DPS control circuit

According to Fig.3, the DPS control circuit has been designed with DPS Blockset Toolbox components in MATLAB & Simulink interface. Fig. 8 shows a simple DPS Blockset circuit schematic for temperature control of four-module induction heater based on DPS theory.

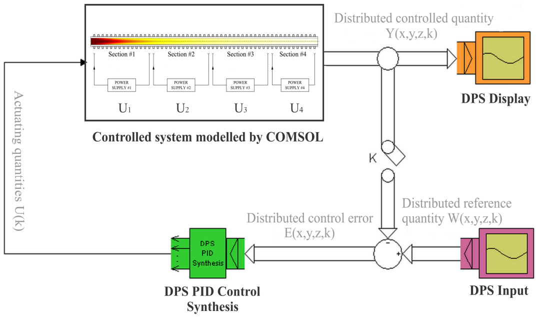

Figure 8. simple schematic of DPS Blockset control circuit

The four coils generate the heat in billet separately, making it a typical lumped-input and distributed-parameter-output system. Dynamic characteristic of the induction heating process has been obtained on numerical model in COMSOL. For our purpose, the steady-state of tinduction heating process has been numerically solved and matrix of dynamic characteristics with both time and spatial components has been imported into control circuit block. In a linearized region around the steady-state let us consider a model situation of a step change – the need to raise the temperature of billets by 30K in full length of inductor in time t=100s. The DPS PID Control Synthesis block operates with properly tuned PI regulator and uploaded dynamic characteristic of model solved by COMSOL, is able to achieve new required time-spatial temperature profile within 400s by changing the actuation quantities U_1-U_4. The U_1-U_4 simply represents the coil currents (see Fig. 9).

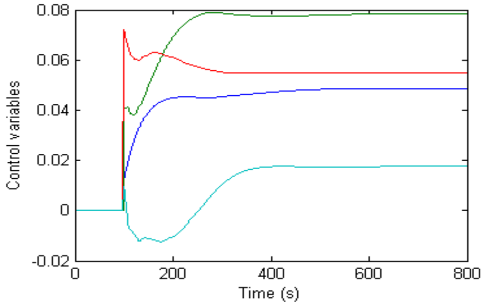

Figure 9. Actuatitions of coil currents

Equally to COMSOL model, ten temperature observation points for monitoring the required temperatures are present. In time t=100s, there is a step change from steady-state to +30K on full length of inductor. Fig. 10 represents the ability of four controlled actuators (coil currents) to achieve required temperature rise.

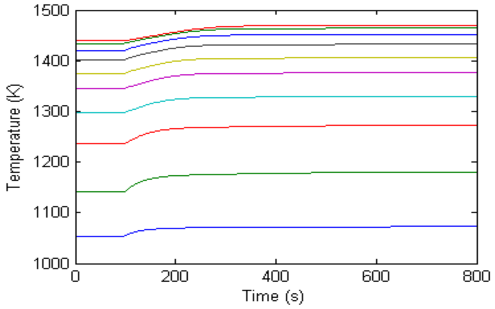

Figure 10. Temperature-to-time profile of controlled system

The final time-spatial temperature distribution profile given by actuating of DPS control circuit illustrates Fig. 11.

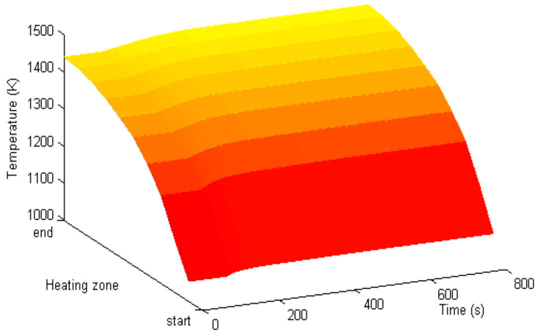

Figure 11. The final time-spatial temperature distribution of controlled system

7. Conclusions

The control of distributed parameter systems on the basis of lumped-input/distributed-output systems (LDS) seems to work properly for multi-coil induction heating processes in off-line mode. There is an ambition to replace the „off-line“ model by on-line thermal models in the near future.

Obtaining the desired dynamic characteristics by COMSOL Multiphysics was very quick, the solving of model takes about one hour on computer based on i5- 2300 equipped with 16GB RAM. Great cooperation and copatibility with MATLAB interface was also very useful.

5. References

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