Optimal programmed control of mass induction heating with guaranteed quality

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***Abstract*— The paper is devoted to the implementation of the optimal programmed control in induction system for steel cylindrical billets heating before hot forming with guaranteed quality. For that purpose the time-optimal control problem with additional restriction on the maximum temperature is formulated for induction heating process and solved using alternance method of parametric opimization. The verified numerical 2D model developed in Altair FLUX® software is integrated in optimization procedure. The obtained optimal control algorithms are approved by experimental results obtained on laboratory setup at ETP (Leibniz Universität Hannover).**

Keywords—induction heating, optimal programmed control, numerical simulation, FLUX, alternance method, restriction, guaranteed quality.

I. INTRODUCTION

Nowadays the traditional and innovative technologies of the metal heating play the vital role in different industrial processes. In the last decades, induction heating installations are wide-spread because of their undeniable advantages, e.g. intensive local heating of the workpiece, effective use in industry, repeatability of the process, high reliability and small operating expenses. Industrial processes of induction through heating of metal billets up to desired temperatures within the whole volume are widely used for heat treatment of the metals before subsequent technological operations such as plastic deformation in forging, pressing and rolling.

The interest in optimization of induction through heating processes is tightly connected with constantly increasing requirements to effectiveness of production processes with guaranteed quality of the end product.

The main goal of the researches is the development, implementation and investigation of the optimal programmed control in induction system that assures the heating of steel cylindrical billets with prescribed accuracy for a minimum time without overheating during the process. For that purpose the time-optimal control problem with additional restriction on the maximum temperature is formulated and solved using alternance method of parametric opimization.

II. TIME-OPTIMAL CONTROL PROBLEM WITH RESTRICTION ON THE MAXIMUM TEMPERATURE OF THE BILLET

The time-optimal control problem for static induction heating of cylindrical billets with additional restriction on the maximum temperature within the billet' volume can be mathematically formulated as follows. It is necessary to obtain such time-dependent optimal control $u_{opt}(t)$ by voltage of power supply limited by the constraint $0 \le u_{opt}(t) \le u_{max}$, which provides transfer of the controlled object, described by the Maxwell-Fourier system of equations (1)-(2), from the initial condition (3) to desired final state (4) for a minimum time when additional constrain on the maximum temperature (5) is satisfied [1].

$$curl\bar{H} = \sigma(T)\bar{E} + \frac{\partial \bar{D}}{\partial t}; curl\bar{E} = -\frac{\partial \bar{B}}{\partial t}; div\bar{B} = 0; div\bar{E} = 0; \quad (1)$$

$$\begin{gathered} c(T)\gamma(T)\frac{\partial T(r,l,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(T) r \frac{\partial T(r,l,t)}{\partial r}\right) + \\ + \frac{\partial}{\partial l}\left(\lambda(T) r \frac{\partial T(r,l,t)}{\partial l}\right) + \frac{1}{\sigma(T)}\left(\frac{\partial H(r,l,t)}{\partial r}\right)^2, \end{gathered} \quad (2)$$

$$T(r,l,t) = T(r,l,0) = T_0(r,l), r \in [0;R]; l \in [0;L]; \quad (3)$$

$$\max_{\substack{r\in[0;R];\\ l\in[0;L];}} \left| T\left(r,l,t^0\right) - T^* \right| \le \varepsilon_0, \quad (4)$$

$$T_{\mathbf{max}}(t) = \max_{\substack{r\in[0;R]\\ l\in[0;L]}} T(r,l,t) \le T_{adm}. \quad (5)$$

Here $\bar{H}$ - vector of magnetic field strength, $\sigma(T)$ - electrical conductivity, T - temperature, $\bar{E}$ - vector of electrical field strength, $\bar{D}$ - vector of electric flux density, t – time, $\bar{B}$ - vector of magnetic flux density, $\gamma(T)$, $c(T)$, $\lambda(T)$ - specific heat, density and thermal conductivity of heated metal respectively, $r \in [0;R]$ and $l \in [0;L]$ - radial and longitudinal coordinates respectively, R – radius of the billet, L – length of the billet, ε_0 - maximal admissible deviation of temperature from the desired value T^*, T_{adm} - maximal admissible temperature value.

The solution of the time-optimal control problem without the restriction on the maximum temperature of the billet has the relay shape [1-2]:

$$u_{opt}(t) = \frac{u_{max}}{2}\left[1 + (-1)^{j+1}\right], \sum_{i=1}^{j-1}\Delta_i < t < \sum_{i=1}^{j}\Delta_i, j = \overline{1,N}, \quad (6)$$

where Δ_i is the duration of the i-th interval of the control algorithm.

It is shown in [1,3] that the additional restriction on the maximum temperature of the workpiece leads to changing the algorithm (6) to the following shape:

$$u_{opt}(t)=\begin{cases} u_{max}, t\in(0,t_1); \\ u^T(t), t\in\left[t_1;\Delta_1^0\right); \\ \dfrac{u_{max}}{2}\left[1+(-1)^{j+1}\right], \Delta_{j-1}^0\le t<\Delta_j^0, j=\overline{2,N} \end{cases} \quad (7)$$

The unknown parameters of the time-optimal control algorithm (7) can be found by solving the system of equations written according alternance method of optimal control theory for systems with distributed parameters. The solution of the system represents the solution of the initial formulated optimal control problem.

III. NUMERICAL SIMULATION OF INDUCTION HEATING PROCESS

The considered induction heating system consists of five-turn inductor and steel cylindrical billet of 100 mm diameter. Temperature is controlled by five thermocouples installed along one cross-section located at the distance of 25 mm from the top of the billet (coordinate 70 via y axis).

The heating system was simulated in finite-element software Altair FLUX® [4]. The developed model was verified by comparing the results of the simulation with results of experiments carried out on the real induction heating installation at ETP (Leibniz Universität Hannover) (Fig.1).

IV. OPTIMAL CONTROL PROBLEM SOLUTION AND EXPERIMENTAL RESULTS

The optimal control problem described in section II was formulated for the cross-section of the billet where the thermocouples were installed. Maximal admissible temperature was set on the value of 530°C.

The optimal control algorithm, obtained by coupling of MATLAB® and FLUX® software [5] can be written as:

$$u_{opt}(t)=\begin{cases} 237V, t\in(0,63.5); \\ 3320e^{-0.0634t}+233.4e^{-0.0065t}, t\in[63.5,183); \\ 0, t\in[183,219.9]. \end{cases} \quad (8)$$

Time-temperature history for optimal control process obtained using FLUX model is shown in fig. 2.The obtained optimal control algorithm was implemented on experimental laboratory setup and approved using temperature measurements by thermocouples during heating process with defined optimal parameters.

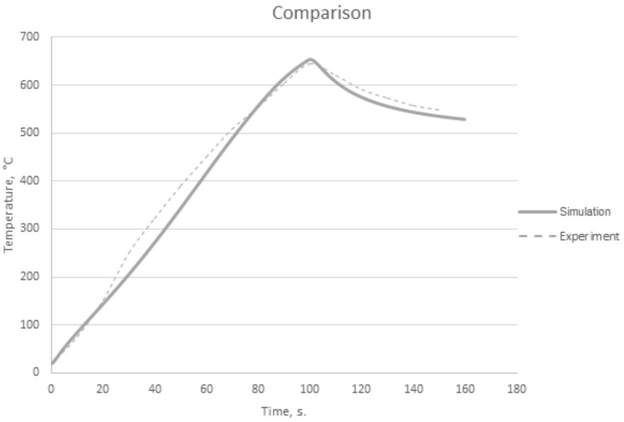

Fig. 1. Verification of the model by test heating during 155 seconds: solid line – FLUX simulation; dotted line – experimental results.

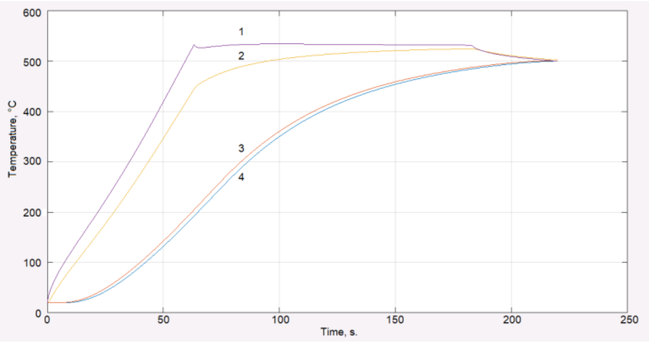

Fig. 2. Results of FLUX simulation - time-temperature history for points of thermocouples installation with coordinates starting from the center of the billet: 1-44 mm, 2-23.34 mm, 3-11 mm, 4-0 mm.

CONCLUSIONS

Time-temperature history obtained by measurements using installed thermocouple during time-optimal control algorithm has confirmed the results of optimal control problem solution. Further analysis and comparison of the FLUX simulation with experimental results lead to the conclusion about quite a good coincidence. The received results also demonstrate that the maximal temperature within the billet volume does not exceed the prescribed admissible level during the whole optimal heating process.

ACKNOWLEDGMENTS

The work is partly supported by Russian Foundation for Basic Researches (project №19-08-00232)».

REFERENCES

[1] E. Rapoport, Yu. Pleshivtseva. Optimal Control of Induction Heating Processes, CRC Press/Taylor & Francis Group, New York, USA.

[2] Yu. Pleshivtseva, A. Popov, A. Diakonov Two-dimensional problem of optimal with respect to typical quality criteria control of through induction heating processes [*Dvumernaya zadacha optimalnogo po tipovim kriteriyam kachestva upravleniya protsessom skvoznogo induktsionnogo nagreva*]. Vestnik of Samara State Technical University. Technical Sciences Series, 2014. №2(42). pp. 148-163.

[3] A. Popov, A. Diakonov Time-optimal control of batch induction heating process with respect to maximum temperature restriction [*Optimalnoe po bistrodejstviyu upravleniye protsessom periodicheskogo induktsionnogo nagreva s uchetom ogranicheniya na maksimalnuyu temperaturu*]. Vestnik of Samara State Technical University. Technical Sciences Series, 2015. №3(47). pp. 56-68.

[4] *Altair FLUX*. URL: http://hyperview.eu/product/Flux (accessed 10.01.2020)

[5] Yu. Pleshivtseva, G. Rogachev, A. Popov "MATLAB-FLUX Coupling for numerical modeling in education". SHS Web of Conferences 29,02033 (2016).