International Scientific Colloquium
**Modelling for Electromagnetic Processing**
Hannover, October 27-29, 2008

# Special Method of Parametric Optimization of Induction Heating Systems

**Yu. Pleshivtseva, E. Rapoport, A. Efimov, B. Nacke, A. Nikanorov**

## Abstract

The paper describes special method of parametric optimization and its application to the solution of practical engineering problems in the field of metal induction heating before hot forming operations. Numerical examples, that help to illustrate the methodology of proposed optimal control techniques, verify their validity and represent descriptions of practical applications.

## Introduction

Optimization methods today enjoy a central role in every branch of engineering due to very strict typical technological requirements to different technological processes and constant increasing the number of such requirements. Optimization was always the goal of any design and control problems [1-3].

Processes of induction heating are a very complicated subject for optimization due to distributed parameters, multiple variables and constraints as well as difficulty in formulation of the goal (cost) function. Final temperature distribution is usually the output control function of the optimization process [4]. On the other hand: electromagnetic processing technologies are very suitable objects for automation and optimization due to their flexibility, controllability, existence of well-known mathematical models, monitoring possibilities and so on. At the same time, modern society would appreciably benefit from optimization of this energy consuming technology.

At the present, analytical theory of optimization of induction heating systems is developed and gives good guidelines for a strategy of optimization. This paper presents special optimal control techniques and illustrates the theory by some examples of optimization in the different fields of induction heating.

## 1. Optimization Strategy

Suggested optimal control technique developed in Samara State Technical University has emerged as one of the most effective methods to improve different technological processes and to solve a wide variety of optimal control problems. Types of the optimization problems include minimization of temperature deviation from the required profile, minimization of energy consumption, heating time, metal loss due to scale formation, etc.

The main goal of presented investigations consists of combination special optimization approaches with advanced mathematical models and application of the developed optimization strategy to the optimal design and control of different induction heating systems.

The need to develop new optimization technology was caused by such circumstance that availability of mathematical models and numerical optimization algorithms (whatever complex and precise they are) may be not sufficient for successful design and modification of complex technological processes. It is important to note that in conformity with practical problems the mechanical combination of mathematical models and standard optimization tools as a rule did not allow to derive practically valuable results.

To create competitive technology it was necessary to integrate the mathematical models with such optimization method that would be able to give an alternating technical solution, which could not be improved regarding to chosen optimization criteria. In this case it is necessary to develop special optimization method, which combines problem-oriented process model with appropriate optimal control tool.

The described optimization technique is based on physical properties of controlled non-stationary heat conductivity processes during induction heating. The method sets universal qualitative features of temperature distribution within the heated workpiece at the end of optimal control processes. These features have a clear physical meaning and are described in many publications [1-3, 5]. Mathematically rigorous proof of these properties is provided in [3].

The fundamental importance of these properties deals with the fact that they can be written in the form of set of equalities closed in the mathematical sense with respect to all optimized parameters of the heating process. In other words, the number of equalities proves to be equal to number of all sought parameters that completely define process under control. This provides potential capability to transform a set of equalities into set of equations that ought to be solved with respect to unknown parameters that leads to the final solution of optimal control problem [1-3].

## 2. Automatic Optimization Complex

With improvement in software and hardware, automatic optimization became a special area of computer simulation and the number of publications in this field increases explosively [4]. Special optimization software is developed in order to provide numerical multi-parameter optimization of design and operational modes of industrial electrothermal installations. Developed optimization tools can be used very efficiently both for optimization of design and for optimal control of induction heating installations.

Automated and user-guided special optimization procedure based on optimal control theory has became an effective alternative to the typical optimization methods. Figure 1 shows a structure of optimization complex that represents effective calculation codes that could be run on personal computers.

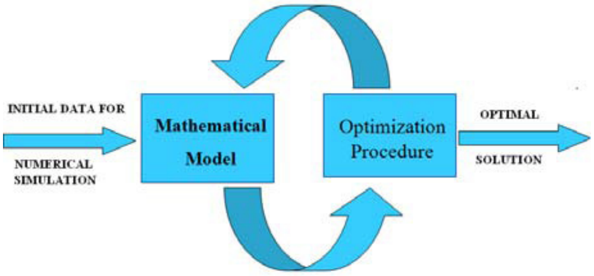

Fig. 1. Structure of optimization complex

Optimization algorithm is oriented on minimization of number of objective function calls because function calls with fixed values of optimized parameters can be extremely computationally expensive. This algorithm of numerical multiparameter optimization is based on general properties of temperature fields, in particular, on the alternance properties of temperature deviations of the final temperature distribution from required one at the end of optimal heating processes. That is why the algorithm allows reaching the extreme value of optimization criteria, i.e. it leads to the absolute optimal solution, which could not be improved regarding to chosen optimization criteria.

Though considered class of optimization problems represents problems of nondifferential optimization, taking into account the alternace properties allows to refuse from traditional approaches to solution of uneven optimization problems, that significantly accelerates process of searching for extreme point during numerical optimization procedure.

Suggested optimization procedure allows also to take into account restrictions imposed on control functions without any additional complications in algorithm.

Due to development of universal user-friendly interface, optimization complex could include different models of heating processes created by different simulation tools.

Implementation of developed algorithm demonstrates enough high rate of convergence, effectiveness and reliability for both test problems and practically oriented applied problems of multiparameter optimization.

## 3. Examples of application

### *3.1. Optimal Design and Control of Induction Heaters for Forging*

Let us consider the problem of optimal control for induction through heating process with continuous movement of billets (Fig. 2). The main typical technological requirement to through heating is to provide a uniform temperature distribution on the level of required outlet temperature. That is why the optimization goal is to minimize the deviation of outlet temperature in cross-section of the billet from the required one.

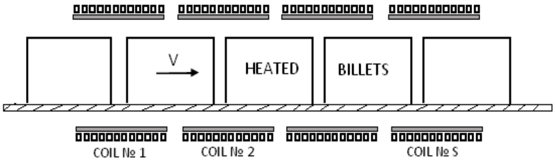

Fig. 2. Induction through heater

In the most typical technological processes admissible deviation $\varepsilon^*$ of temperature from the required outlet temperature is prescribed. It means that at the end of the heater temperature in any point of the billet cross-section should deviate not more than on value $\varepsilon^*$ from required temperature $\theta^*$.

Let us consider one practically oriented example of optimization of continuous heating process controlled by a power supply voltage. If the number of sections *S* and their sizes are defined by the given IHI design, the chosen voltages $U_1, U_2, ..., U_S$ (or appropriate heat powers $u_1, u_2, ..., u_S$) for all *S* coils of induction heater can be considered as control inputs. In this case the typical problem statement for induction through heating optimization can be formulated as a problem of determining optimal coil voltages that provide the most uniform heating.

One industrial continuous heater with ten coils designed for heating of steel billets up to 1250°C has been investigated. All the computations have been done using a complex electrothermal model of temperature distribution within the ferromagnetic billets. This model has been developed at the Institute of Electrotechnology of Leibniz University (Hannover, Germany) [2, 5, 6]. The specialized software package performs electrical calculation of induction heating installation and represents temperature profiles within billet cross-sections that will depend upon coil voltages. The optimal values of coil voltages $U_i^0,\ i = \overline{1,S}$ can be found according to universal technique of alternance method in the typical cases of single-section and two-section heater design ($S = 1$ and $S = 2$) that allows to obtain maximum possible heating accuracy at the level of $\varepsilon_{\min}^{(1)}$ and $\varepsilon_{\min}^{(2)}$ respectively.

All induction heating coils should be grouped and it should be decided how many sections are necessary and how many coils would be located in those sections. Figure 3 shows how a number of inductor coils in the second controlled section ($S = 2$) affects on the minimax value $\varepsilon_{\min}^{(2)}$ and maximum temperature that took place during heating cycle [2, 5].

As one can see, the attainable accuracy of heating does not depend on a number of coils in the second section. At the same time, the maximum temperature surplus as a function of a number of coils in the second section has a well-pronounced minimum. Therefore, the minimum overheat can be reached for the case when 6 inductors are included in the first controlled section and 4 inductors - in the second section. Based on this conclusion, this scenario can be recommended as optimal design solution for multi-coil heater under technological constraint of maximum temperature during heating.

The optimally controlled induction heater of the given design has been investigated for different throughputs. Computations have been conducted for heating of slabs with cross-section 170 mm x 170 mm at a nominal throughput of 7000 кg/h. Figures 4-6 show the optimal coil voltages $U_1^0$ and $U_2^0$, minimax $\varepsilon_{\min}^{(2)}$ and overheat $\theta_{\max} - \theta^*$ as functions of throughput when there are four coils located in the second controlled section.

If billet speed will be varied within a wide range, the maximum temperature deviation $\varepsilon_{\min}^{(2)}$ still does not increase significantly (from 9°C up to 12°C). At the same time, the temperature surplus above the required temperature $\theta_{\max} - \theta^*$ does not exceed 15-40°C that is in a good agreement with technological requirements. The difference $U_1^0 - U_2^0$ tends to zero if throughput of induction heater is 50% of its nominal value, representing the transition to the case of single section under control. Further reducing of throughput down to 30% leads to the sign inversion of the difference $U_1^0 - U_2^0$ because the heater length exceeds minimum length required for heating. Optimal process parameters are not greatly affected by a variety of billet sizes [2].

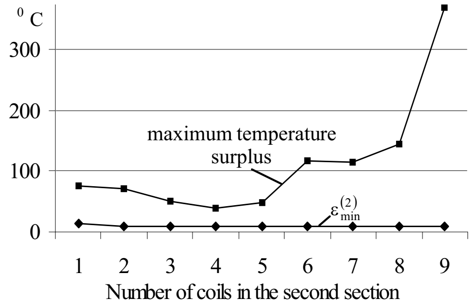

Fig. 3. Heating accuracy $\varepsilon_{\min}^{(2)}$ and overheat for different distribution of coils to sections

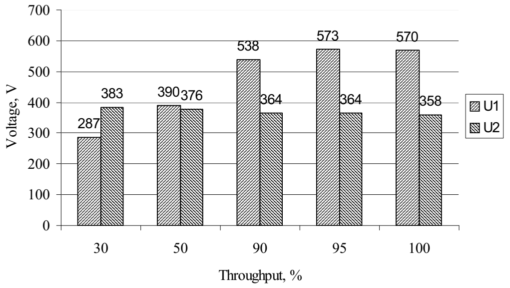

Fig. 4. Optimal voltages $U_1^0$ and $U_2^0$ as function of throughput

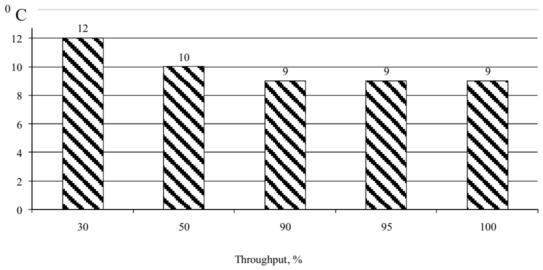

Fig. 5. Minimax value $\varepsilon_{\min}^{(2)}$ as function of throughput

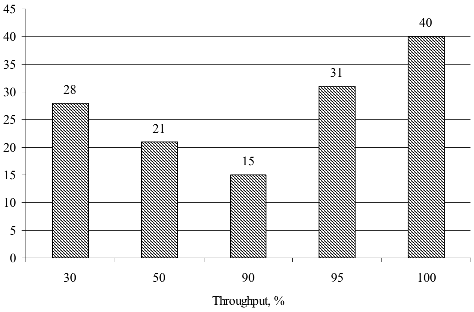

Fig. 6. Maximum temperature surplus $\theta_{\max} - \theta^*$ as function of throughput

### *3.2. Time-optimal Control of Heating of Aluminium Billets Rotating in DC Magnetic Field*

The next example deals with the time-optimal control problem for induction heating of billets rotating in DC magnetic field. The temperature distribution within billet cross-section at the end of heating could be treated as an output controlled function of the process. Variation of rotation frequency over time $f(\tau)$ is chosen from the set of admissible controls to influence temperature distribution and dynamic behavior of induction heating system.

In order to investigate heating process the numerical 2D ANSYS model has been used that allows to simulate the DC magnetic field, the rotating billet inside the field and the generation of eddy currents inside the aluminium billets [7]. The results of modeling represent electric current, heat density and temperature distribution within the billet cross-section.

Induction installation should provide metal billet at the hot working stage with the desired temperature of $500^0$C across its diameter, a temperature deviation of ± $12.5^0$C (± 2.5%) is usually admitted.

When maximum productivity is required, a minimal total heating time $\tau_{end}$ can be considered as a cost function. Then it is required to select such time-dependent control function $f(\tau)=f_{opt}(\tau)$ that provides steering billet' initial temperature distribution to desired temperature $\theta^*$ with prescribed accuracy $\varepsilon^*=12.5^0$C in minimal optimal process time. Frequency of rotation is bounded by maximum and minimum allowable values $f_{max}=50$ rps and $f_{min}=0$.

Let us consider the heating of aluminum cylindrical billets of 0.2 m diameter under 323200 A current of power supply. Common results of one-stage heating process computations are presented in the Table 1. These results show that admissible temperature deviation of $\pm 12.5^0$C (± 2.5%) can be obtained under rotation frequency lower than 16 rps that is sufficiently smaller than $f_{max}$. It leads to significant increase of heating time. The deviation of $41.4^0$C, obtainable under maximum rotation speed, defines non-uniformity of heating, which is typically unacceptable for majority of hot forming applications where usually the higher accuracy is required. Then it is necessary to provide two-stage optimal control, i.e. “heating-temperature soaking” mode. Optimal variation of frequency rotation over time is shown on Figure 7. Heating time under maximum rotation speed is 173 sec, time of temperature smoothing is 11 sec, maximum temperature deviation $\varepsilon^*=12.5^0$C. Final optimal temperature distribution along billet diameter will take a shape shown in Figure 8 [7].

Tab. 1. One-stage heating process

| Frequency of rotation, round per sec | Time of heating, sec | Maximum temperature during heating process, $^0$C |
|---|---|---|
| 8 | 536,137 | 507,834 |
| 16 | 346,964 | 515,357 |
| 25 | 264,18 | 523,056 |
| 35 | 214,849 | 530,966 |
| 50 | 172,229 | 541,402 |

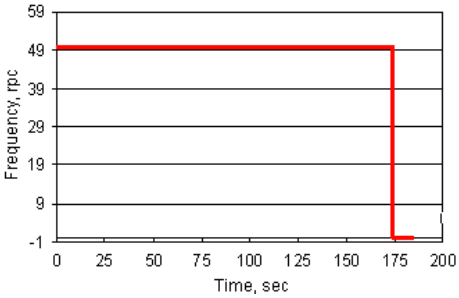

Fig. 7. Two-stage time-optimal control of rotation frequency

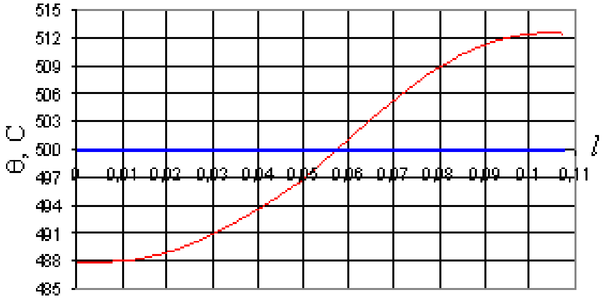

Fig. 8. Temperature radial profile at the end of two-stage time-optimal heating

## Conclusions

In presence new optimal control method and practical application techniques are developed for solving engineering optimization problems. New highly-effective approach for optimization of induction heating processes prior to metal working delivers an essential advantages over presently used classical approaches. Novel optimization technique can be applied not only for induction heating applications but also for optimization of wide range of technological processes. Described technique proves to be efficient for variety of specific mathematical models, different cost functions, control input types, special requirements and restraints of practical technology. The method is based on fundamental properties of temperature distributions of induction heating processes, which remain invariable for the whole gamut of the technological processes. In particular application the use of these properties allows to develop an appropriate set of equations in regard to sought-for parameters of optimal process taking into consideration a specifics of particular physical properties of technological process. Described optimization technique can be applied for similar problems and for problems that remain beyond the bounds of this paper.

## References

[1] Rapoport, E.: *Optimization of induction heating of metal.* Metallurgia**,** Moscow, 1993, 279 pp.

[2] Rapoport, E., Pleshivtseva, Yu.: *Optimal Control of Induction Heating Processes*. DK6039, CRC Press/Taylor & Francis Group, 6000 Broken Sound Parkway, NW Suite, 300. Boca Raton, FL 33487 (USA), 2006, 349 pp.

[3] Rapoport, E.: *Alternance method in applied optimization problems*. Nauka**,** Moscow**,** 2000, 336 pp.

[4] Muehlbauer, A.: *History of Induction Heating & Melting*, Vulkan-Verlag, Essen, 2008, 202 pp.

[5] Pleshivtseva, Yu., Efimov, A., Rapoport, E., Nacke, B., Nikanorov, A.: *Optimal Design and Control of Induction Heaters for Forging Industry*. Proceedings of the International Seminar "Heating by Electromagnetic Sources" HES-07, Padua, Italy, June 19-22, 2007, pp. 251-258.

[6] Boergerding, R., Muehlbauer, A.: *Numerical Calculation of Temperature Distribution and Scale Formation in Induction Heaters for Forging.* Proceedings of the International Seminar on Simulation and Identification of Electroheat Processes, June 17-19, Lodz, Poland, 1997, pp. 134-141.

[7] Pleshivtseva, Yu., Zaikina, N., Nacke, B., Nikanorov, A.: *Time-optimal control of energy-efficient heating of aluminum billets rotating in DC magnetic field.* Proceedings of International Congress of Electricity Applications, Cracow, Poland, May 19-21, 2008 (in print).

## Authors

Dr. Pleshivtseva, Yulia
Faculty of Heat-and-Power Engineering
Samara State Technical University
Molodogvardeyskaya St. 244,
443100 Samara, Russia
E-mail: yulia_pl@mail.ru

Prof. Rapoport, Edgar
Faculty of Automatic and Control in Technical Systems
Samara State Technical University
Molodogvardeyskaya St. 244,
443100 Samara, Russia
E-mail: erapoport@samgtu.ru

Dr.-Ing. Nikanorov, Alexander
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: nikanoro@ewh.uni-hannover.de

Dr. Efimov, Alexander
Faculty of Heat-and-Power Engineering
Samara State Technical University
Molodogvardeyskaya St. 244,
443100 Samara, Russia
E-mail: a_efimov@newmail.ru

Prof.-Dr.-Ing. Nacke, Bernard
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: nacke@ewh.uni-hannover.de