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THE USE OF MULTIFREQUENCY INDUCTION HEATING FOR TEMPERATURE DISTRIBUTION CONTROL

ZASTOSOWANIE WIELOCZĘSTOTLIWOŚCIOWEGO NAGRZEWANIA INDUKCYJNEGO DO STEROWANIA ROZKŁADEM TEMPERATURY

The paper presents possibilities of controlling temperature field distribution in inductively heated charge. The change of its distribution was obtained using the sequential one-, two-, and three-frequency heating. The study was conducted as a multi-variant computer simulation of hard coupled electromagnetic and temperature fields. For the analysis, a professional calculation software package utilizing the finite element method, Flux 3D, was used. The problem of obtaining an appropriate temperature distribution in the heated charge of a complex shape is very important in many practical applications. A typical example is hardening of gear wheels. For such an application, it is necessary to obtain (on the surface and at a desired depth) an uniform temperature distribution on the tooth face, top land and bottom land of the gear. The obtained temperature should have proper distribution and value. Such a distribution is very difficult to achieve.

Keywords: induction heating, computer simulation, electromagnetic field, temperature field

W artykule przedstawiono możliwość kształtowania rozkładu pola temperatury w nagrzewanym indukcyjnie wsadzie. Zmianę rozkładu temperatury uzyskano wykorzystując sekwencyjne nagrzewanie jedno-, dwu- i trój-częstotliwościowe. Badania przeprowadzono jako wielowariantową symulację komputerową silnie sprzężonego ze sobą pola elektromagnetycznego i pola temperatury. Do analizy wykorzystano profesjonalny pakiet obliczeniowy Flux 3D wykorzystujący metodę elementów skończonych. Problem uzyskania odpowiedniego rozkładu temperatury w nagrzewanym wsadzie o złożonej geometrii jest bardzo istotny w wielu zastosowaniach praktycznych. Typowym przykładem jest hartowanie kół zębatych. Dla takiego zastosowania wymagane jest uzyskanie równomiernego na powierzchni i na zadanej głębokości zęba i wrębu rozkładu temperatury o określonej wartości. Uzyskanie tak zdefiniowanego rozkładu jest bardzo trudne.

1. Introduction

Induction heating is a modern, relatively simple technology ensuring a lot of flexibility and a precise control of the spatial temperature distribution within the treated element [1–6]. This method of treatment allows both surface heating for high field frequencies and, hence, low depths of its penetrating as well as volume heating for low frequencies. For some products, especially those of complex geometries, it is necessary to implement both surface and volume heating. A tool for the implementation of such a process can be provided by multi-induction heating [7–9].

In the article, an analysis of the induction heating mechanism for the heat treatment process of the gear wheels is presented.

2. Induction heating

Induction hardening involves two basic steps: rapid heating of the surface to reach the predetermined temperature, and then intensive cooling. Thus, surface hardening requires the use of a heating method that provides high thermal power to the element surface. For this purpose, the most common method is induction hardening, but some other electro-thermal technologies, like laser or electron methods, may also be applied [10].

Selection of parameters for the induction heating process is very important if a good distribution of temperature in the preheated work-piece is to be obtained. Obviously, more complex and complicated objects affect the choice of the proper process and its parameters. Gear hardening processes have been conducted for many years [11–14]. However, although the induction heating process is well described in references and used in many metallurgical technologies, its application for hardening of gear wheels is still rather rare.

Basic parameters of the induction heating are current frequency and duration of heating. They allow controlling the temperature distribution which must be adjusted to the contour of hardness to be finally obtained. In the case of gear wheels, quenching should occur on the surface, involving the side surface and a top and root of the tooth, see Fig. 1 [1].

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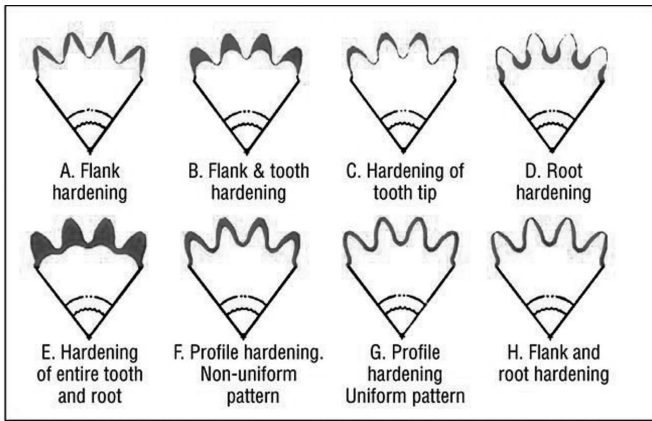
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Fig. 1. Desired temperature distribution

In order to obtain a more uniform temperature distribution on the surface, various procedures are applied [15, 16]. One of them is multi-stage heating using different frequencies of the field current (Fig. 2).
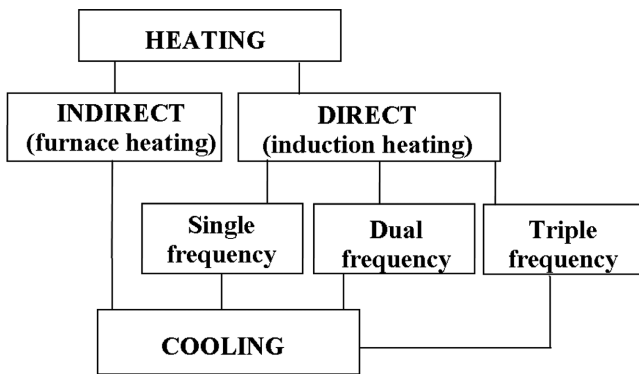

Fig. 2. Schematic diagram of induction hardening

The results presented in the article concern the hardening process for four various configurations (Table 1).

TABLE 1

Calculation variants

No.	Variants
1	Indirect heating in furnace
2	Induction heating – single frequency
3	Induction heating – dual frequency
4	Induction heating – triple frequency

The variants presented in the table above describe typical ways of heating before quenching. They were taken into account for selection of the easiest way to obtain the desired temperature distribution. In the first case, the simplest heating technique is considered, but for surface heating, the furnace chamber temperature should be extremely high (Fig. 3) [17-18].
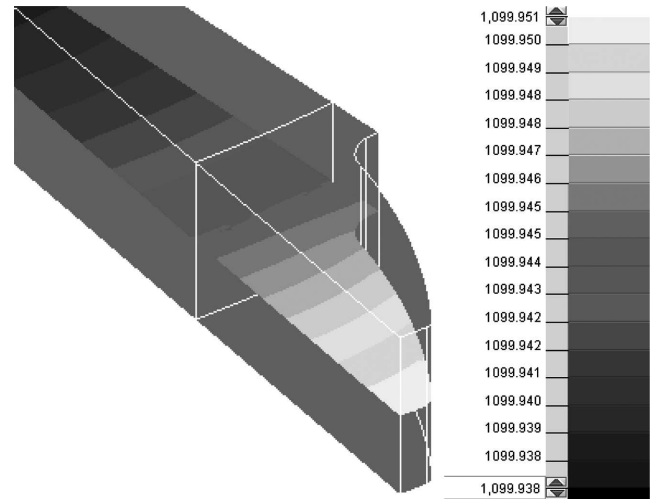

Fig. 3. Indirect heating in a furnace

For induction heating (variants 2 to 4) the surface heating is possible, but for such shapes as gear wheels, it is impossible to achieve the required pattern with using only one frequency. The best results are obtained with the dual and triple frequency approach.

3. Calculation model

The object used as an illustrative example is a gear wheel with the outer radius (to the top of the tooth) of 52 mm and inner radius of 30 mm. This wheel has 64 teeth of 6 mm in height. The wheel is placed inside a circular, single inductor with the inner radius of 57 mm whose height is 8 mm. It is made of 50CrMo4 carbon steel intended for quenching and tempering (Table 2).

TABLE 2

Chemical composition of the steel

C	Mn	P	S	Si	Cr	Mo
0.46-0.54%	0.5-0.8%	0.035%	0.035%	0.4%	0.9-1.2%	0.15-0.3%

The code FLUX 3D was used for the calculations. The algorithm is based on two pairs of potentials, electric vector potential T and magnetic scalar potential Φ, defined by the following equations [19–22]:

In the workpiece area:

$$H = T - \nabla\Phi \qquad (1)$$

$$(2)$$

In the air:

$$H = H_j - \nabla\Phi \qquad (3)$$

where:

J – eddy current density,

H – magnetic field strength,

H_j – magnetic field strength calculated according to Biot-Savart law.

The temperature field is calculated only for the tooth of gear wheel area, according to the Fourier-Kirchhoff law [23-28]:

$$\nabla \cdot (-\lambda \nabla T) + \rho c \frac{\partial T}{\partial t} = w \qquad (4)$$

where:

T – temperature,
λ – thermal conductivity,
$w = \rho |J|^2$ – volumetric Joule losses.

Heat transfer between the charge and its surroundings includes both convection and radiation:

$$-\lambda \frac{\partial T}{\partial n} = \alpha_c (T - T_{oc}) + \varepsilon \sigma (T^4 - T_{or}^4) \qquad (5)$$

where:

α_c – convection heat transfer coefficient,
T_{oc} – temperature of the convection surroundings,
ε – total emissivity,
σ – Stefan-Boltzmann constant,
T_{or} – temperature of the radiation surroundings.

It is not easy to estimate values of the convection coefficient and emissivity because of fast rotation of the gear wheel and proximity of the inductor. For the calculation purposes, it was taken as:

$\alpha_c = 15$ W·$(\text{m}^{-2}\text{K}^{-1})$ and $\varepsilon = 0.7$.

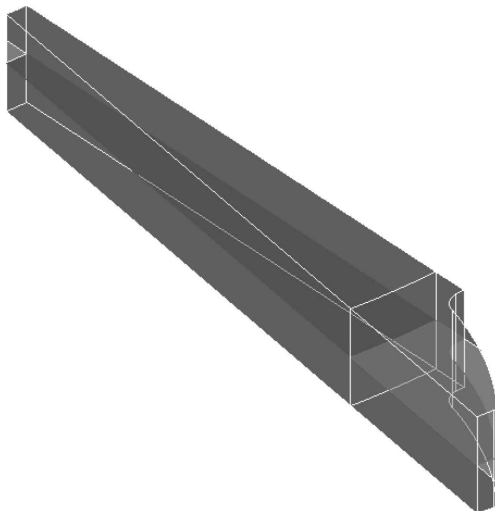Figure 4 presents the arrangement used for numerical modeling.

Fig. 4. Calculation model

4. Study results and their discussion

Over 100 numerical calculations were carried out. The study involved an analysis of heating in accordance with Table 1. Moreover, the temperature distribution was also controlled by varying the following parameters: duration of heating, power delivered to the heated body and its frequency. For all the variations, the tooth temperature distribution was observed in a few selected areas.

The research involved a lot of cases and only some of them are presented. The variants were analyzed for different field currents and then other parameters were selected following assessment of these variants. The analysis began with the classical heating in the furnace. In that case, the tooth of gear wheel heated up evenly, but in the entire volume of the wheel. The next stage of the study was a single-frequency induction heating approach. The study was conducted for the middle frequency (MF), Fig. 5a, and also for high frequency (HF), Fig. 5b.
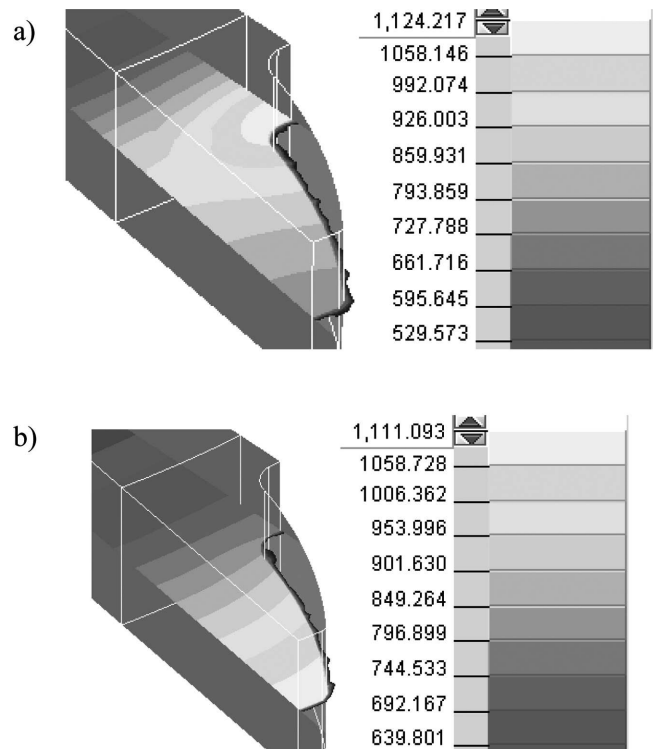

Fig. 5. Induction heating – single frequency: a) $f = 2$ kHz $t = 2$ s, b) $f = 100$ kHz, $t = 2$ s

For the MF heating, the tooth was heated more uniformly, while for the HF the difference between the top and root is about 450°C. Thus, the next stage of research was sequential double frequency induction heating. First, the gear wheel was heated by the MF field current and then by the HF field current (Fig. 6).
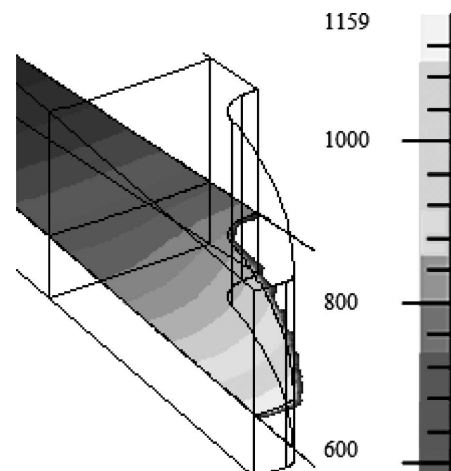

Fig. 6. Dual induction heating: MF = 2 kHz, $t_{MF} = 2$ s, HF = 100 kHz, $t_{HF} = 0.8$ s

Figure 6 shows that the gear wheel heats up more evenly than in the previous variants. However, more or less heated places are also observed. Therefore, an attempt to change other parameters, such as the heating time and the tooth temperature, was made after the first heating step (MF). When the parameters of the process are changed, the uniformity of the temperature distribution in the desired locations can be increased, but the difference between the peak and the tooth temperatures is still about 300°C. therefore, one more step of heating (triple-frequency sequential induction hardening) was included. The first results of this approach are shown in Figure 7.
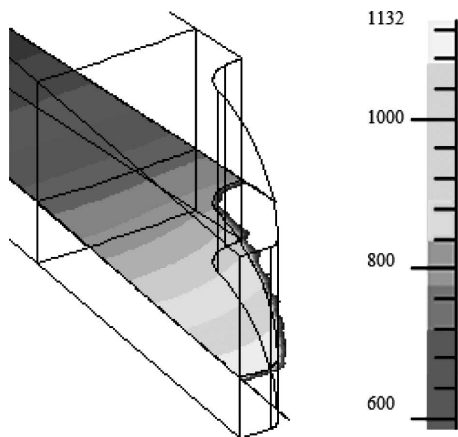

Fig. 7. Induction heating – triple frequency: MF = 2 kHz, t_{MF} = 2 s, H_1F = 60 kHz, t_{H1F} = 1 s, H_2F = 100 kHz, t_{H2F} = 0.8 s

5. Conclusions

The paper presents results of a numerical analysis of non-linear induction hardening of teeth of a gear wheel made of the 50CrMo4 steel. The temperature dependencies of all material properties and heat transfer parameters are respected. The following conclusions were reached:

1. Precise achievement of desired temperature distribution, in the considered case, is still a challenge. For indirect heating of the workpiece, a zone reaching high temperature was always too large.
2. A new idea of triple frequency hardening was introduced.
3. Good results were obtained both for dual and triple frequency induction hardening.
4. The best way to solve the task is using an optimization procedure instead of the multi variant calculations. However, in the optimization procedure, nine parameters should be applied.
5. A disadvantage of this methodology is a long calculation time for one variant (about several hours even for the single frequency approach).
6. The investigations will be continued within the framework of a new project realized at the Silesian University of Technology.

REFERENCES

[1] V. Rudnev, D. Loveless, R. Cook, M. Black, Induction hardening of Gears: a Review, Heat Treatment of Metals **4**, 97-103 (2003).

[2] J. Barglik, A. Smalcerz, R. Przylucki, I. Doležel, 3D modeling of induction hardening of gear wheels, Journal of Computational and Applied Mathematics **270**, 231-24 (2014).

[3] J. Barglik, Induction Steel Tubes by Means of Internal Inductor, Journal of Iron and Steel Research International **1-2**, 722-725 (2012).

[4] A. Glowacz, Diagnostics of induction motor based on analysis of acoustic signals with the application of eigenvector method and K-Nearest Neighbor classifier, Archives of Metallurgy and Materials **57** (2), 403-407 (2012).

[5] G. Perun, J. Warczek, R. Burdzik, B. Lazarz, Simulation and laboratory studies on the influence of selected engineering and operational parameters on gear transmission vibroactivity, Key Engineering Materials **588**, 266-275 (2014).

[6] S. Golak, R. Zagorski, Model and optimization of electromagnetic filtration of metals, Metalurgija **52** (2), 215-218 (2013).

[7] M. Niklewicz, A. Smalcerz, A. Kurek, Estimation of system geometry and inductor frequency importance in induction hardening process of gears, Przeglad Elektrotechniczny **84** (11), 219-224 (2008).

[8] P. Karban, I. Mach, I. Dolezel, Induction heating of nonmagnetic cylindrical billets by rotation in magnetic field produced by static permanent magnets, Przeglad Elektrotechniczny **86** (12), 53-56 (2010).

[9] M. Niklewicz, A. Smalcerz, Application of three-coil cylindrical inductor in induction heating of gears, Przeglad Elektrotechniczny **86** (5), 333-335 (2010).

[10] L. Blacha, G. Siwiec, B. Oleksiak, Loss of aluminium during the process of Ti-Al-V alloy smelting in a vacuum induction melting (VIM) furnace, Metalurgija **52** (3), 301-304 (2013).

[11] A. Kohli, H. Singh, Optimization of processing parameters in induction hardening using response surface methodology, Sadhana – Academy Proceedings in Engineering Sciences **36** (2), 141-152 (2011).

[12] A. Candeo, C. Ducassy, P. Bocher, F. Dughiero, Multiphysics Modeling of Induction Hardening of Ring Gears for the Aerospace Industry, IEEE Transactions on Magnetics **47** (5), 918-921 (2011).

[13] A. Smalcerz, Aspects of application of industrial robots in metallurgical processes, Archives of Metallurgy and Materials **58** (1), 203-209 (2013).

[14] R. Przylucki, A. Smalcerz, Induction heating of gears – pulsing dual-frequency concept, Metalurgija **52** (2), 235-238 (2013).

[15] J. Barglik, M. Czerwiński, M. Hering, M. Wesołowski, Radiation in modelling of induction heating Systems, Chapter in IOS Press **29**, 202-211 (2008).

[16] L. Blacha, J. Mizera, P. Folega, The effects of mass transfer in the liquid phase on the rate of aluminium evaporation from the Ti-6Al-7Nb alloy, Metalurgija **53** (1), 51-54 (2014).

[17] K. Brunelli, M. Dabala, F. Dughiero, M. Magrini, Diffusion treatment of Ni-B coatings by induction heating to harden the surface of Ti-6Al-4V alloy, Materials Chemistry and Physics **115** (1), 467-472 (2009).

[18] T. Merder, A. Boguslawski, M. Warzecha, Modelling of flow behaviour in a six-strand continuous casting tundish, Metalurgija **46** (4), 245-249 (2007).

[19] G. Siwiec, B. Oleksiak, A. Smalcerz, J. Wieczorek, Surface tension of Cu-Ag alloys, Archives of Metallurgy and Materials **58** (1), 193-195 (2013).

[20] T. Merder, M. Warzecha, Optimization of a Six-Strand Continuous Casting Tundish: Industrial Measurements and Numerical Investigation of the Tundish Modifications, Metallurgical and Materials Transactions B-Process Metallurgy and Materials Processing Science **43** (4), 856-868 (2012).

[21] J. Barglik, D. Dołęga, A. Smagor, Coupled temperature electromagnetic flow fields in the electromagnetic stirrer with a rotating magnetic field, Magnetohydrodynamics **46** (4), 387-392 (2010).

[22] J. Myalski, J. Wieczorek, A. Plachta, Physical and mechanical properties of composites with aluminum alloy matrix designed for metal forming, Solid State phenomena **212**, 59-62 (2014).

[23] M. Warzecha, T. Merder, P. Warzecha, G. Stradomski, Experimental and Numerical Investigations on Non-metallic Inclusions Distribution in Billets Casted at a Multi-strand Continuous Casting Tundish, ISIJ International **53** (11), 1983-1992 (2013).

[24] A. Głowacz, A. Głowacz, P. Korohoda, Recognition of color thermograms of synchronous motor with the application of image cross-section and linear perceptron classifier, Przeglad Elektrotechniczny **88** (10A), 87-89 (2012).

[25] A. Smalcerz, R. Przylucki, Impact of Electromagnetic Field upon Temperature Measurement of Induction Heated Charges International Journal of Thermophysics **34** (4), 667-679 (2013).

[26] J. Zgraja, Computer simulation of induction hardening of moving flat charge IEEE Transactions on Magnetics **39** (3), 1523-1526 (2003).

[27] A. Fornalczyk, S. Golak, M. Saternus, Model of Infiltration of Spent Automotive Catalysts by Molten Metal in Process of Platinum Metals Recovery, Mathematical Problems in Engineering **461085**, (2013).

[28] J. Barglik, I. Doležel, P. Karban, B. Ulrych, Modeling of continual induction hardening in quasi-coupled formulation, Compel **24** (1), 251-260 (2005).