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doi:10.15199/48.2018.04.15

Influence of material properties of charge on electrical parameters of induction heating setup

***Abstract**. For the induction heating process, the knowledge of the material parameters of the charge is great importance both at the stage of the design and its operation. Study is presenting the sensitivity analysis of electrical parameters of induction heating setup and dedicated magnetic flux probe on electrical parameters of induction heated charge. These dependencies can potentially be used to estimate the value of material parameters, as long as the sensitivity tested is sufficiently large and unambiguous. Results of conducted examinations allows to implement proposed method on real laboratory stand.*

***Streszczenie.** Przy nagrzewaniu indukcyjnym znajomość parametrów materiałowych wsadu ma istotne znaczenie zarówno na etapie projektowania stanowiska, jak i jego eksploatacji. W pracy przedstawiono analizę wrażliwości łatwo mierzalnych parametrów elektrycznych nagrzewnicy indukcyjnej oraz dedykowanego czujnika strumienia magnetycznego, na zmianę elektrycznych parametrów materiałowych nagrzewanego wsadu. Tego typu zależności mogą być potencjalnie wykorzystywane do szacowania wartości parametrów materiałowych, o ile badana wrażliwość jest dostatecznie duża i jednoznaczna. Osiągnięte rezultaty pozwalają podjąć próbę wykorzystania zaproponowanej metody na rzeczywistym stanowisku badawczym (**Wpływ parametrów materiałowych na parametry elektryczne indukcyjnego układu grzejnego**).*

Keywords: resistivity, nondestructive methods, material parameters, induction heating
Słowa kluczowe: rezystywność, metody nieniszczące, parametry materiałowe, nagrzewanie indukcyjne

Introduction

Industrial processes associated with the heat treatment of conductive materials requires a knowledge of exact material properties of the treated charge. It is great importance both at the stage of the design the process and its operation. In induction heating processes such knowledge can be potentially acquired during the heating process itself or during induction heating on special designed stand [1, 2, 3], and may concern both thermal [4, 5, 6] and electrical material parameters. However, in order these potential possibilities to be used in practice, the measured signals must, on the one hand, be readily available and, on the other hand, must be highly and selective sensitive to the estimated material parameters of the charge.

At this paper the analysis of influence of electrical parameters of heated charge on electrical parameters of induction heating circuit is presented. To avoid significant costs of laboratory experiments simulations using software for field analysis of conjugated electromagnetic and thermal phenomena were performed. Simulation calculations are based on model that corresponds to geometry of real laboratory stand which is dedicated to non-contact determination of thermal and electrical parameters of conductive material by using induction heating method. Laboratory stand is going to have highly autonomous and automated sequential test procedures. This paper is dedicated to present theoretical and simulation analysis the influence only of the electrical parameters of induction heated charge on the parameters of heating circuit.

The stand for induction heating contains a cooperating together power source and load in the form of an induction-charge system. To utilize resonance sources effectively, impedance matching between load and source is necessary which are influenced by the actual material properties of treated charge that can vary within one batch of the sample material. This fundamental impact of material properties on heating process influences on power that is delivered to circuit and frequency of inductor current. The question arises whether by measuring such electrical parameters it is possible, by indirect method [7, 8], to use mentioned dependence to determine thermal characteristics of electrical parameters of heated charge. Sensitivity analysis and interdependence of electrical parameters of the circuit and electrical parameters of heated charge material were performed. Investigated the charge resistivity ρ (for nonmagnetic samples) and additionally relative magnetic permeability μ_r for ferromagnetic samples.

Computational model

The simulation of the influence of the material parameters of the load on the parameters of the supply circuit of the induction-charge system was realized by solving the circuit-field task. The task from the field side was based on solving Maxwell's equations defining the magnetic field:

$$rot\,\boldsymbol{H} = \boldsymbol{J}, \quad div\,\boldsymbol{B} = 0, \quad \boldsymbol{B} = \mu \cdot \boldsymbol{H} \tag{1}$$

and electric field:

$$rot\,\boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \quad div\,\boldsymbol{J} = 0, \quad \boldsymbol{J} = \frac{\boldsymbol{E}}{\gamma} \tag{2}$$

where: $\boldsymbol{H}$, $\boldsymbol{E}$ – vector of magnetic and electric field strange, $\boldsymbol{B}$ – vector of magnetic flux density, $\boldsymbol{J}$ – vector of current density, μ - magnetic permeability, γ - electrical conductivity.

The calculation of the temperature field in the charge was accomplished by solving Fourier-Kirchhoff equation:

$$div[(-\lambda) grad\,\vartheta] + \rho_d c \frac{\partial \vartheta}{\partial t} = p_v \tag{3}$$

where: λ – thermal conductivity, ρ_d – density, c – specific heat, p_v – volumetric heat source power density,

with the existing boundary and initial conditions taken into consideration.

For induction heating setup with a quality factor Q>4 which is supplied by series inverter with relative (compare to period T) dead time T_d/T <0.15 the participation of the higher harmonics in the inductor current usually does not exceed a few percent [9]. Taking into account that above conditions will be fulfilled in considered setup, the simulation analysis of the electromagnetic field was carried out as a time harmonic analysis.

Simulations were performed using dedicated commercial software for conjugated electrical and thermal calculations –

Flux®. Taking into account the methodology as presented in [10] the time harmonic analysis of electromagnetic field was carried out by Flux program for ferromagnetic charge too.

In this paper model from Fig. 1 was used. It includes initially tested real geometry. Additional probe was proposed for measuring magnetic flux in gap between charge and inductor. Axisymmetric model, Fig. 1, contains of 1 - cylindrical charge with diameter D=30 mm and height H=10 mm, 2 - three loop inductor with internal diameter ID=40 mm, 3 – dedicated magnetic flux sensor (single loop with diameter of Ds=33,5 mm) placed in air gap between charge and inductor.

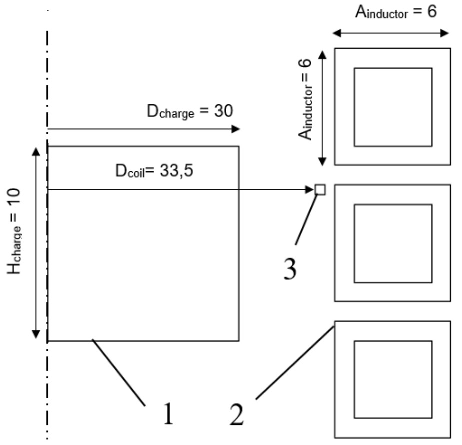

Fig. 1. The computational model of inductor-charge setup: 1 – charge, 2 – inductor, 3 – magnetic flux sensor.

Sensitivity analysis of electrical parameters of induction heating system on change of material parameters of the charge

To verify influence of magneto-electrical material properties of the charge on electrical parameters of the induction heating system (IHS), dependence of resistance of HIS (load) R_{load} in function of two parameters: charge material resistivity ρ and its relative magnetic permeability μ_r were investigated, Fig. 2 and Fig.3 respectively. The induction heating system was supplied by effective current I_{rms}=1500 A with frequency f=40 kHz.

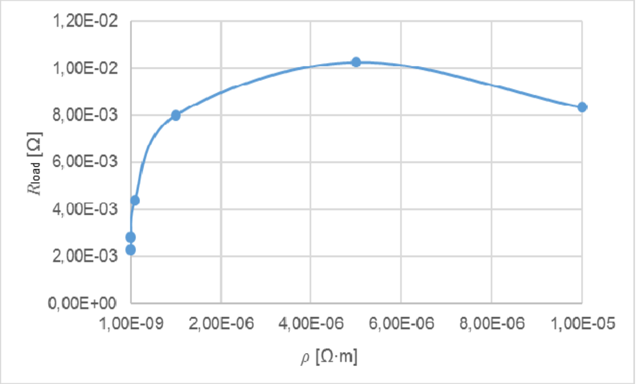

Fig. 2. Influence of the resistivity ρ of the charge material on the resistance R_{load} of the induction heating system.

Additionally Fig. 4 and Fig. 5 presents dependence of inductance of HIS (load) L_{load} in function of change material resistivity ρ and relative magnetic permeability μ_r.

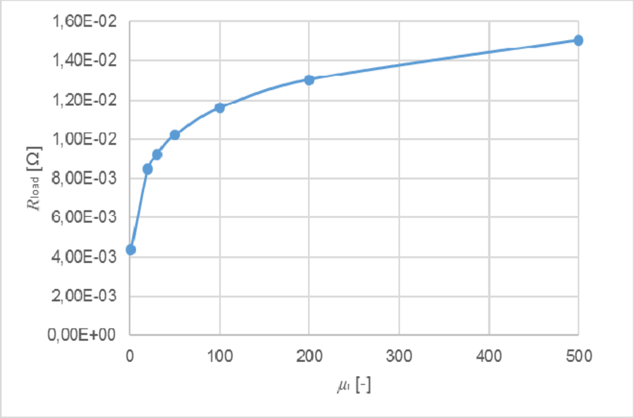

Fig. 3. Influence of the relative magnetic permeability μ_r of the charge material on the resistance R_{load} of the induction heating system.

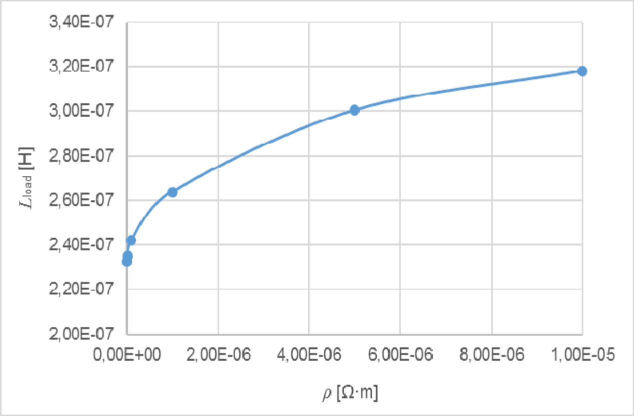

Fig. 4. Influence of the resistivity ρ of the charge material on the inductance L_{load} of the induction heating system.

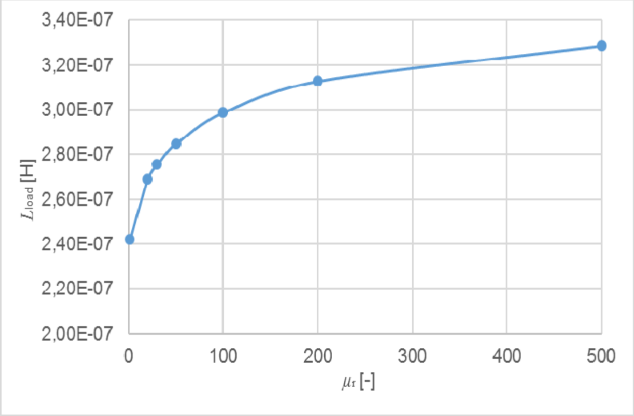

Fig. 5. Influence of the relative magnetic permeability μ_r of the charge material on the inductance L_{load} of the induction heating system.

Dependence of two above mentioned parameters on resistance R_{load} of IHS is significant. With assumed physical dimensions of the charge and given frequency for resistivity higher than $5{\cdot}10^{-6}$ Ωm significant drop of the substitute resistance of load due to increasing skin depth and despite charge resistance rise of material is visible. That kind of dependence create ambiguity in determining resistivity of a charge material based on substitute resistance R_{load} of IHS. Additionally, high nonlinearity of $R_{\mathrm{load}}(\rho)$ relation is also impeding determination of resistivity and in practical usage it will give highly unclear results. These restrictions are also powered by inaccuracy of method and difficult measurements of load resistance R_{load}. As it is presented in Fig. 4 and 5, change of material properties also influence on substitute load induction L_{load} level. In resonance systems (induction heating) it provides frequency shift which are responsible for resistance change too. It is possible to limit mentioned influences by adding air inductance to resonance system, but it limits only frequency variations and it gives higher losses of active power what changes R_{load}. Indirect determination of resistivity depending on substitute resistance R_{load} of IHS is possible but it will not give satisfactory results in real application.

Influence of electrical material properties on magnetic flux in inductor

Magnetic flux in inductor is dependent on its physical dimensions, flowing current and material properties of the heated charge. Due to mentioned above dependences, to verify sensitivity of material properties on value of magnetic flux utilization of additional magnetic flux probe (Fig. 1), placed in air gap between inductor and charge is needed. The electromotive force E in probe which is dependent on derivative of magnetic flux value can be, assuming sinusoidal signals with constant frequency f, calculated with relation (1):

(1) $$E=-\mathrm{j}\omega\Phi$$

where: pulsation $\omega=2\pi f$; Φ - magnetic flux.

Presented setup allows to measure level of induced voltage in dedicated probe giving signal U_{sig}. Knowledge of this value gives a possible chance to validate its sensitivity on material properties of the charge. The computer simulation were used to establish relation (2) and (3):

(2) $$U_{sig}=f(\rho)$$

(3) $$U_{\mathrm{sig}}=f(\mu_{\mathrm{r}})$$

From conducted simulation calculations with single coil probe with D_{coil}=33.5 mm and $I_{\mathrm{rms\_coil}}$=1500 A two relations were prepared: $U_{\mathrm{sig}}(\rho)$ presented in Fig.7 and $U_{\mathrm{sig}}(\mu_{\mathrm{r}})$ presented in Fig.8.

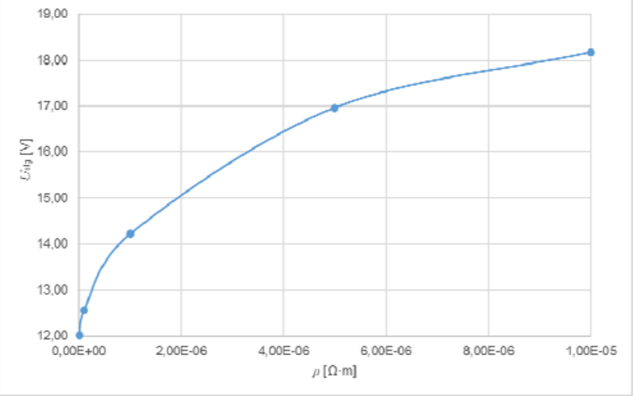

Fig. 6. Relation of induced voltage U_{sig} in dedicated probe in function of charge resistivity, for nonmagnetic sample μ_{r}=1.

Basing on presented results it is possible to assume that value of induced voltage U_{sig} in probe is strictly dependent on resistivity and relative magnetic permeability of the charge (probe) material. For non-magnetic samples where $\mu_{\mathrm{r}}\approx1$ it is possible to determine resistivity of the charge from relation presented in Fig. 6. In case of magnetic samples where μ_{r}>>1 considering both parameters simultaneously ($U_{\mathrm{syg}}=f(\mu_{\mathrm{r}}\cdot\rho)$) is necessary due to its similar dependence on induced signal. In final consideration, separation of these two dependences is important. Example relation of induced voltage U_{sig} with product of relative magnetic permeability and resistivity for three examined samples is presented in Fig. 8. As can be noticed the relation $U_{\mathrm{syg}}=f(\mu_{\mathrm{r}}\cdot\rho)$ is practically independent of the values of individual variables (charge resistivity ρ and charge relative magnetic permeability μ_{r}), but only on their product. This gives possibility to use that characteristic for indirect determination of magnetic charge resistivity too, if its magnetic permeability will be separately determined.

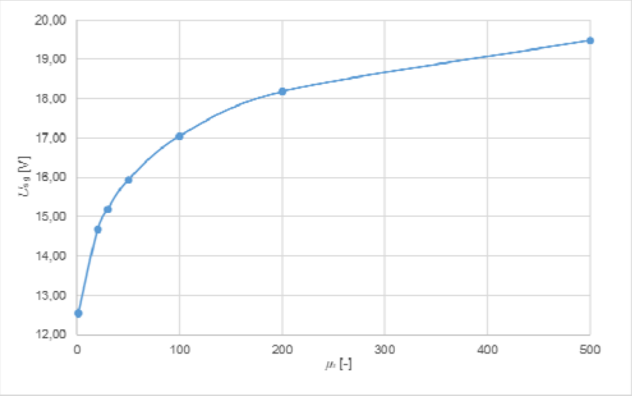

Fig. 7. Relation of induced voltage U_{sig} in dedicated probe in function of charge relative magnetic permeabilty, for magnetic sample with resistivity ρ=1e-7 Ω·m.

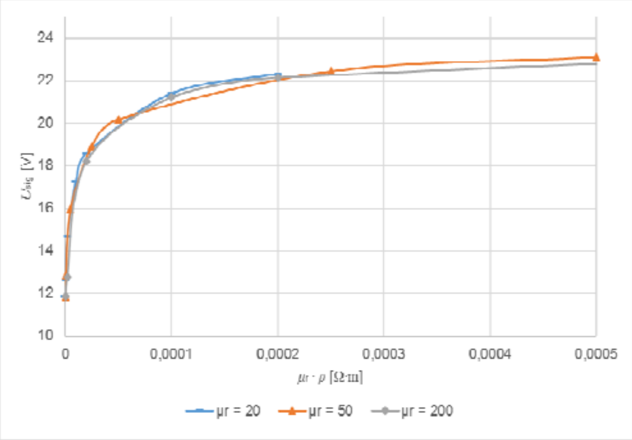

Fig. 8. Relation of induced voltage U_{sig} on product of resitivity and relative magnetic permeability, for samples with μ_{r}=20, 50, 200.

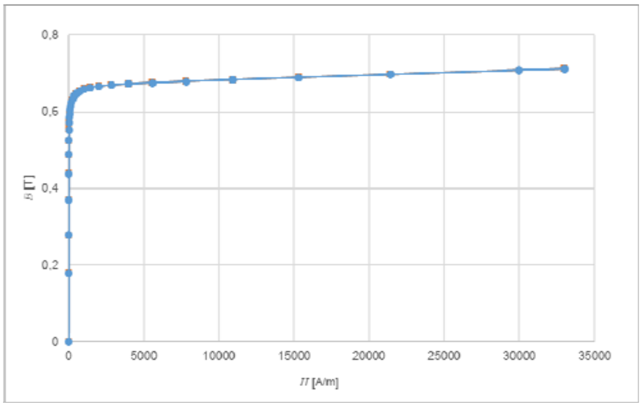

Fig. 9. Relation of magnetic density B and magnetic field strength H for Mumetal sample.

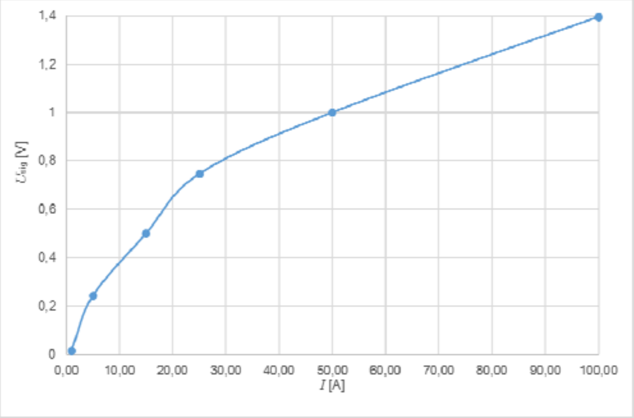

Fig. 10. Relation of induced U_{sig} voltage and value of inductor current I for Mumetal sample.

Value of measured signal should be dependent only from material properties of the charge, not from strength of magnetic field which influences voltage induced in dedicated probe. This problem complicates the nonlinear influence of the current value on the magnetic flux in the inductor (dedicated probe).

For ferromagnetic sample of charge – Mumetal (75% nickel, 15 % ferrite) with magnetizing curve defined in Fig. 9, the relation between induced U_{sig} voltage in dedicated probe placed in air gap (Fig. 1) and value of inductor current I is presented in Fig.10.

From relations presented above it is possible to assume that value of induced voltage is strongly but non-linear dependent from inductor current value.

To include this in measurements, it will be needed additional differential measurement where induced voltage U_{syg} will be reduced by voltage induced in additional probe placed on supply of inductor which is dependent only from current flowing in inductor. Additionally for magnetic charge the value of magnetic field strength should be know if we want to take into account the separately determined its magnetic permeability for determining charge ρ resistivity.

Summary

Conducted in initial phase analysis showed that dependence between material properties of charge on electrical parameters of IHS is negligible. That arrangement is marked by a negligible sensibility to change of parameters mentioned above and there are no grounds in order to implement this method on the real laboratory stand. Analysis of the influence of the change of material parameters of the charge on the induced voltage in dedicated in air gap probe was a further step of analysis. Achieved results, on account of relatively greater sensitivity of the method, let state that using the additional measuring probe is a promising idea, in addition one should pay special attention to the need to separate the influence (similar) of both parameters: resistivity and relative magnetic permeability in case of ferromagnetic charges.

The work funded from the means of the National Centre for Research and Development (Polish abbreviation: NCBiR) within the project of Applied Research, agreement no. PBS1/A4/2/2012

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