Adam CIEŚLAK, Jerzy ZGRAJA

Lodz University of Technology, Institute of Applied Computer Science

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Induction heating laboratory stand for estimating thermal properties of a charge

Abstract*. Study is presenting the description of the laboratory stand for estimating thermal properties of inductively heated charge and aspects associated with implementing arrangements and control procedures, measuring and data handlings. Results of conducted examinations and practical conclusions resulting from analysis of problems that come across in the performance of a task were made.*

Streszczenie*. Opracowanie przedstawia opis stanowiska laboratoryjnego do szacowania cieplnych parametrów materiałowych indukcyjnie nagrzewanego wsadu oraz aspekty związane z wdrożeniem układów i procedur sterujących, pomiarowych oraz obróbki danych. Przedstawiono rezultaty przeprowadzonych badań oraz wnioski praktyczne wynikające z analizy trudności napotkanych w realizacji zadania. (****Wykorzystujące nagrzewanie indukcyjne stanowisko do szacowania cieplnych parametrów materiałowych****)*

Keywords: specific heat capacity, flash method, material parameters, induction heating
Słowa kluczowe: ciepło właściwe, metoda flash, parametry materiałowe, nagrzewanie indukcyjne

Introduction

In the industrial processes associated with the heat processing of material a knowledge of material properties of the examined charge is significant. At this paper it is presented laboratory stand built to the purpose of the implementation and the verification of the methods for determining thermal parameters of induction heated charge. Laboratory stand is supposed to be autonomous especially in case of measurements. It is leading strong integration between internal measurement systems, data acquisition and processing systems, process control procedures supported with simulation results and knowledge base. This approach allows to carry on complex process of estimation thermal properties in industrial surrounding with a reduced need of participation of qualified specialists.
To avoid high costs of laboratory experiments simulations using software for field analysis of conjugated electromagnetic and thermal phenomena were done.

Methods for estimation thermal properties of induction heated charge

One of the functions of presented laboratory stand is estimation (with possible high accuracy) a set of thermal properties of the induction heated charge i.e. thermal diffusivity and heat capacity which are connected with the relation:

(1) $$a = \frac{\lambda}{c \cdot \rho}$$

where: a – thermal diffusivity, λ - thermal conductivity, c - specific heat capacity, ρ - density.

For the determination of thermal diffusivity impulse method was used [1,5] which is leading on direct exposure of cylindrical charge with electromagnetic radiation with the possibly close do Dirac impulse character and registration of the temperature on opposite to heated side of the sample. In this method it is essential so that the level of the provided energy is enough great as well as evenly distributed on the surface. Unlike earlier, well-known for literature [1,3,6], applications of the radiator lamp or also a laser as sources of impulse of the electromagnetic radiation, on the discussed stand were picked up the unique attempt to use the generator of the high-frequency for the induction heating as source of the provided energy. In the discussed method thermal diffusivity is determined by a halftime (time in which temperature of sample achieves half of the maximum temperature) of a sample which is specific for every material (Fig. 1), according to the relation:

(2) $$a = 1{,}38\frac{L^2}{\pi^2 t_{1/2}}$$

where: L – height (thickness) of the charge.

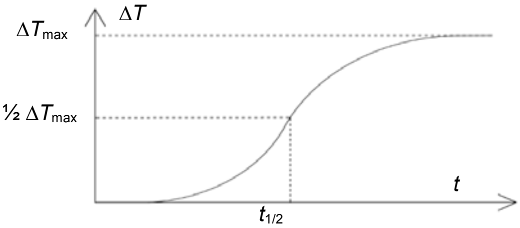

Fig. 1. Temperature course on the opposite to heated side of the sample.

For determining the specific heat capacity a method being based on checking the time derivative of the temperature in an inductively heated sample was used which causes to seek the constant value of the temperature derivative.

In fact it meant the need to search for the value of the temperature derivative in the point, in which the increase in the temperature has character possibly close linear. In this method source (high frequency generator) is generating current impulse (rectangular RMS) with the given duration. This time closely is depending on previously appointed halftime and it is longer for about 5-6 times. After this time, time derivative of temperature is stabilizing achieving the maximum value. Assuming the evenness of the temperature distribution in the sample, it is possible to appoint the specific heat capacity from the relation:

(3) $$c = \frac{P_{charge}}{m \cdot \frac{dT}{dt}} \qquad [c] = \frac{J}{kg \cdot K}$$

where: P_{charge} - power generated in the sample, m – mass of the sample, dT/dt – time derivative of the temperature.

Presented methods were analyzed (at first by simulation) in the arrangement of heating "natural" for cylindrical sample with the diameter of 30 mm and height of 10 mm made from: of magnetic steel, nonmagnetic steel, copper, brass and aluminum. The simulation model was presented in Fig. 2.

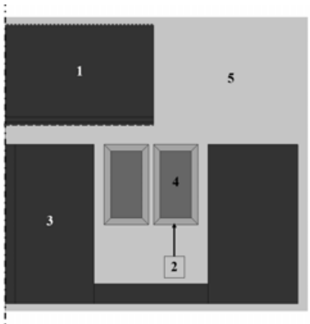

Fig. 2. Heating setup „natural”: 1 – chargé , 2 – inductor, 3 – magnetic core, 4 – cooling liquid, 5 – surrounding.

Description of the laboratory stand

A laboratory stand was designed and implemented for verification methods and calculations which were described above. A dedicated generator with the power of 15 kW of the ENIKA company, in which the phenomenon of the series resonance was used is a main element of the stand. It was adapted specially for the purposes of carrying out trial runs with impulse character for appointment of thermal diffusivity and specific heat capacity of the charge. In this position an inverter was applied on the basis of the bridge H, with four IGBT transistors for extorting of tension rectangular wave with the amplitude U_f with the filling of the 50% and the changeable frequency (from 20 up to 50 kHz). Altarpiece of the value U_f is being carried out in the arrangement of the booster of the type BUCK with the chopper transistor *Tc* and the choke *Lc*, straightened from network 3 * 400 the V UP tension. Transformer Tr with the 25:1 transmission gear is increasing the current in the circumference inductor towards the electricity of the inverter. That allows for achieving currents in the heating arrangement on the level of 1,5 kA RMS value (Fig. 3).

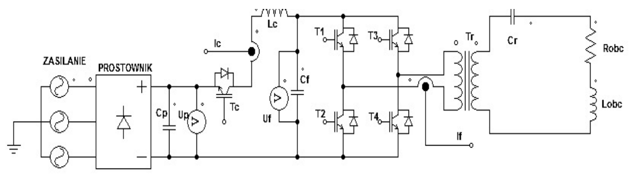

Fig.3. Idea scheme of power circuit in high frequency induction generator.

The control system of the generator is based on the DSP processor of the Microchip company and the programmable layout of CPLD series Lattice company. In order to fulfil stand requirements one should appropriately select elements with induction and capacitive character and to apply the proper guidance. High capacity capacitors were used. It is very cost demanding solution, capacitors are taking up much space what affects on arranging of powering bus bars in the generator, and in consequence causes the appearance of phenomena connected with inductances of elements taking the power supply

Taking into account above, C_f condenser was applied capacitance of 4.7 mF. Using the L_c reactor as the element smoothing the provided electricity for the inverter is also an important component of the circuit. Too small value of inductance caused the suitable tension for the first phenomenon of discontinuities of the electricity at low powers provided the arrangement and problems associated with it with the stable maintenance, secondly big thumping of the current in the route of short attempts of the high power what led to strong permeating the reactor and the unchecked growth of the current. The big inductance of the reactor led the market to the excessive increase of time constants of circuit, towards the expectations associated with the duration of impulse of enclosing the generator. For the value after all was selected on level 10 mH, at the rated current of the 40A .

Carrying out the fixed amplitude of the current of the inverter in the circuit of performed attempts, or it were setting the control system of a few short millisecond strong-power-driven impulses or long (multiple second) of circuit, but about the definitely smaller amplitude. It bound itself with the need by keeping the constant value of the tension U_f in the circuit of the inverter in the attempt. Parameters of experiment were set the PC by the master computer, controlling the work of the position, in it of generator. A possibility of adjusting the resonance frequency exists in the arrangement, tensions U_f rump of the set on-the-fly inverter, of predicted value of the electricity of the inverter I_c rump and of tp testing time with resolution 1 ms.

Correctness of carrying out heating experiment with permanent impulse of the power requires commencing the heating process at appropriately (for the power given to the value) selected values of tensing the rectangular wave of the inverter U_f and of current of the chopper Ic. For, the momentary power is achieving short attempts value of a dozen or so kilowatts. For attempts connected with the realization of individual impulse the power is on the level up to 500 watts. Keeping the permanent delivered power is an important aim of the guidance to inductor in the course of every of these attempts. Therefore the completion of experiment was divided in stages. First has the task of charging the C_f condenser to the value U_f rump set the PC from the computer. It is being carried out in order to

in the moment of achieving the expected value phew the rump had a current of the L_c reactor simultaneously value Ic ex. In fact the current of the reactor is achieving its value before charging the condenser. It is being carried out by the arrangement with the PI adjuster giving linear growing of the current to the set value, then it holds set value till the inverter switches on (voltage reaches U_f value). In the second stage regulator switches on cascade mode: voltage regulator with current output, current regulator with PWM output. Value of the integrative part of the regulator is supplied by the actual value of reactor current. On this stage circuit is responsible for voltage stabilizing. In the circuit U_p voltage is influenced with the 300 Hz tensions due to the 3-phase rectifier supply. To minimize mentioned effect feed-forward circuit was implemented. It was given from zero condition for the mean value of the reactor voltage for the PWM period. ($t_{pwm}/T_{pwm} = U_f/U_p$, where t_{pwm} trigger time of the transistor , T_{pwm} PWM period).
Idea scheme of control circuit is presented in Fig. 4.

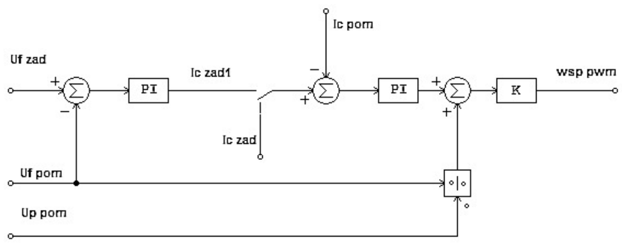

Fig. 4. Idea scheme of control circuit.

In Fig. 5. various curves are presented. U_f red color and currents I_c –violet color, I_f – yellow color for two cases. In Fig.5a i 5b power impulse with the character of the Dirac impulse is presented, and in Fig.5c step impulse.

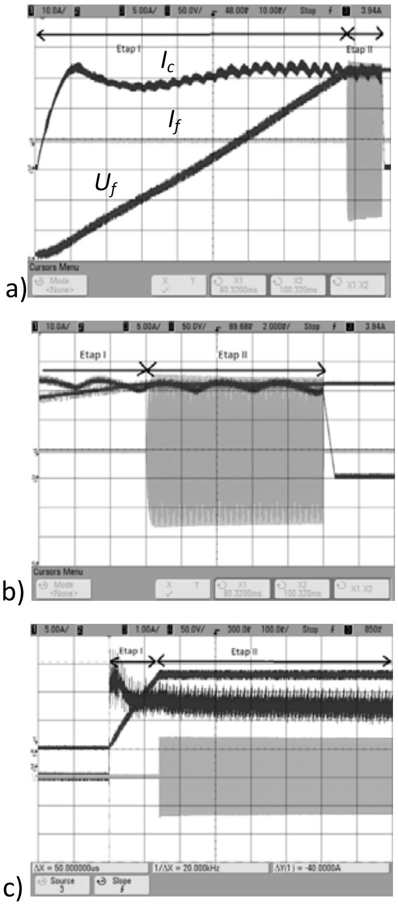

Fig. 5. Curves for inverter voltage U_f, reactor current I_c i inverter current, I_f for impulse experiment (a) i (b) and for step impulse experiment (c).

In the more distant stage of work a possibility of using the generator for appointing the set of thermal properties of the material was considered. Specially designed inductor is an integral part of the generator and the set of elements of responsible for a positioning of the sample i.e. the magnetic core or the thermal insulation. In Fig. 6b part of the stand with the inductor was presented. In the first phase of the construction flat spiral 3-coil inductor was designed (Fig. 6 a) with the external diameter of 39 mm and the inside diameter of 2 mm. On account of small dimensions and keeping the greater precision inductor was made using the CNC machine tool.

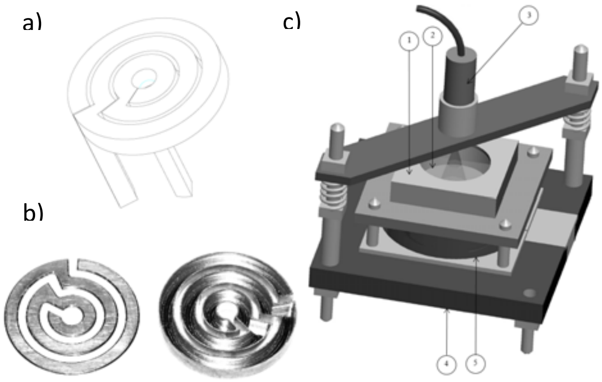

Fig. 6. Part of the laboratory stand: a) sketch of the inductor, b) inductor made with CNC technology , c) view of the stand: 1 – thermal insulation, 2 – charge, 3 – temperature sensor, 4 – insulator, 5 – magnetic core.

Preliminary validation of the simulation models and measurement methods.

Various experiments were carried out with the presented stand to verify previously assumed simulation models and measurement methods. Simulation and real results were compared. At first attempt current impulse of 1,5 kA RMS value and 10 ms was reached. Such high value of the current was determined by the measurable value of temperature. Real measured temperature rise (1-2 K) for the steel sample was much lower than expected with the value of 7 K. This triggered investigation for the reason of the inaccuracy. Analysis started from verification an comparison of the boundary conditions with the real one.

Basing on previously made attempts and simulations it was claimed that temperature distribution in charge is not highly influenced by the cooling intensity of sample. Next stage of investigation was check of the material properties assumed in a simulations. Authors sharply focuses on magnetic permeability which was set as a linear part of magnetizing curve. To verify and confirm appearing of the strong magnetic saturation phenomena, inductor voltage was measured while regular impulse attempt. Fig. 7 presented current curve I_{wzb} and voltage U_{wzb} which illustrates well the phenomena of the saturation of magnetic elements.

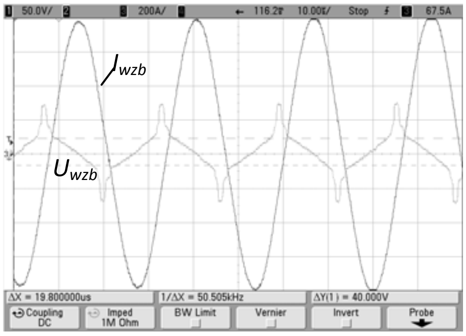

Fig. 7. Current curve on the primary side of the supply transformer and voltage curve of the inductor.

For low values of the current – near zero value sharp rise of the voltage is appearing (increase of the circuit inductance) and next its radical reduction at the growing value of the current. Strong saturation lead to the rapid change of the substitute inductance of the circuit. Magnetic core which was positioned in the axis of the inductor was replaced with newly designed core and new dedicated 2 coil flat inductor with external diameter of 39 mm and internal 20 mm.

Temperature measurement

It is essential to measure temperature of the sample to determine thermal properties of the given material. From technical point of view it is important to provide sensor which has ability to measure dynamic changes of the temperature. Two specific types of the temperature sensors was applied: contact and non-contact. Thermocouple K with the sensor diameter of 0,5 mm (OMEGA) was used with dedicated transducer 4-20 mA Lumel P20. Generator was adapted to the receiving and processing the signals from the transducer and it is synchronized with the control circuit of the generator which allows to trigger impulse and start of the measuring simultaneously. All of the attempts was made with the 1,5 kA RMS value of the current, 100 ms and frequency of 38,1 kHz.

First attempt of measurement a temperature using thermocouple was inaccurate and halftime of the steel sample was longer that expected (2120 ms to expected 1200 ms). To verify if the temperature sensor is the reason of the inaccuracy response time of the thermocouple was measured. To bypass the transducer voltage amplifier (100x) directly connected to thermocouple and oscilloscope was used. Basing on experimental attempts response time (90% of the stable value) of the sensor was determined on the level of 80 ms. With the reference to the above mentioned results a sensor was ruled out as the source of the problem and it was said that transducer is a reason of delay and signal losses. It has response time on a level of 300 ms which makes it useless in application which requires good dynamic imaging of the temperature changes. Non contact sensor which was used at the laboratory stand is OMEGA OS-36 infrared sensor which has nominal 80 ms response time. In real conditions (surface of the solid part) non contact sensor has lower delays and it is less sensitive on surrounding noises and easier to mount on stand. Although sample has to be covered by the black paint which increases emissivity. Sensor needs to be accurately positioned on the sample. In further applications only non contact sensor was used. Finally thermal imaging camera FLIR A655 with great 8 ms response time was used. This device coupled with the dedicated software allows to record temperature field distribution on whole upper surface of the cylindrical sample. Output data was processed in MATLab and analyzed in MS Excel. Sample results given from thermal imaging camera were presented in next chapter.

Comparison of the simulations and real measurements.

To verify simulation results several experiments using high frequency generator were done. There were used 5 typical materials such as: copper, aluminum, brass, magnetic steel, non magnetic steel. Table 1 presents main material parameters used in simulations.

Table 1. Material properties of analyzed samples

Material/parameter	μ_r	ρ	λ	$c \cdot \rho_v$	density ρ_v
	-	Ωm	W/m/K	J/m^3/K	kg/m^3
Al.	1,000	2,65E-08	237	2 430 000	2 700
Cu.	0,999	1,68E-08	401	3 389 600	8 920
Brass	1,500	0,075E-06	110	3 223 350	8 550
Non mag. steel	1,008	7,2E-7	16,2	4 000 000	8 000
Magnetic steel	curve	1,43E-7	65,2	3 510 000	7 800

Thermal diffusivity estimation

Attempt of estimating thermal diffusivity was carried out in configuration with: 2 coil flat inductor, cylindrical sample with the diameter of 30 mm and height of 10 mm. Because of the unevenness of temperature distribution it was assumed that temperature measurement should be done not in the axis of the sample but in a area which is located 10 mm from the axis (it is a position which corresponds with the internal edge of the inductor, internal radius of the inductor is equal to 10 mm). Comparison of the thermal diffusivity for given above materials is presented in table 2.

Table 2. Comparison of real measurements and simulation results – thermal diffusivity

Material	Assumed thermal diffusivity	Th. diffusivity (simulation)	Uncertainity (simulation)	Th. diffusivity (measured)	Uncertainity (measured)
	m^2/s	m^2/s		m^2/s	
Aluminium	9,75E-05	8,96E-05	-8%	7,77E-05	-20%
Copper	1,18E-04	1,08E-04	-8%	1,08E-04	-9%
Brass	3,41E-05	3,39E-05	-1%	3,78E-05	11%
Mag. steel	1,86E-05	2,04E-05	10%	2,01E-05	8%
Non mag. steel	4,10E-06	4,09E-06	0%	4,16E-06	1%

Simulation results are on a satisfactory level of uncertainty – below 10% and measured values – 20 %.

Specific heat capacity estimation

Attempt of the heat capacity estimation was driven on the same configuration as above. Current step impulse has value of several hundred amperes and takes about 5-6 multiple of halftime of given material. Table 3. presents comparison of real measurements with assumed values.

Table 3. comparison of real measurements with assumed values – specific heat capacity

Material	c [J/(kgK)]		Uncertainity
	Assumed	Measured	
Aluminium	900	1062	18%
Copper	380	454	19%
Brass	377	404	7%
Magnetic steel	450	496	10%
Nonmagnetic steel	500	470	-6%

Real measurements has level of uncertainty lower than 20 % in comparison with assumed values. That allows to claim that this method gives results on satisfactory level of uncertainty and it can be used in further, more accurate process of determining material properties.

Summary

Experiments showed several important conditions that have to be fulfilled to minimize results uncertainty. It is significant to take into consideration phenomena of strong saturation of elements (especially magnetic cores) in magnetic circuit while carrying out an experiment of estimation thermal diffusivity. Analysis and knowledge of inductor voltage is significant in case of analysis a mentioned phenomena. It is important to provide stable amplitude value of current while impulse. In case of short pulses (10 ms) with the power of 15 kW it is possible to reach relatively high level a energy above 100 J which is transmitted by the electromagnetic wave.

It is competitive for commercial devices which are using laser as source of energy. More over it is very important to concentrate on measuring devices such as sensors and transducers. It have to provide good dynamic parameters – below 10 ms in this application.

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Autors: *dr hab. inż. Jerzy Zgraja, prof. PŁ, Politechnika Łódzka, Instytut Informatyki Stosowanej, ul. Stefanowskiego 18/22, 90-924, Łódź, E-mail: jzgraja@p.lodz.pl; mgr inż. Adam Cieślak, Politechnika Łódzka, Instytut Informatyki Stosowanej, ul. Stefanowskiego 18/22, 90-924, Łódź, E-mail: acieslak@kis.p.lodz.pl*.

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