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Pulse method for estimation thermal diffusivity of induction heated charge

Abstract. *The study was devoted to analysis of possibility of using the impulse Flash method for determination thermal diffusivity of induction heated charge. Cylindrical shape samples were analysed in two setup's: "natural" and "side". A process of determination the relation taking the radial heat flow into account which allows to determine thermal diffusivity was described.*

Streszczenie. *Opracowanie poświęcono analizie możliwości wykorzystania metody impulsowej Flash do wyznaczenia dyfuzyjności cieplnej materiału w układzie nagrzewania indukcyjnego. Analizie poddano próbki walcowe wsadu nagrzewane w układzie: „od czoła" i „od boku". Przedstawiono zależność umożliwiającą wyznaczenie dyfuzyjności cieplnej w metodzie Flash przy radialnym przepływie ciepła wewnątrz nagrzewanej próbki walcowej.* ***(Metoda flash do szacowania dyfuzyjności cieplnej indukcyjnie nagrzewanego wsadu)***

Keywords: thermal diffusivity, flash method, indirect method.
Słowa kluczowe: dyfuzyjność cieplna, metoda flash, metody odwrotne.

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Introduction

In industrial processes such as induction heating, the knowledge of material properties is useful and often necessary. It allows to evaluate the applicability of the material, as well as the use of computer simulations of the induction heating system. In practice, it is appropriate to determine the material parameters as cheap as possible without the participation of specialized experts. The computer software (e.g. CEDRAT Flux) gives a opportunity to simulate process with avoiding high costs of carrying out a real experiment. This paper is devoted to preliminary attempt to seek a solution for determining thermal diffusivity of induction heated charge using indirect pulse method which is a kind of wave method [1]. Principle of the method is based on analyses of temporary response of one-side heated flat charge by impulse of luminous flux [2]. In original applications of pulse method halogen bulb or laser beam was used as source of power impulse.

Present paper is devoted to investigation of possibility of using the pulse method with the existing in laboratory induction heating set up to determine thermal diffusivity of electric conductor. Analysis consists of the tests such as: possibility of applying the induction heating set up as a source of forcing thermal signal, possibility of using cylindrical charge because of simple built and relative simple 2D dimensioning for computer simulations in accordance to electromagnetic and thermal occurrences. A current literature is lack of applications for induction heating in process of determination material properties. As it was mentioned above, determination of thermal diffusivity is mainly based on analysis of time dependent thermal reply of flat sample which is radiated with luminous flux. On that account only relations describing the variant with the one – direction heat flow in flat sample are well-known. Generally, the geometry of the set up's of the induction heating causes, that evenly heating flat surfaces is troublesome. Cylindrical shape charge is probably better solution in this specific set up. Lack of relations describing radial heat flow in mentioned charge is a main concern for which present article is devoted.

Measurement of thermal diffusivity using pulse method

Relation given below determines relation between thermal diffusivity a and thermal conductivity as follows:

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

where: λ – thermal conductivity, c – specific heat, ρ – density.

Pulse method presented initially by W.J. Parker in 1961 is one of methods which allows to determine thermal diffusivity. Procedure of measuring consists of giving impulse (close to Dirac's impulse) of electromagnetic radiation to one side of the flat sample and then registration of changes of temperatures on the other side (Fig. 1). Required impulse character of signal determines laser as a appropriate and often used solution. Value of thermal diffusivity is described by relation (2) [2].

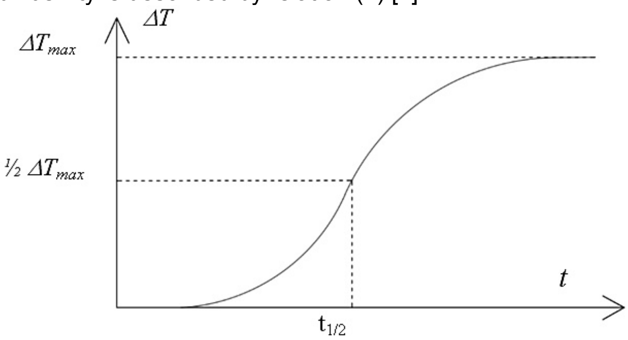

Fig. 1. Time dependent temperature characteristic of sample.

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

where: L – thickness of sample, $t_{1/2}$ – halftime of maximum temperature.

One of implementation where cylindrical charge and induction heating was recalled appears in B. Hay and others research [3]. Difference is that they considered induction heating only to achieve appropriate level of temperature of heated charge but not as energy impulse. Measured heat flow refers axial flow as in flat samples.

Implementation of pulse method in induction heating process of determining material properties

A) "Natural" setup

Originally flash method was intended for an instance of one-way heat flow in flat sample. Analysed case of cylindrical charge heated from the front (in "natural" arrangement) is fully accordant with the known relations for flat sample with temperature measuring point located on opposite to heated side of charge. The schematic diagram of recalled solution applied into induction heating setup was presented in Fig.2. A commercial software Flux from

CEDRAT was used for coupled fields, electromagnetic and thermal calculations. A sensitivity analysis of the methods for material and geometrical parameters of samples were one of accomplished aims of examinations. For that purpose computations analysis for two samples were made. Samples were made of material varied by thermal conductivity at the level of: λ=40 and 400 W/(m·K) and heights such as: h=30 and 50 mm.

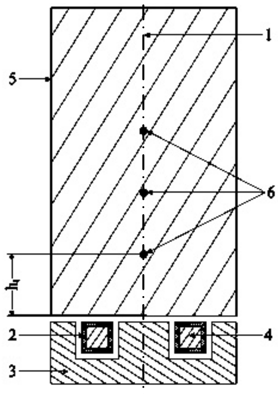

Fig. 2. Schematic diagram of „natural" heating setup: 1 – charge, 2 – inductor, 3 – magnetic shunt, 4 – cooling liquid, 5 – thermal insulation, 6 – temperature measuring points.

Table 1. Calculation results for samples with various thermal conductivity and height

h	λ	Δt	a	a_{obl}	$t_{1/2}$	$\lvert a-a_{obl}\rvert/a$
mm	W/(m·K)	s	m²/s	m²/s	s	%
30	40	0,2	1,026 ·10⁻⁵	$1{,}241\cdot10^{-5}$	4,51	20,91
		0,3		$1{,}227\cdot10^{-5}$	4,56	19,58
50		0,2		$1{,}112\cdot10^{-5}$	5,03	8,41
		0,3		$1{,}101\cdot10^{-5}$	5,08	7,34
30	400	0,2	1,026 10⁻⁴	$1{,}017\cdot10^{-4}$	0,55	0,89
		0,3		$9{,}390\cdot10^{-5}$	0,60	8,48
50		0,2		$9{,}231\cdot10^{-5}$	0,61	10,03
		0,3		$8{,}523\cdot10^{-5}$	0,66	16,93

Table 2. Calculation results for samples with various location of temperature measuring point

h	λ	h_t	α	α_{obl}	$\lvert a-a_{obl}\rvert/a$
mm	W/(m·K)	mm	m²/s	m²/s	%
30	40	10	1,026 10⁻⁵	$1{,}250\cdot10^{-5}$	21,84
		20		$1{,}241\cdot10^{-5}$	20,91
50		10		$1{,}250\cdot10^{-5}$	21,87
		20		$1{,}112\cdot10^{-5}$	8,41
		30		$1{,}138\cdot10^{-5}$	10,91
30	400	10	1,026 10⁻⁴	$6{,}991\cdot10^{-5}$	31,86
		20		$1{,}017\cdot10^{-4}$	0,89
50		10		$6{,}991\cdot10^{-5}$	31,86
		20		$9{,}231\cdot10^{-5}$	10,03
		30		$1{,}035\cdot10^{-4}$	0,87

Additional, the following analyses were made: dependence of duration of heating pulse (Δt), height of temperature measuring point (h_t, Fig.2), arrangement with cooling set which improves and assures near to one – direction heat flow in sample. Table 1 describes comparison of achieved results for two heights of the sample 30 and 50 mm and two durations of heat impulse Δt=0.2 and 0.3 s. According to presented results it is possible to state that the influence of the pulse duration Δt on the inaccuracy of received results is particularly noticeable for charges with the higher thermal conductivity λ (short halftime). To focus more on the accuracy of estimating thermal diffusivity a, in the Table 2 results of such analysis (at t=0.2 s) were presented.

According to presented results it is possible to state, that results for the sample with thermal conductivity at the level of λ=400 W/(m·K) in general are overvalued and for the charge with λ=40 W/(m·K) undervalued. Increasing length of diffusion of heat flux through the sample is increasing accuracies of the results in both of considered cases, but here appears a limitation of distance from temperature test point associated with increasing dispersion flux.

Results which were presented above concerns the model with the forced cooling of the sample. In the objective of simplification of the structure of the measurement system there was analysed arrangement without the forced cooling. As a replacement for the cooling setup, thermal insulation on the lateral and one front surface was applied, excluding from a model influence of convection losses. Results were presented in Table 3.

Table 3. Results for setup without forced cooling

h [mm]	λ [W/m/K]	h_t [mm]	a [m²/s]	a_{obl} [m²/s]	$\lvert a-a_{obl}\rvert/a$ [%]
50	40	10	$1{,}026\cdot10^{-5}$	$1{,}261\cdot10^{-5}$	22,88
		20		$1{,}095\cdot10^{-5}$	6,70
		30		$9.11\cdot10^{-6}$	11,18
	400	10	$1{,}026\cdot10^{-4}$	$6{,}755\cdot10^{-5}$	34,17
		20		$9{,}245\cdot10^{-5}$	9,90
		30		$8{,}334\cdot10^{-5}$	18,78

Comparing results from table 2 and 3 it is easy to notice the influence of removing the cooling system. Received results are at the 20% level of measurement uncertainty. Only for the sample with λ=400 W/(m·K) and h=10 mm the result exceeded the recalled level.

B) Side heating setup

As a geometrical arrangement of side heating setup a configuration in which the heat flow is moving radially towards an axis of symmetry of the cylinder was assumed. It changes already published descriptions of pulse method so radically that there is need to appoint such a relation for radial heat distribution in induction heated cylinder. The described model assumes using the flat sample and preserving the one-way heat flow. In literature researches such as [4, 5] concerning the application of the Flash method with impulse pointed to the lateral surface of the cylinder was presented, however it isn't regarding the radial flow of the heat flux. One should notice, that according to studies [4, 5, 6] halftime $t_{1/2}$ only and exclusively depends on thermal diffusivity a and heat flux diffusion distance R. It is possible to describe with relation:

(3) $$t_{1/2} = A \cdot R^2 / a$$

where: A – characteristic factor of the given instance.

Table 4. Material properties of considered charges

Material	μ_r	ρ_e	λ	c	ρ
	-	Ω·m	W/(m·K)	J/(kg·K)	kg/m³
Cooper	0,999994	$1{,}67785\cdot10^{-8}$	401	380	8920
Aluminium	1,00002	$2{,}65252\cdot10^{-8}$	237	900	2700
Steel	100	$1{,}7100\cdot10^{-7}$	58	466	7860
Titanium	1,000075	$4{,}2735\cdot10^{-7}$	21,9	520	4507
Graphite	0,999984	$3{,}75\cdot10^{-6}$	140	710	2267

Accepting the correctness of the relation (3) also in the analysed case (where R will be equal to the radius of cylindrical sample) of heating "from the side" an attempt of computational appointing the A coefficient value was conducted. Calculations were based on numerical

simulations, instead of an analytical considerations what receives discreet coefficient values of A. In order to increase the correctness of the examination five typical materials (with various material properties) of the sample were subjected to computational analysis (Table 4).
Calculations of A factor was carried out with the 1D numerical model of cross section of cylinder (Fig. 3).In order to avoid heating unevenness, a linear heat source (with specified power) was applied on circumference of the charge.

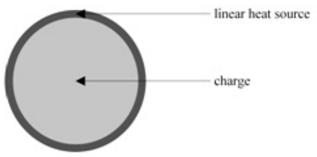

Fig. 3. Numeric model of theoretical setup representing radial heat flow.

Calculations of the $\boldsymbol{A}$ factor were carried out by using the relation (3) in which partial time was appointed by simulation at assumed material parameters (definied thermal a) but the value of thermal diffusivity were accepting equal of the value used in the simulation. In Fig. 4 a relation of the inaccuracy of setting the factor A was described with the relative error taken back to the value $A_{0,001}$ achieved for the various materials at the pulse duration τ = 0.001 sec. (as Dirac impulse).

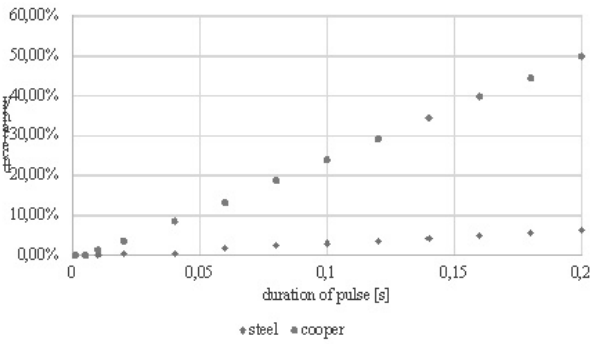

Fig. 4. Relation between uncertainity of determining factor A and duration of heat impulse.

Analysis of the influence the power of the surface heat source state, that higher value of power causes increase of result inaccuracy. However the appearing mistake is negligible and at the change of the power from 250 in to 1000 W grew about 2.5 %.

For forcing impulse much different than impulse Dirac the influence of the radius of the sample on the accuracy of achieved results is significant. In Fig. 5, for two pulse durations, a value of the inaccuracy of the appointment was described but for two materials: steel and copper additionally varied by the value of the radius.

Conducted calculations and the analysis of the results explicitly allow to state, that (at pulse durations technically possible to carry out) the value of the radius of the charge has a large impact to the achieved result. Along with the growth of the radius of the sample, i.e. extending the distance, with which the heat flux is flowing reduces the uncertainty of determining the factor A. Increasing the diameter of the cylinder is preferred, although it is important that it simultaneously the value of measured temperature is reduced which is certain technical issue to consider.

Theoretical analysis which was described above states the coefficient A at the value of 0,1073 and formulates the relation for the halftime for the case of the radial heat flow as:

(4) $$t_{1/2} = 0{,}1073 \cdot R^2 / a$$

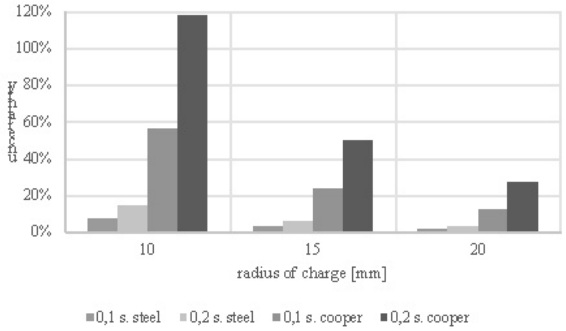

Fig. 5. Influence of radius of charge on accuracy in determination of factor *A*.

Additionally it is stated that to achieve least sensitive to the kind of material method one should apply:
- possibly shortest, technically possible, pulse duration of the power;
- possibly high power of impulse, at the level of (500 ÷ 1000) W.
- possibly high diameter of the sample, at preserving the appropriate to measure increase of the temperature.

Summary

Based on made simulations and performed calculations it was stated about a real opportunity of the application of the Flash method in the layout of the induction heating to determine thermal diffusivity of material. Appointed relation (4) taking the radial heat flow into account inside the cylinder charge allows to use the arrangement of heating "from the side" for appointing temperature characteristics of thermal diffusivity (determining at different levels temperatures of the charge), and in the more distant prospect also of characteristics of the thermal conductivity of materials.

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