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Thermal analysis of excitation circuit for pulsed eddy current transducer

***Abstract**. The aim of this paper is to determine correlation between parameters of a pulse current source and temperature of an excitation coil in eddy current Printed Circuit Board (PCB) transducer. A flow of microsecond pulse current having tens of amperes amplitude is causing significant rise of a copper trace temperature. Therefore, finding a safe working range through a proper selection of amplitude, frequency and duration of the pulse current, is an important task which can prevent damage of the transducer.*

***Streszczenie.** Celem niniejszego artykułu jest ustalenie współzależności pomiędzy parametrami impulsowego źródła prądowego a temperaturą cewki wzbudzenia wiroprądowego przetwornika wykonanego w technologii obwodów drukowanych (PCB). W obwodzie wzbudzenia podczas przepływu mikrosekundowego impulsu prądu o amplitudzie rzędu kilkudziesięciu amperów dochodzi do znaczącego wzrostu temperatury miedzianej ścieżki. Dlatego też, określenie bezpiecznego zakresu pracy poprzez odpowiedni dobór amplitudy, częstotliwości oraz czasu trwania impulsu prądu może zapobiec uszkodzeniu przetwornika. (**Cieplna analiza obwodu wzbudzenia dla impulsowego wiroprądowego przetwornika**).*

Keywords: printed circuit, Joule heating, pulse current, PCB transducer.
Słowa kluczowe: obwód drukowany, ciepło Joule'a-Lenza, prąd impulsowy, przetwornik PCB.

Introduction

Eddy current testing is one of the most popular nondestructive testing techniques used for inspection of conducting materials. The new industrial safety demands, require substantial improvements of this technique, both in sensitivity and reliability. One type of systems for eddy current nondestructive testing is a pulse system. On the basis of the output pulse signal waveform obtained in the time domain it is possible to identify and characterize defects in conductive materials, which are widely used in the chemical, nuclear and aerospace industry [1, 2]. The ability to detect defects depends on the proper selection of the excitation parameters. The demand for detection of the deep located defects is the cause of increasing excitation currents. Widely used standards for design rules of printed circuit boards don't include guidelines concerning the temperature rise due to the flow of pulse current. Therefore, experimental works focused on practical tests of temperature rise, supervised by infrared thermography were carried out.

According to the Joule's law, heat Q generated in time t, during the flow of pulse current i through the copper trace with an electric resistance R, can be written in form:

$$Q = R\int_0^t i^2(t)dt \tag{1}$$

The electrical resistance of trace R is characterized by geometry circuit and local temperature T.

$$R = \frac{l\rho_0(1+\alpha(T-T_0)}{A} \tag{2}$$

where: l – length of the copper trace, A – cross-section area of the trace, ρ_0 – copper electrical resistivity at temperature T_0, α – temperature coefficient of resistivity, T_0 – reference temperature.

The electrical resistivity ρ of the copper trace at temperature 273 K is equal to $1.678*10^{-8}$ Ωm and the electrical resistance increases with temperature approximately at a rate of α = 0.0039 K^{-1} [3]. In practice, the temperature of a copper trace on a PCB is the result of thermal equilibrium between Joule heating and convective heat transfer to the ambient environment. During design of PCB some technological restrictions have to be taken into account. In example a glass transition temperature for FR4 (grade of glass epoxy laminate) must not exceed 110 °C [4]. Temperature rise of the copper trace depend on the cross sectional area, thickness of the PCB, kind of utilized dielectric material, ambient temperature, amount and adjacency of copper in the board [5, 6]. Additionally, the parameters of the excitation current pulse affects significantly the achieved results. Research focuses on one of the most common excitation coil structure.

Specification of test coil

Figure 1 shows configuration of the PCB transducer used in the research. The transducer consists of two detections coils and one excitation coil fabricated on four layers of FR4 material. A separate excitation coil was manufactured in order to carry out the thermal analysis.

a)

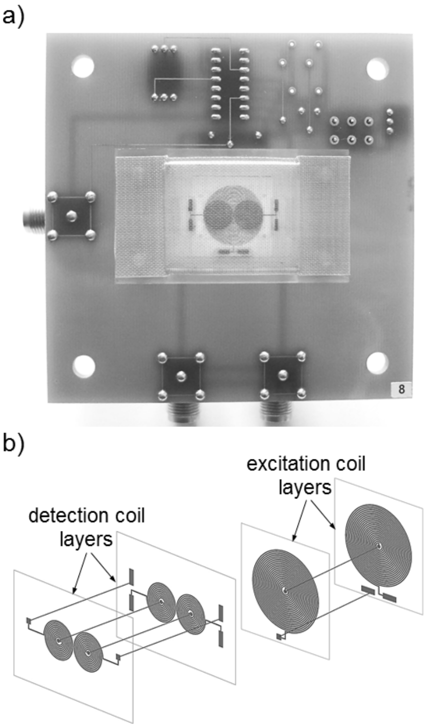

Fig.1. PCB transducer: a) photo, b) schematic view

The test coil was manufactured on double-sided board. It has a square shape (l = 20 mm, h = 20 mm), with a thickness of 0.2 mm. Top and bottom side board has 22.5

of Archimedean spiral turns made of copper without a solder mask. The trace thickness is 35 μm and width is 0.15 mm, while the spacing between of two neighboring traces is 0.15 mm. Photos and a schematic view of the test coil is shown in Figure 2.

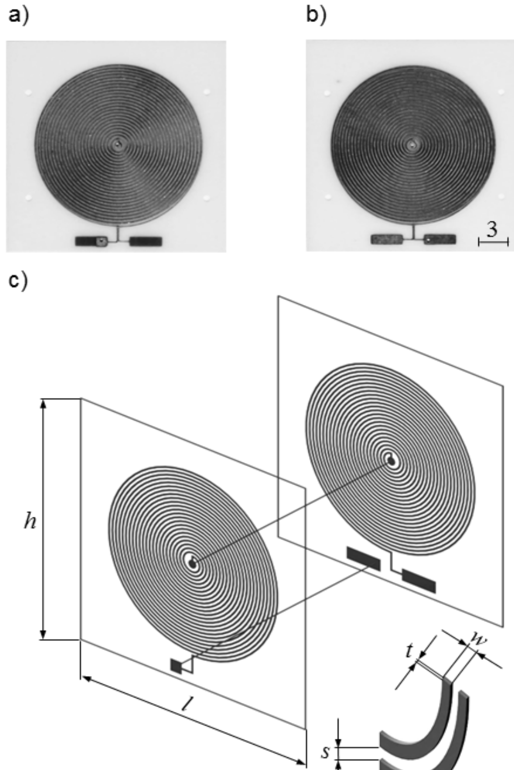

Fig.2. Test coil: a) photo of the top side, b) photo of the bottom side, c) schematic view (h = 20 mm, l = 20 mm, s = 0.15 mm, t = 35 μm, w = 0.15 mm)

Measurement system

A block diagram of the measurement system is shown in Figure 3. The main component of the system is a pulse current generator. A schematic diagram and parameters of the pulse current generator are described in [2]. Data acquisition of output signals was carried out using a oscilloscope with a sampling frequency 150 MHz and a thermographic camera with a sensitivity <0.1 °C at 25 °C. The thermographic camera was placed 10 cm above the tested PCB coil. The temperature was measured from the top side of the coil.

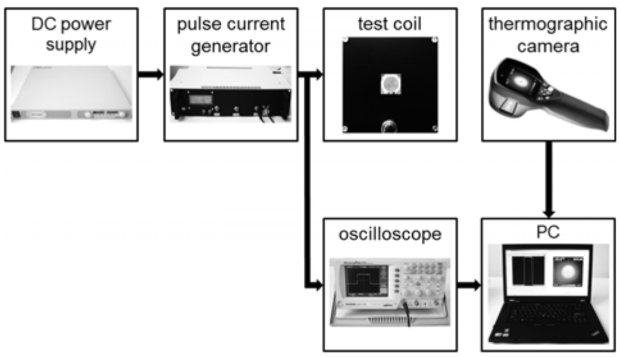

Fig.3. Block diagram of the measurement system

Results of experiments

During the tests, the duration of pulse current was from 10 μs to 100 μs. For each pulse current duration time the amplitude of current was adjusted to achieve temperature of the trace around 100 °C. This temperature was selected because of the maximum permissible glass transition temperature of the laminate. The analyzed PCB board was free standing in a laboratory environment with the ambient temperature at 22 °C. The individual values of temperatures were recorded after reaching the steady temperature of the trace. Selected waveforms of the pulse excitation current are shown in Figure 4.

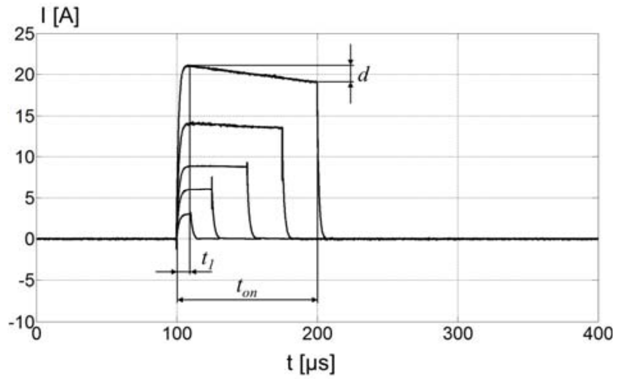

Fig.4. Examples of waveforms of pulse current (t_1 - time to peak of amplitude pulse current, t_{on} - duration of pulse current, d - drop of pulse current)

As shown in Figure 4, increasing amplitude of the pulse current is causing a greater drop of signal became greater. The drop of pulse current d can be calculated as:

$$d = \frac{i(t_1) - i(t_{on})}{i(t_1)} 100\% \tag{3}$$

Temperature of the trace was measured on the top side of the board. The highest temperature was observed at the middle of the test excitation coil. Heat spreading topology is dominated by the pulse energy, the footprint of the copper trace, electrical and thermal conductivity of the copper and substrate. Exemplary thermal images of the test coil are presented in Figure 5.

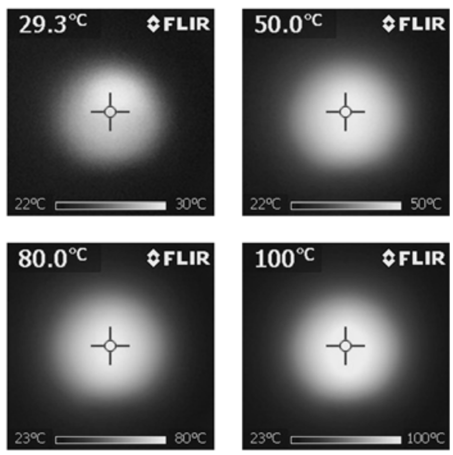

Fig.5. Thermal images of the test coil obtained during experiments

Figure 6 shows dependency between a temperature of the excitation and an average value of the current pulse. Results of experiments show a big variations of temperature rise. In case of temperature trace 100 °C, change of frequency from 1 Hz to 10 Hz brings about a threefold increase in the average value of the pulse current (Fig.7).

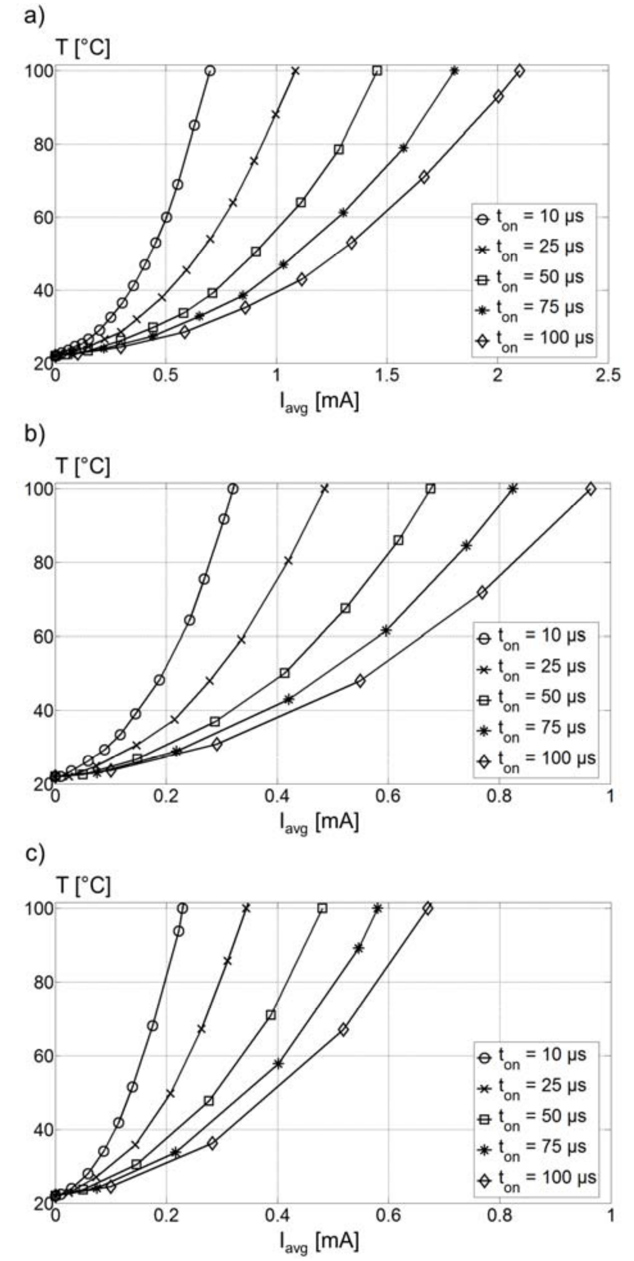

Fig.6. Temperature of the excitation coil as function of average value of current pulse for frequency: a) 1 Hz, b) 5 Hz, c) 10 Hz

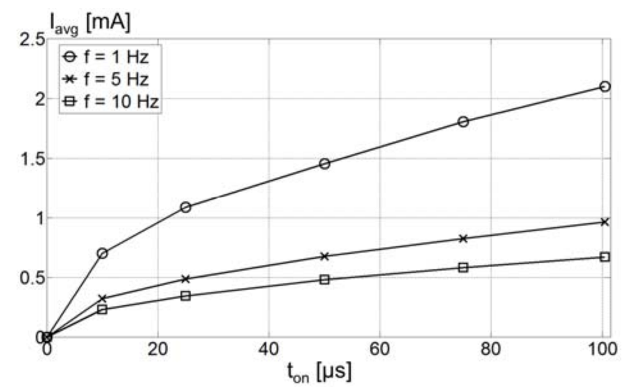

Fig.7. Average value of pulse current as function of duration time of the pulse current; temperature of the copper trace was equal to 100 °C

Conclusions

The results of measurements show that temperature rise of the PCB coil depends on the current amplitude, the pulse width and the frequency. The frequency change from 1Hz to 10Hz is causing a significant increase of the coil temperature. The relation between parameters of the current pulse and temperature of the coil highly depends on the particular parameters of the PCB structure. Therefore, the thermal analysis should be carried out for each individual structure of the PCB transducer.

The results of the experiments can be regarded as a starting point for the design of the excitation circuit. In case of a multilayer structure, which restricts the heat transfer to a surrounding environment a cooling structure has to be applied. Otherwise, changes of the excitation circuit resistance caused by the rising temperature will have a negative impact on the measurements repeatability.

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