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Evaluation of Heterogeneity of Paint Coating on Metal Substrate Using Laser Infrared Thermography and Eddy Current

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Abstract**—**Non contact evaluation of the thickness of paint coatings can be attempted by different destructive and nondestructive methods such as cross-section microscopy, gravimetric mass measurement, magnetic gauges, Eddy current, ultrasound or terahertz. Infrared thermography is a nondestructive and non-invasive method that can be envisaged as a useful tool to measure the surface thickness variations by analyzing the temperature response. In this paper, the thermal quadrupole method for two layered samples heated up with a pulsed excitation is firstly used. By analyzing the thermal responses as a function of thermal properties and thicknesses of both layers, optimal parameters for the excitation source can be identified. Simulations show that a pulsed excitation with duration of ten milliseconds allows obtaining a substrate-independent thermal response. Based on this result, an experimental setup consisting of a near-infrared laser diode and an Infrared camera was next used to evaluate the variation of paint coating thickness between 60 µm and 130 µm on two samples. Results show that the parameters extracted for thermal images are correlated with the estimated thicknesses by the Eddy current methods. The laser pulsed thermography is thus an interesting alternative nondestructive method that can be moreover used for nonconductive substrates.

Keywords**—**Nondestructive, paint coating, thickness, infrared thermography, laser, heterogeneity.

I. INTRODUCTION

COATING technology with a thickness of few dozen is widely used in various industries to achieve functional surfaces (wear resistance, corrosion resistance, cosmetic aspect, etc.) [1]. The thickness of the paint coating has to be controlled in several manufacturing industries such as automotive and aerospace, because it influences directly product performances aspect, etc.

Destructive methods such as cross-section microscopy or gravimetric (mass) measurement [2] induce surface damage. These methods are used when nondestructive methods are not possible, or as a way of confirming nondestructive results.

In the field of nondestructive inspection of paint coatings, many measuring techniques are commonly used:

- *Magnetic gauges* [3], [4] are based on magnetic flux measurement through the layer of sample. The inadequacy of this method is the determination of thickness for multilayered coating layer.
- *Eddy current method* [5] use the interaction between a magnetic field source (i.e. coil probe) and the testing material to determine the thickness of the coating. The interpretation of the signals collected require a comparison with those provided by a reference sample [6].
- *Ultrasound testing* [7] estimates the paint thickness on nonmetal substrates via the velocity of ultrasonic waves in the layer. The ultrasonic sensor may be combined with other method such as Eddy current [2] or capacitance sensors. Ultrasound testing generally requires homogeneous surfaces, not being adapted on the measurement of heterogeneities.
- *Terahertz methods* measure the time delay of a terahertz waveform using different analyzing methods such as terahertz imaging [8], terahertz sensor [9] or time-domain spectroscopy [10], but most of these methods are required a refractive index for calculating the coating thickness.

Infrared thermography is a non-invasive method that can be used as a sensitive tool to measure the surface thickness variations by analyzing the temperature response. A laser, which is monochromatic and unidirectional, provides enough homogeneous heat for highlighting the thickness variations of paint coatings. Besides, it provides safe, low power [11] and a constant precision over the operational range [12].

This paper is devoted to prove the capacity of the infrared thermography to assess the heterogeneity of paint coatings on steel substrate. Firstly, a numerical simulation model has been used to examine the thermal behavior of the variations of the paint coating layer. This analysis allows optimizing the excitation parameters, thus generating prior information for real experimentations. Then, an experimental test setup using a laser and an Infrared thermal camera was used to analyze paint coatings varying between 60 µm and 130 µm. Results show that our system using pulsed laser combined to infrared thermography allows an accurate evaluation of the heterogeneity of paint coatings as compared with the results given by the Eddy current method.

II. MATERIALS AND METHODS

A. Samples

Two paint coated samples of the same dimensions 1000 mm x 70 mm are considered. A black paint layer (epoxy) was

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heterogeneously disposed on the steel substrate. Samples are thus composed of two layers: a steel layer of around 2mm thickness and a second layer of paint coating with a means thickness of 80µm and 100µm respectively for the first and second sample. The coating thicknesses variations were in the range of 60 µm-90 µm and 75 µm-130 µm respectively. The heterogeneity of the paint coatings was evaluated with the Eddy current method over one direction in the middle of the sample with a spatial resolution of 15 mm. For this reason, the laser infrared thermography method was applied on the same two samples along the same direction in the middle of the sample and with the same spatial resolution of 15 mm.

B. Thermal Modeling

In the case of two layers samples (paint coatings on steel substrate); the thermal response may arise from each one of the layers. A thermal response that will be measured by an infrared camera will therefore reflect the thermal properties of both layers. To obtain a substrate-independent thermal response, the properties of the heating source should be addressed. In order to get an insight on the influence of the substrate and be able to highlight only the thermal response of the paint coating, a finite element model based on physic-thermal representation was developed under Comsol™ [13].

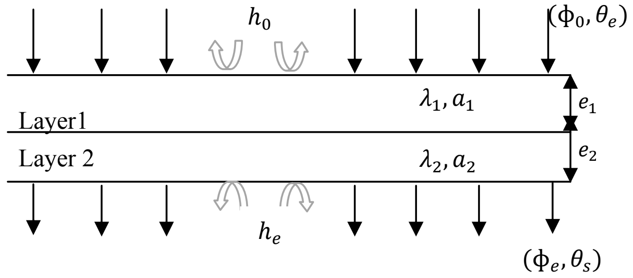


Fig. 1 Model for a two-layered structure [14]

This model takes into account the different thermal response according to the thicknesses of the two layers and the excitation parameters, as shown in Fig. 1. This model requires the physical parameters of each layer and the parameters of the excitation, as indicated in Table I. In this model, each layer was represented by a thermal quadrupole, as shown in Fig. 2, and the heat transfer was considered to be one dimensional [15].

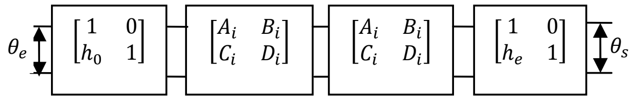


Fig. 2 Representation of three cascaded quadrupole of two-layered samples [14]

The heat transport inside the sample is described by Stefest algorithm and Laplace transformation. Equation (1) represents the fundamental result of thermal quadrupole method which linearly relates the input vector (temperature, heat flux) to its corresponding output vector through a square matrix called thermal quadrupole matrix [16]. The transformed heat flux $\phi_0(0, x=0)$ and temperature $\theta_0(0, x=0)$ can thus be expressed according to quantities $\phi_e(0, x=e_1)$ and $\theta_e(0, x=e_1)$ as [17]:

$$\begin{bmatrix} \theta_e \\ Q \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ h_0 & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ h_0 & 1 \end{bmatrix} * \begin{bmatrix} \theta_s \\ 0 \end{bmatrix} \quad (1)$$

The different steps of the method are not presented here, but can be found in [15]. The resolution of this matrix system led to:

$$\theta_e = \frac{[h(A_1B_2+B_1D_2)+A_1A_2+B_1C_2]Q}{h^2(A_1B_2+B_1D_2)+h(A_1A_2+B_1C_2+C_1B_2+D_1D_2)+C_1A_2+D_1C_2} \quad (2)$$

with:

$$A_i = ch(\sqrt{\frac{p}{a_i}}e_i); \; B_i = \frac{sh(\sqrt{\frac{p}{a_i}}e_i)}{\sqrt{\frac{p}{a_i}}k_i}; \; C_i = \sqrt{\frac{p}{a_i}}k_i\, sh(\sqrt{\frac{p}{a_i}}e_i); \; p = \frac{i\ln(2)}{t};$$

and $D_i = ch(\sqrt{\frac{p}{a_i}}e_i)$.

TABLE I

UNITS FOR THERMAL PROPERTIES

Symbol	Quantity	Units[a]
ϕ_0	Front heat flux density	$\mathrm{W.m^{-2}}$
a	Thermal diffusivity in layer	$m^2.s^{-1}$
ϕ_e	Rear heat flux density	$\mathrm{W.m^{-2}}$
θ	Laplace transform of the temperature	K°
e_i	Thickness in layer *i*	m
h_0	Front heat losses	$\mathrm{W.m^{-2}.K^{-1}}$
h_e	Rear heat losses	$\mathrm{W.m^{-2}.K^{-1}}$
A	Quadrupole Coefficient	-
B	Quadrupole Coefficient	$\mathrm{K.m^2.W^{-1}}$
C	Quadrupole Coefficient	$\mathrm{K.m^2.W^{-1}}$
D	Quadrupole Coefficient	-
λ_i	Thermal conductivity in layer *i*	$\mathrm{W.m^{-1}.K^{-1}}$
i	Index	–
t	Time	s

[a], W = Watt, K° = Kelvin, m = meters and s=seconds.

The estimation of the flux density allows modeling the thermal response of the two layers sample. Varying the physical parameters according to real samples that will be analyzed and the thickness of both layers, we are able to simulate different thermal responses and thus to pick up the optimal parameters of the excitation that highlight only the thermal response of the paint coating.

C. Experimental Setup

The experimental setup for the measurement of thermal properties on paint coating samples is shown in Fig. 3.

The specimen is heated by laser diode in the near-infrared region (λ=810 nm, power of 3W/cm^2). The laser beam passes through the mirror of a deviation device and heats the sample at a determinate position.

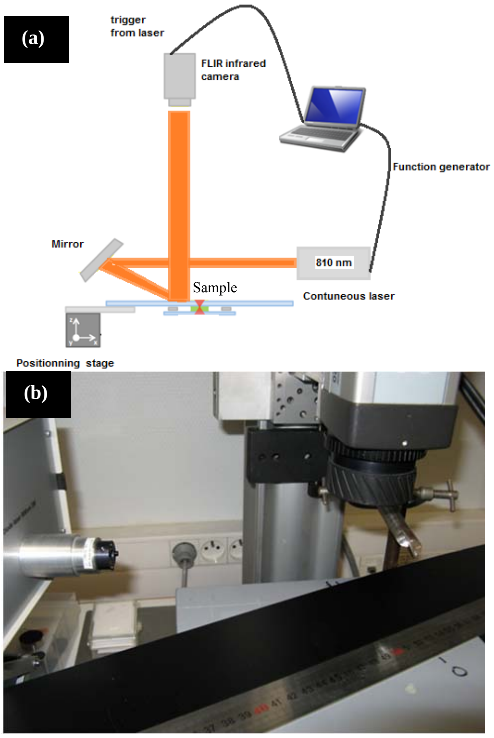
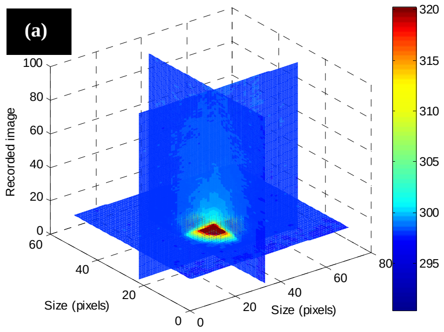


Fig. 3 Experimental setup: (a) Schematic representation. (b) Picture of the real setup implemented

A continuous acquisition by an Infrared (IR) camera (range of 7.5-13 µm, 640 × 480 matrix detector) is placed at 30 cm from the sample in 90° direction so as to detect the whole area heated by the laser. A programmable delay between the laser trigger and the infrared camera was set by the camera control unit. The position of the specimen is marked with a step of 15 mm. For one acquisition point, the IR camera provides a spatiotemporal collection of images called thermogram. After the thermogram record ended, the same procedure is repeated with another position.

This system provides high precision, quick response, non-contact measurement of the sample surface temperature through the laser pulse.



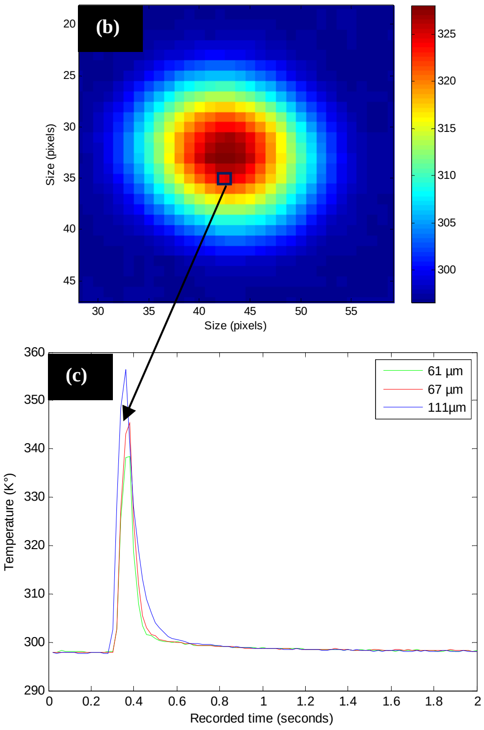


Fig. 4 Representation of 3D data corresponding to the spatiotemporal collection of thermal images for an acquisition point (b) The thermal image recorded at the maximum heat. (c) Temporal variations of the temperatures recorded by IR camera at the selected X-Y coordinate for coating thickness of 61µm (green), 67 µm (red), and 111 µm (blue)

D. Infrared Data Acquisition

The thermogram recorded at one acquisition point, as shown in Fig. 4 (a), can be modeled by a 3D data. This data cube is constructed by stacking up the temporal sequences of thermal images [18].

Theoretically, heating the sample with a laser, only one point of the analyzed sample should present a thermal variation. Practically, after passing through the mirror in the deviation device, heat dispersion is generated on the surface of the sample. Moreover, the sample itself is subject with thermal diffusion. As a consequence, each thermal image of the spatiotemporal collection has a Gaussian distribution as shown in Fig. 4 (b). This phenomenon can lead to misinterpretation of the thermal response. For this reason, we chose X-Y the coordinates in the thermal image sequences in which the maximum temperature is reached. Once the chosen coordinates, we are able to extract the thermal response of the sample analyzed as a function of time. Fig. 4 (c) shows the temporal variations of the temperatures recorded by an IR camera at three acquisition points presenting different coating thicknesses.

E. Data Processing

In this work, a spline analytical interpolation [19] of the discrete function defined by the temporal variations of the temperatures recorded by IR camera at the selected X-Y coordinate is used to achieve a better estimation of these temporal variations. Indeed, as the IR camera records images with a specified frequency, the temperature variation is sampled with the same frequency and the highest temperature can by missed out. As shown in Fig. 5, the interpolation allows identifying the highest temperature for an acquisition point as well as to better describe the temporal variations of the temperature.

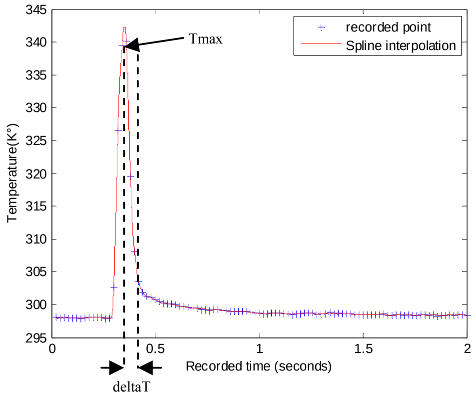


Fig. 5 Temporal variations of the temperatures recorded by the IR camera at the selected X-Y coordinate (dotted line) and temporal variations interpolated by spline (continuous line)

Once the temporal variation of the temperatures recorded by IR camera in an acquisition point were interpolated, we can extract two parameters: Tmax, representing the highest temperature that the acquisition point can reach and DeltaT, representing the time needed for a temperature decreasing to 25% from the maximal thermal excursion in the cooling phase. These two parameters are in concordance with the two-layered thermal model since, for an optimized excitation, the thermal variations related only to the thickness of the paint coating are highlighted by the highest temperature and the cooling phase.

III. RESULTS AND DISCUSSIONS

A. Identification of Optimal Heating Excitation Duration through Simulation

Numerical simulations of the thermal response of two-layered sample have been employed to determine the optimal thermal pulse excitation duration. This investigation was helpful to understand the relationship between the layer parameter (thicknesses, thermal properties) and the influence of excitation input on the thermal behavior of paint coating.

First, simulations were performed by varying simultaneously the thickness of the painting layer and the pulse heating duration in order to study their effects on the thermal response. Fig. 6 presents the thermal responses for three paint coating thicknesses varying in the range 60µm - 80µm for pulse excitation of duration 1, 10 and 60 ms. The metal substrate thickness of 500 µm was the same. The paint thickness variation has a radiative influence to transfer temperature to the metal substrate which has a high thermal conductivity.

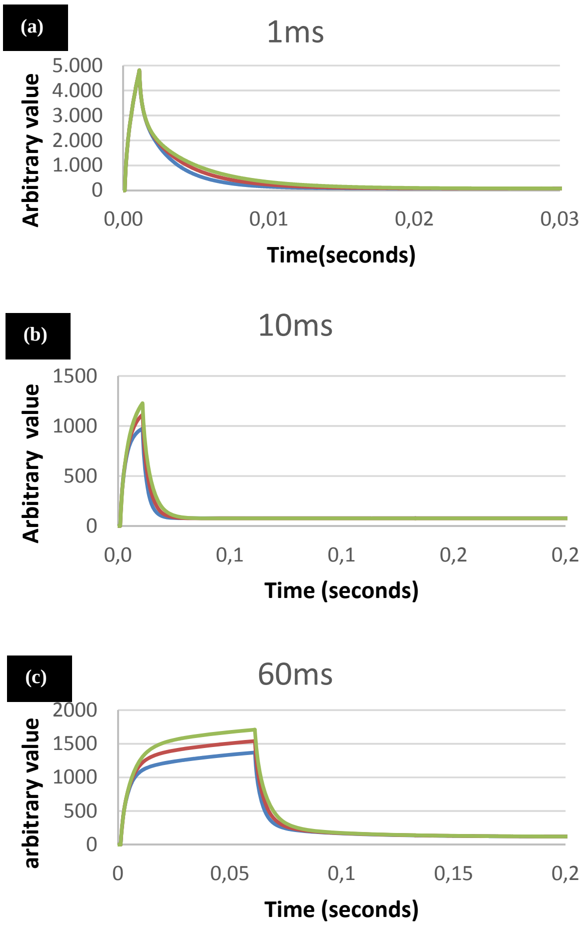


Fig. 6 Thermal response of paint coatings for laser pulse duration of (a) 1ms, (b) 10ms, and (c) 60ms for three paint coating thicknesses: 60µm (blue), 70µm (red), and 80µm (green). Fixed metal substrate thickness

These figures show that the time needed for a temperature decreasing to 25% from the maximal thermal excursion in the heating phase, i.e. DeltaT, is sensitive to the paint coating thickness whatever the duration of the excitation. The highest temperature that the acquisition point can reach, i.e. Tmax, is sensitive to the paint coating thickness only for excitation pulse above 10 seconds. As the epoxy thickness increases, there is a linearly increase in hotspot temperature. Hence, the measurement of thermal response can provide useful information of thickness variability. To conclude, from the first set of simulations, the optimal pulsed excitation duration should be between 10 and 60 milliseconds.

In the second simulation, we have studied the effect of the metal substrate thickness in the thermal response since this response is influenced by each one of the layers. Fig. 7 illustrates the fluctuation of temperature obtained for the same pulse excitation (duration of 1, 10 and 60 ms) by fixing the paint coating thickness to 70 µm and varying the metal substrate thickness between 500 and 700 µm.

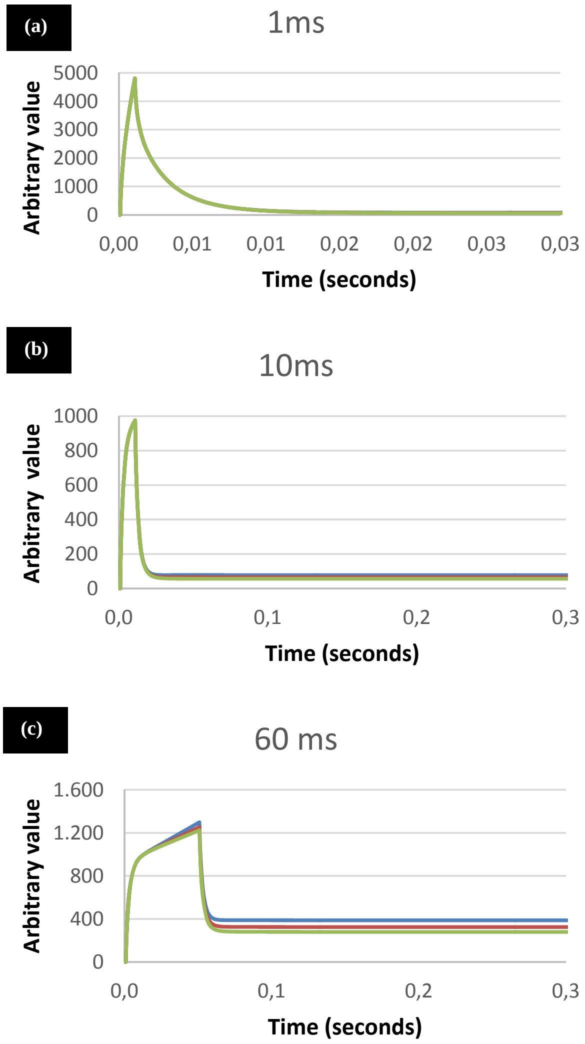


Fig. 7 Thermal response of paint coatings for laser pulse duration of (a) 1ms, (b) 10ms, and (c) 60ms for three metal substrate thicknesses: 500µm (blue), 600µm (red), and 700µm (green). Note that paint coating thickness is fixed

The substrate thickness has no effect on Tmax for pulsed excitation of duration lesser than 10 ms and a relative small effect as compared with the influence of the paint coating thickness for durations greater than 10 ms. The DeltaT parameter is more influenced by substrate thickness and the comparative analysis indicates that the duration of the pulsed excitation should be lesser than 10 ms.

From these two simulation studies, we conclude that a pulsed excitation of around 10 ms duration is needed to highlight only the thickness variation of paint coating layer and hence obtain a substrate-independent thermal response. This result served as the input of the next step of experimental setup in the next section.

B. Application on Real Samples

The laser-based pulsed thermography technique was compared to the Eddy current method for the samples presented in *section II.A* with paint coating thicknesses varying in the range 60µm - 130 µm.

Figs. 8 and 9 show that the thickness variation measurements along the coated sample length using the Eddy current technique is highly correlated to DeltaT and Tmax parameters obtained from the thermograms recorded by the thermography method using a pulsed laser. The correlation rate between the two approaches reaches 92%, confirming that the laser assures the necessary heating.

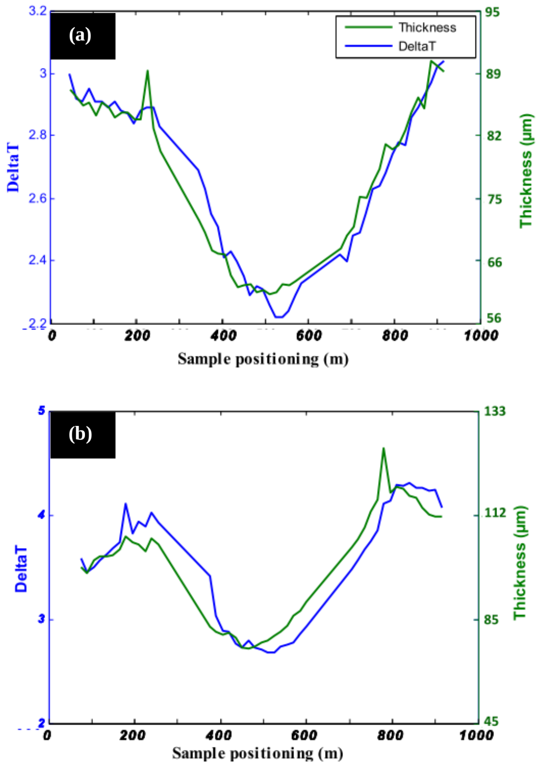


Fig. 8 Comparison of the DeltaT parameter extracted from temporal variations of the temperatures recorded by IR camera (blue curve) with the Eddy current measures (green line) for two samples having thicknesses variations of (a) 60 µm-90 µm (sample 1) and (b) 75 µm-130 µm (sample 2)

The discrimination observed on the thermal response during both heating and cooling stages is found to be conforming to numerical analysis results. Thus, it seems possible to characterize the thermal effect of the paint coating using laser infrared thermography. Another interesting application of the laser thermography can be the evaluation of paint coating heterogeneity on non-conductive substrates.

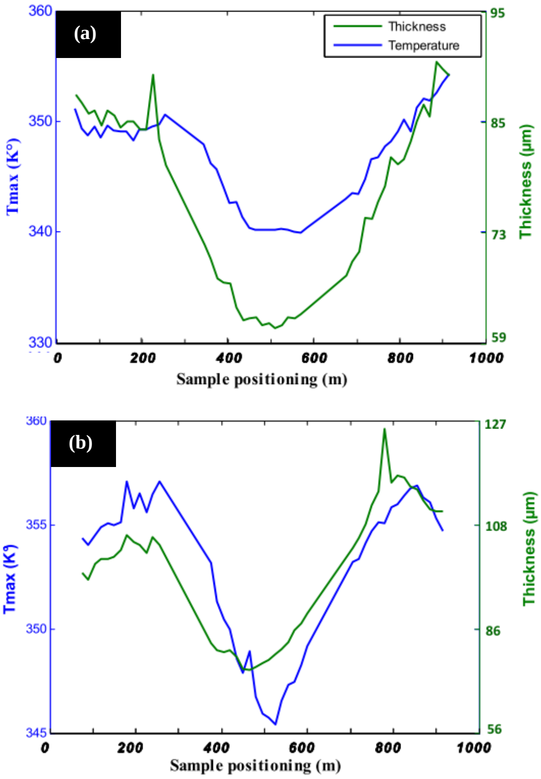


Fig. 9 Comparison of the Tmax parameter extracted from temporal variations of the temperatures recorded by IR camera (blue curve) with the Eddy current measures (green line) for two samples having thicknesses variations of (a) 60 µm-90 µm (sample 1) and (b) 75 µm-130 µm (sample 2)

IV. CONCLUSION

In this research, a non-contact measurement method of coating thickness heterogeneity was suggested. The optimal parameters of the excitation can be identified through numerical simulations that are based on the thermal properties of each layer. The experimental results show that the pulsed laser thermography method can successfully be employed to evaluate the variation of paint coating thickness. Practical use of laser NDE for thickness inspection of coating can thus be considered, as for example as a feedback control system of a painting device for improving the surface quality. Further work will concern a more robust analysis for different type of painting, colors and substrates including nonconductive substrates.

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