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Precision Measurement of Coating Thickness on Ferromagnetic Tube using Pulsed Eddy Current Technique

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The anti-corrosive metal coatings on ferromagnetic tubes are the important components in power plants and need non-destructive evaluation (NDE) techniques to measure their thickness precisely. The objective of this research is to develop pulsed eddy current (PEC) technique for measuring the coating thickness accurately. PEC signals are investigated for the evaluation of coating thickness using a differential PEC probe, which consists of a driving coil and two pickup coils. The characteristics of PEC signals for coating thickness variations show that the related features, such as the time-to-peak and peak value, change linearly with thickness change. A new feature, called as time to the rising point, related to the propagation time of electromagnetic field in conductive metals is adopted for coating thickness measurement. These features can be used to inspect the coating thickness within the accuracy of 0.02 mm.

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1. Introduction

Different types of coatings and surface treatments are applied to protect various engineering materials from corrosion, wear, and erosion in power plants. The anti-corrosive metal coating sprayed on the outside of tubes used in power plants is a crucial component for thermal exchange and prevents ferromagnetic tubes from rust and corrosion. Therefore, the thickness of metal coatings is important for both process control and in-service inspection. To maintain coatings with high quality and integrity, a NDE technique is indispensable to online measure the coating thickness in these structures of various sizes. Though there have been many non-destructive methods such as X-ray and ultrasonic testing for coating thickness measurement at present,[1-4] but they can't be applied to these coating structures with rough surfaces. Pulsed eddy current technique (PECT) is an effective non-contact method and has many applications for its fast speed and high sensitivity without surface roughness effects.[5] Since the PECT signal contains more information of the specimen under interrogation than eddy current testing, PECT technique has received a great deal of interest recently.

For the coating measurement using PECT technique, Tai et al.[6,7] developed a pulsed eddy current method to study current differential signals of PECT in determining the thickness of the conducting layer over an infinite metal substrate of known conductivity. However, PECT systems were made by subtracting measured signals from a reference signal on the substrate, which is not suitable for industrial applications. The single probe detects not only the magnetic elds of the induced eddy currents, but also the magnetic eld due to excitation coil. Therefore, the small eddy current elds due to thickness changes may easily be masked because of the very large excitation magnetic field. And also the noise of single coil is much bigger than other kinds of PECT probes.[8] Therefore, differential probe is developed to suppress noises and improve the detectability and robustness of PECT signal.[9] To obtain the induced eddy current field, the reflection-type PEC probe, which consists of an exciter coil and two pick-up sensors (hall sensors or coils) in a differential arrangement, is used to evaluate the conductive materials.[10-12] The differential probes have an advantage of avoiding the storage of the reference signal before starting the measurements. In this paper, a reflection-type probe consisting of a driving coil and two pick-up coils in a differential arrangement is adopted to evaluate the coating thickness. The probe can detect the multi-layered conductive specimens without the reference signals or reference samples and minimize the

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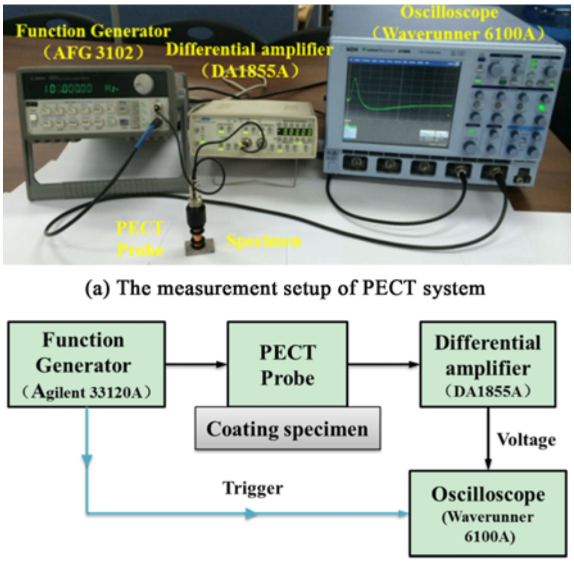


(a) The measurement setup of PECT system

(b) Block diagram of PECT system

Fig. 1 Pulsed eddy current experimental setup

effects of temperature variations due to the differential arrangements of two pick-up coils.

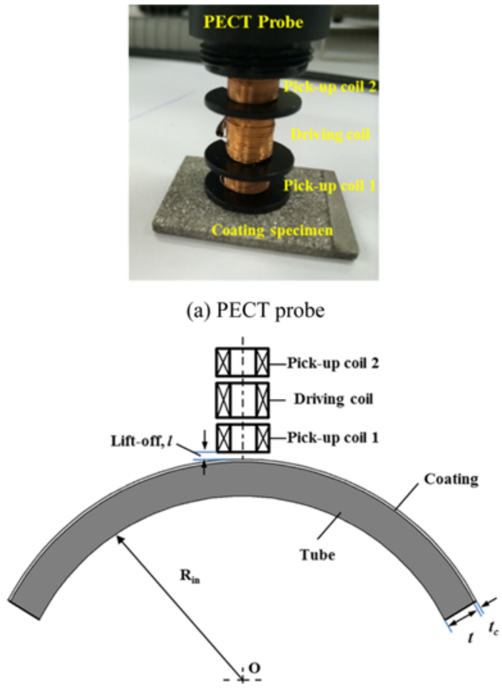
Generally, three PECT signal features such as the peak values, the time-to-peak and the zero-crossing time are applied to investigate coating thickness.[6,7] But for the ferromagnetic materials, the PECT signal does not show the zero-crossing time. A new obvious feature, the raising point of PECT signals obtained by the differential probes, is proposed for coating thickness measurement. The time to raising point changes due to the propagation time of electromagnetic waves in metals. Coating thickness can be measured robustly compare to other features.

The organization of this paper is as follows. In section 2, we describe the experimental setup and measurements. Results are processed described and features of experiment results are adopted for thickness characterization in section 3. Discussions and conclusions are also presented in last section.

2. PECT Experimental Setup and Coating Specimens

2.1 PECT experimental setup

Firstly, the PECT measurements are performed to investigate the coating structures with the new experimental set-up as illustrated in Fig. 1. A square-wave voltage signal is generated by a function generator (Agilent 33120A) that excites the probe's driving coil. The driving coil generates transient magnetic field to induce eddy currents in metallic specimen, then the eddy current magnetic field is generated by eddy currents. So the pick-up coil can detect the voltage change due to the variation of magnetic field. The output voltage of two pick-up coils is amplified by a differential preamplifier (DA 1855A), and the gain of the amplifier is changeable and a factor of 10 is applied in the experiment. Then digitized signals acquired by the oscilloscope (Waverunner 6000A) as shown in Fig. 1(a). The magnitude of the square wave pulse is 3 V, the excitation frequency is 1 kHz, and the duty cycle is 50%. Fig. 1(b) is a schematic diagram showing the PECT equipment developed in this study.



(a) PECT probe

(b) Schematic diagram of PECT probe for the coated steel tube

Fig. 2 PECT differential probe with two pick-up coils

Table 1 Coil parameters of PECT probes

Specifications	Driving coil	Pickup coil 1	Pickup coil 2
Length (mm)	9.0	6.0	6.0
Inner diameter (mm)	4.0	4.0	4.0
Outer diameter (mm)	10.4	10.6	10.6
Lift-off (mm)	9.0	1.5	22.5
Turns	202	405	409

2.2 PECT differential probe

In PECT experiments, the differential probe consists of one driving solenoid coil and two pick-up solenoid coils, which is shown in Fig. 2.[10] And the probe parameters are noted in Table 1. It has one excitation solenoid coil in the middle and two pickup solenoid coils on opposite sides of excitation solenoid coil. Both of the pickup solenoid coils are wound oppositely on plastic bobbins as shown in Fig. 2(a). In winding the pickup solenoid coils, we attempted to obtain a zero PECT response when the probe in the air. This gives slightly different number of turns in two pick-up solenoid coils as noted in Table 1. Therefore, nulling signals are measured when the probe is located in air. Fig. 2(b) shows the schematic diagram of PECT probe measuring above the steel tube. A special jig is designed to reduce the tilt effect of PECT probe and to guarantee the accuracy of measurements.

2.3 Coatings on ferromagnetic tubes

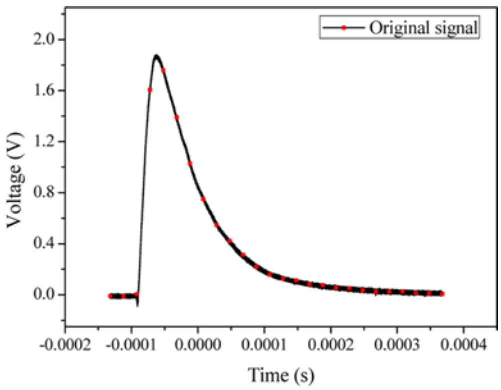
The tube is made of low alloy steel (A710 steel) and the coating is

(a) Coating specimen by arc spraying (b) coating specimen by plasma spraying

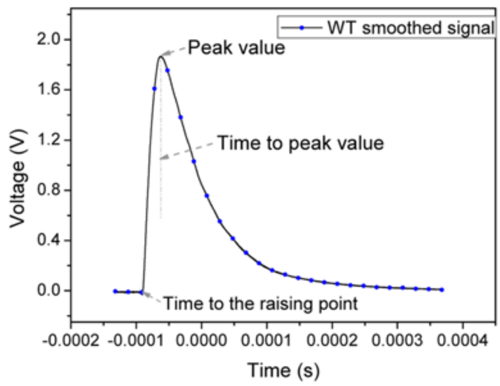
Fig. 3 Coating on ferromagnetic tube specimens

Table 2 The material properties of pipeline

	Material composition	Conductivity	Relative permeability
Plasma spraying coating	NiCrFe	0.65×10^{6}	1.1
Arc spraying coating	NiCrFe	0.45×10^{6}	1.1
Substrate layer	A710 steel	1.5×10^{6}	5.7



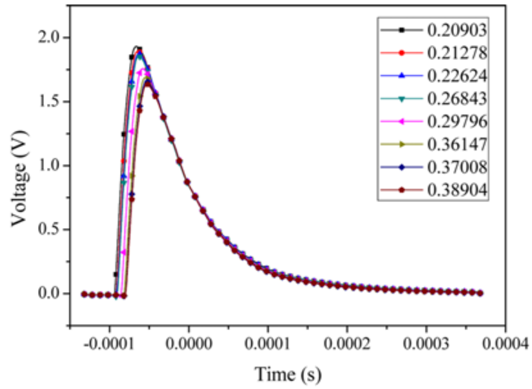
(a) The original transient response signal



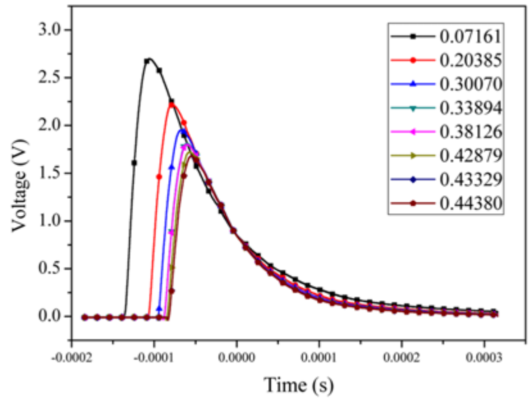
(b) The transient response signal after processing

Fig. 4 The PECT signals of coating on ferromagnetic tube

melted or sprayed the metal powder on the tube surface by arc or plasma spraying methods as shown in Fig. 3. The NiCrFe coating is weak magnetic material. The material properties of coating and pipe are shown in Table 2. The surface topography of plasma spraying



(a) PECT signals of coating thickness change on arc spraying specimens



(b) PECT signals of coating thickness change on plasma spraying specimens

Fig. 5 The PECT signals of coatings on ferromagnetic tube with different thickness

coating was modified by the combination of polishing and surface grit blasting as shown in Fig. 3(b). However, the surface of arc spraying coating was not processed with high roughness as shown in Fig. 3(a). The steel tubes are cut long enough to ensure that the edge effects are inappreciable when the probe was positioned at the center of the tube length.

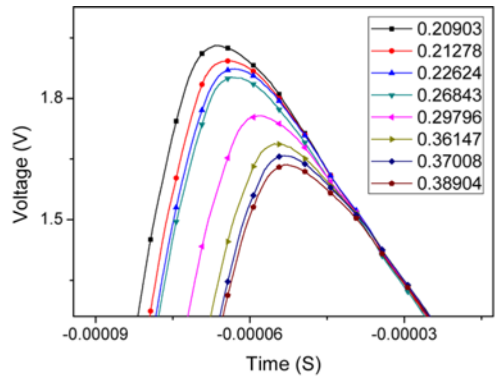
3. Experimental Results and Discussions

3.1 Signal process using wavelet method

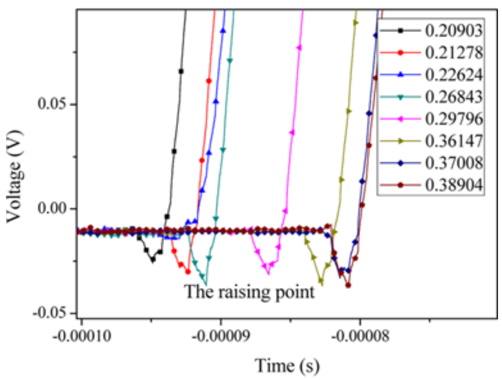
The PECT signal is obtained using the developed PECT system, but the PECT response signal is disturbed by big noise, which leads to the inaccuracy in extracting the feature because of the very rough coating surface.

Fig. 4(a) shows the original response signal of differential PECT probe. In this paper, the averaging method and wavelet smoothing method are used to process the PECT responses. Wavelet analysis is a relatively new technique in signal processing.

The basic theory of wavelet analysis is to analyze according to scale, therefore the fine features of PECT signal can be extracted.[5] Therefore, the wavelet smoothing method is used to remove noise from PECT signals. Fig. 4(b) shows the PECT response signals after processing.

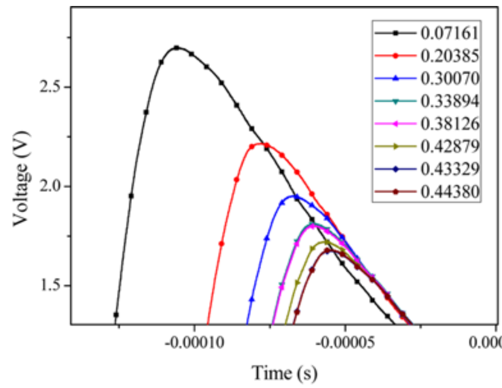


(a) The amplified peak voltage

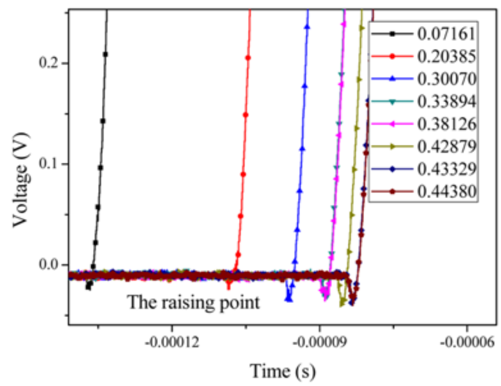


(b) The amplified raising point

Fig. 6 The amplified PECT signals of coating thickness change on arc spraying specimens



(a) The amplified peak voltage



(b) The amplified raising point

Fig. 7 The amplified PECT signals of coating thickness change on plasma spraying specimens

3.2 PECT experimental signals

To verify the measurement accuracy of PECT experiment setup, coating specimens as shown in Fig. 3 are used. The thickness of mild steel substrate t is 6.0 mm. The first kind coating specimens are manufactured using arc spraying method with high roughness, which introduces noise to the measuring signals. And the coating thickness ranges from 0.2 to 0.4 mm. The second kind coating specimens are fabricated using plasma spraying method with surface processing. And the coating thickness ranges from 0.0 to 0.5 mm. The PECT signals were obtained experimentally using coating samples with different coat thickness as shown in Fig. 5. The coating thickness of each specimen on the tube is measured using SEM method directly to compare with PECT measuring results. These specimens are well fabricated by the company with an error in 0.01 mm. The PECT experiment was measured at different position of each coating specimens, we found that the PECT signals almost have no change. Figs. 6 and 7 show the peak voltage and the rising point more clearly by zooming-in pictures for different coating thickness in Fig. 5.

3.3 Features of PECT signals

In this study, the time to peak, the time to the raising point and the peak value are adopted to evaluate the coating thickness as shown in Fig. 4(b). The reason for the new feature of time to the raising point is that the propagation time of electromagnetic waves in conductive metals.[13] In the measurement of metal coating on ferromagnetic substrate using the differential probe, the phenomenon of the raising point also generates due to the propagation of eddy currents in metals. And the penetration depth of the electromagnetic excitation wave, the so-called skin depth, can be found in the follow equation.[13]

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \tag{1}$$

In the equation, δ, f, μ and σ are penetration depth, frequency, permeability and conductivity, respectively. This equation is suitable for the single-frequency sine electromagnetic excitation wave, that is, different depths can be investigated with different exciting frequencies. Because a pulsed signal is rich in spectrum, it potentially covers a broad depth range.[13] The penetration depth δ of a pulsed electromagnetic wave can be described by

$$\delta = \sqrt{\frac{t}{\pi \sigma \mu}} \tag{2}$$

where t is the time slice and different time slices of the transient response containing different depth information of the sample under interrogation.[13]

Therefore, the essential message for thickness measurement is the transient response shift caused by coatings with different thickness. The time to the raising point delays when the thickness of coating increases. To obtain the relationship between the features of PECT signals and coating thickness, the fitting functions are developed.

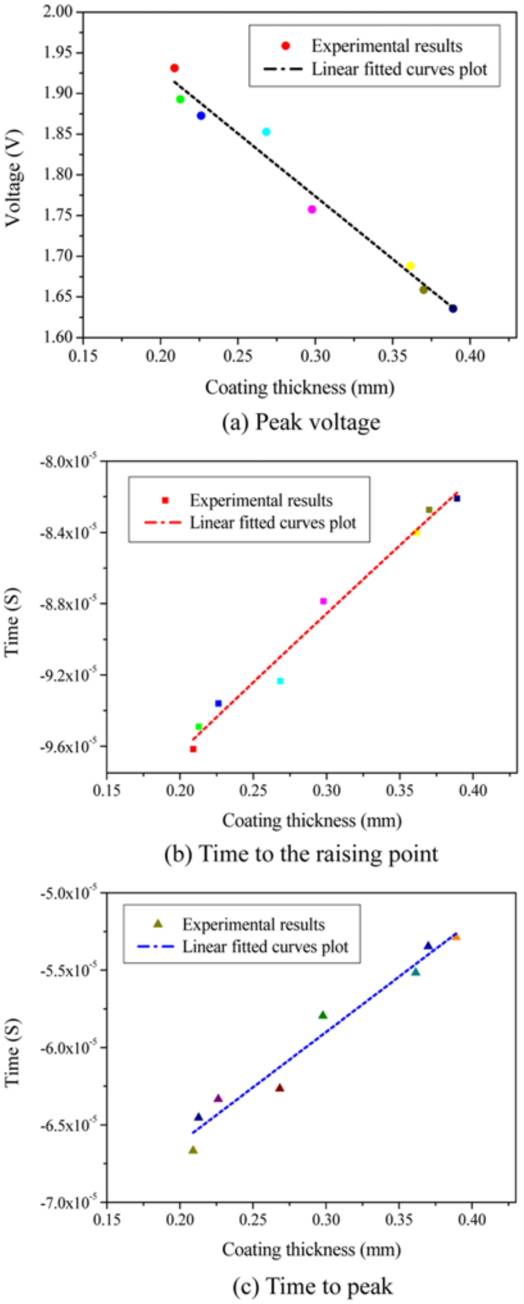


Fig. 8 Comparison of the fitting curve with experimental results of arc spraying specimens

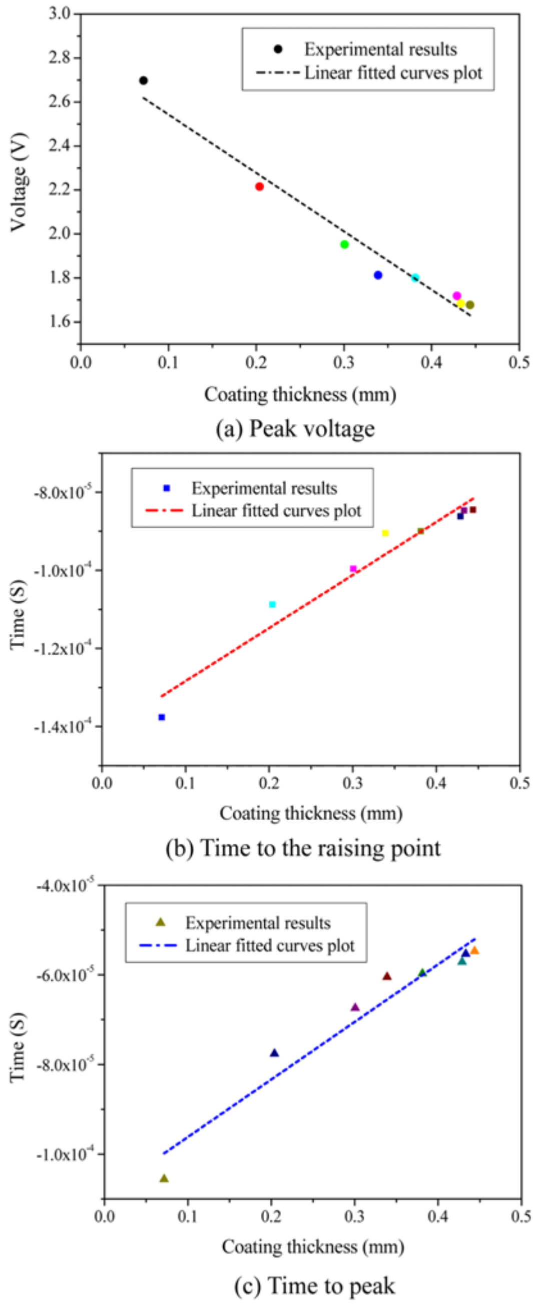


Fig. 9 Comparison of the fitting curve with experimental results of plasma spraying specimens

3.4 Fitting functions of PECT features

Firstly, the linear fitting curves of PECT features built using experimental results of arc spraying specimens are shown in Fig. 8.

$$\begin{aligned} V &= 2.23666 - 0.154328 \cdot t_c \\ T_R &= -1.11681E-4 + 7.69695E-5 \cdot t_c \\ T_P &= -8.04413E-5 + 7.14788E-5 \cdot t_c \end{aligned} \quad (3)$$

where, V is the peak voltage (V), T_R is the fitted function related to the rising point time, T_P is the fitted function related to the time to peak value, and t_c is the coating thickness (mm).

Then the linear fitting curves of PECT features built using experimental results of plasma spraying specimens are shown in Fig. 9.

$$\begin{aligned} V &= 2.80813 - 2.65435 \cdot t_c \\ T_R &= -1.41919E-4 + 1.35794E-4 \cdot t_c \\ T_P &= -1.09014E-4 + 1.28399E-4 \cdot t_c \end{aligned} \quad (4)$$

where, V is the peak voltage (V), T_R is the fitted function related to the rising point time, T_P is the fitted function related to the time to peak value, and t_c is the coating thickness (mm).

There are some influence factors which can cause measurement errors such as lift-off, tilt of probe roughness of coatings and the material's inhomogeneity.[14] To reduce the lift-off effect, a proper force is applied on the probe to contact with coating specimen. A special jig is designed to ensure the probe perpendicular to the coating pipeline.

Because the magnetic permeability of A710 steel is ferromagnetic, this is not equal to the vacuum permeability. We have done the PECT measurement only on the substrate material, fortunately, the PECT signal remains unchanged, which is different to the other ferromagnetic materials. Because these coating specimens are fabricated by two different spraying techniques, the conductivities of each specimen are different. The PECT signals are different for the same thickness of these coating specimens. These combined factors introduce errors to the experimental results. Comparing the features of the experimental results with the linear fitted curves, the good agreement is achieved within the accuracy of 0.02 mm from Figs. 8 and 9. The fitted curves verified the precision of the presented method and system.

4. Conclusions

As a study for application of pulsed eddy current technique (PECT) in nondestructive inspection of coatings on ferromagnetic tube, coating thickness can be evaluated using three features of PEC signal of differential reflection type probe. The peak value, the time to peak value and the time to the raising point can be used to identify the different coating thickness within the accuracy of the destructive measuring results. The new feature of the raising point may also offer very fast measurement of metal thickness and therefore can be used for online inspection. Verification of the developed PECT system for evaluation of coating on steel tubes via the mathematics modelling will be undertaken in the future.

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