JOURNAL OF MATERIALS SCIENCE 30 (1995) 2251–2253

Non-destructive examination of paint coatings using the thermal wave interferometry technique

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Thermal wave interferometry technique is used as a means of assessing paint coatings on metal and non-metal substrates. The non-contact technique employs a modulated laser and infrared detection of thermal waves. The experimental results presented include measurements showing the suitability of the technique for non-destructive examination of paint coatings on mild steel and fibre-reinforced composite substrates.

1. Introduction

The investigation of coatings and their defects has been of interest because paint and other coatings are important for the protection of metals and non-metals alike against environmental aggression. To optimize the protection one may need to monitor the coating deterioration. Coating deterioration probably can be checked by measuring its thickness with a thickness gauge (e.g. Elcometer 300). However, such thickness gauges only work for coating on metals and are rendered useless if the need for non-contact measurement arises. On other hand, a non-contact technique reported by Imhof *et al.* [1, 2] is restricted for coating on high thermal conductivity substrates. Thermal wave investigations of paint coating on polymers [3, 4], though not supported by any mathematical modelling, have shown that the phase of the thermal wave, measured at the front surface of the sample, is influenced by coating thickness and polymer substrate.

In this paper, an investigation is presented of the suitability of thermal wave interferometry technique [5–7] for the non-contact and non-destructive evaluation of paint coatings on metal (mild steel) and non-metal (carbon fibre composite, polyester glass fibre composite, and glass fibre phenolic resin composite) substrates. In this technique, the thermal wave signal is generated by the heat propagation within the coating during periodic laser heating of the surface. Provided that coating thickness is comparable with thermal diffusion length (μ), $\mu = [\alpha/(\pi f)]^{1/2}$, the reflected thermal wave from the coating/substrate interface combines vectorially with the incident thermal wave which results an interference at the sample surface that depends on the depth of the interface (L), the thermal diffusivity of the coating (α), and the reflection coefficient at the interface (R). The phase difference ($\Delta\varphi$) between the reference and the sample thermal wave signals is given as [7]

$$\Delta\varphi = (180/\pi)\text{atan}\{-2R\ \exp[-2L(\pi f/\alpha)^{1/2}] \times \sin[2L(\pi f/\alpha)^{1/2}]/\{1 - R^2 \times \exp[-4L(\pi f/\alpha)^{1/2}]\}\} \quad (1)$$

where f = modulation frequency. Therefore paint condition can be checked in terms of changes in its thickness (L), thermal diffusivity (α) and binding properties that may affect the value of R. As in any other photothermal technique, the technique needs no special sample preparation or sample geometry and thus can be performed *in situ* on the real surface of a coating. Beside being non-destructive and non-contact, the technique is independent of incident intensity, energy absorbed, scattered excitation light and surface reflectivity.

2. Experimental details

A schematic diagram of the apparatus is shown in Fig. 1. A directly modulated beam from a semiconductor laser diode module (Spectra Physics 7200) was used for sample periodic heating. The thermal signal was detected by a pyroelectric infrared detector. The signal was then fed into the lock-in amplifier which also received a reference signal from the laser modulator. The phase of the thermal wave could be read directly from the lock-in amplifier or more conveniently interfaced with a PC.

The phase of the thermal wave was measured along stepped paint coating thickness test-pieces. The coatings were prepared by systematically applying two types of spray paint (i.e. black and metallic graphite) on cleansed surface of mild steel and fibre reinforced composites samples. Each test-piece had five steps which were produced by one, two, three, four, and five layers of paint. The thickness of each step was measured by a digital micrometer (Mitutoyo 293).

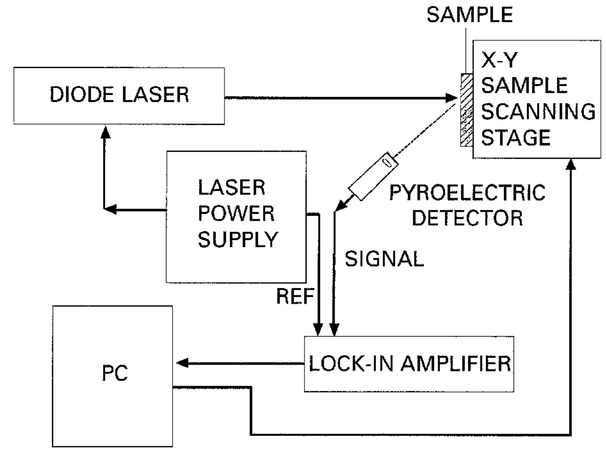

Figure 1 Schematic diagram of the apparatus.

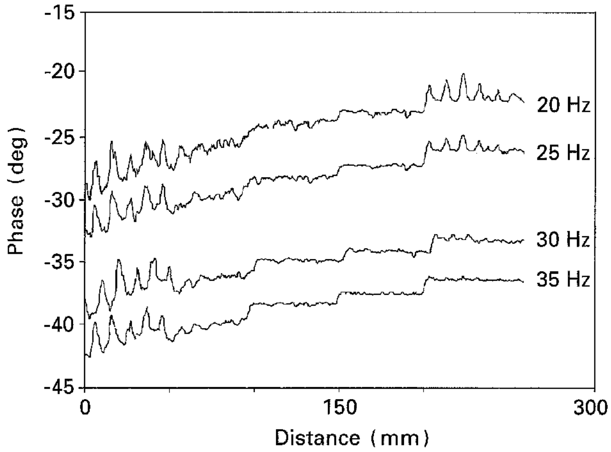

Figure 2 Phase of thermal wave measured at the respective given modulation frequency along stepped coating thickness test-piece of metallic graphite paint on polyester glass fibre composite substrate.

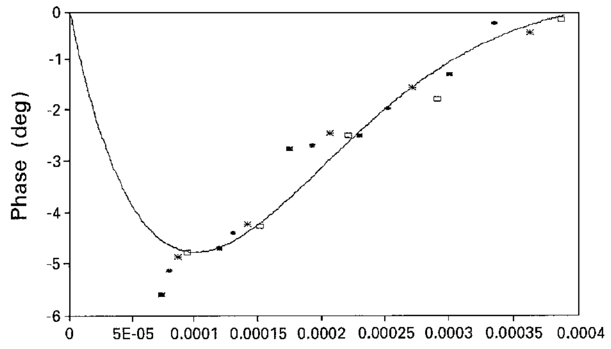

Figure 3 Measured phase of thermal wave from a test-piece of metallic graphite paint on polyester composite substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = 0.13$ and $\alpha = 2.0 \times 10^{-7}\ \text{m}^2\text{s}^{-1}$. ■ 25 Hz; ✱ 30 Hz; ✳ 35 Hz; □ 40Hz.

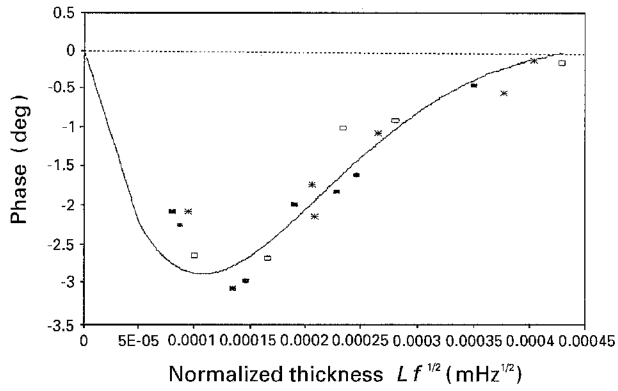

Figure 4 Measured phase of thermal wave from a test-piece of black paint on polyester composite substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = 0.08$ and $\alpha = 2.3 \times 10^{-7}\ \text{m}^2\text{s}^{-1}$. ■ 30 Hz; ✱ 35 Hz; ✳ 40 Hz; □ 45 Hz.

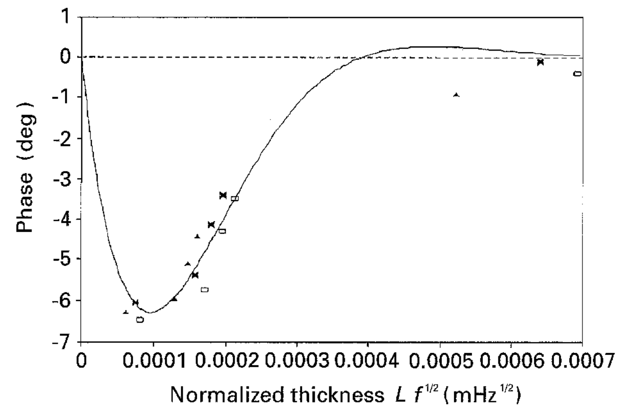

Figure 5 Measured phase of thermal wave from a test-piece of metallic graphite paint on phenolic resin composite substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = 0.17$ and $\alpha = 1.95 \times 10^{-7}\ \text{m}^2\text{s}^{-1}$. □ 35 Hz; ✕ 30 Hz; ▲ 20 Hz.

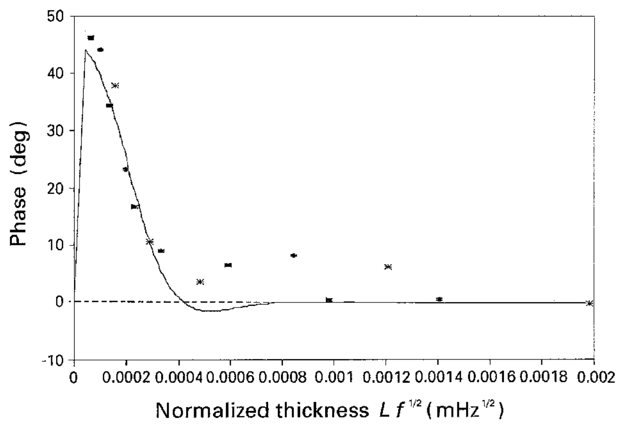

Figure 6 Measured phase of thermal wave from a test-piece of black paint on mild steel substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = -0.99$ and $\alpha = 2.2 \times 10^{-7}\ \text{m}^2\text{s}^{-1}$. ■ 5 Hz; ✱ 10 Hz; ✳ 20 Hz.

3. Results

Fig. 2 shows typical changes in the phase of the thermal wave measured at several modulation frequencies along a stepped coating thickness test-piece of metallic graphite paint on polyester glass fibre composite substrate. The phase largely varies with coating thickness and also varies to much smaller extent from point to point due to sample heterogeneity which probably could be smeared out by using a larger diameter of heating beam spot.

Figs 3–9 summarize the data obtained in a similar way to that shown in Fig. 2. These figures show the phase change produced by the respective paint thickness. To incorporate data obtained at different

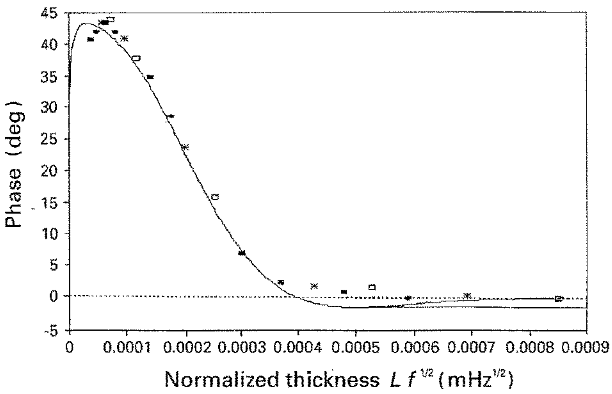

Figure 7 Measured phase of thermal wave from a test-piece of metallic graphite paint on mild steel substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = -0.99$ and $\alpha = 2.0 \times 10^{-7}\ m^2 s^{-1}$. ■ 10 Hz; ✱ 15 Hz; ✳ 20 Hz; □ 30 Hz.

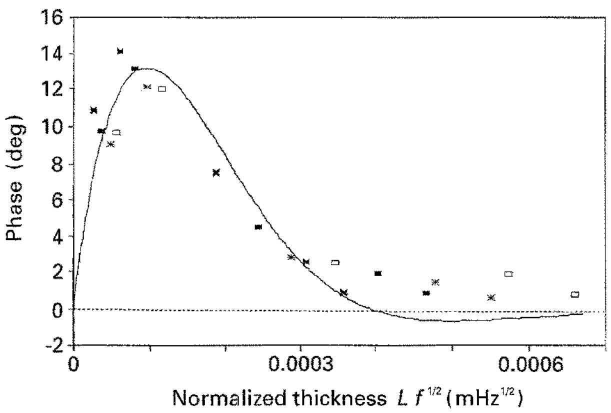

Figure 8 Measured thermal wave from a test-piece of black paint on carbon fibre composite substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = -0.23$ and $\alpha = 2.3 \times 10^{-7}\ m^2 s^{-1}$. ✖ 3 Hz; ■ 5 Hz; ✳ 7 Hz; □ 10 Hz.

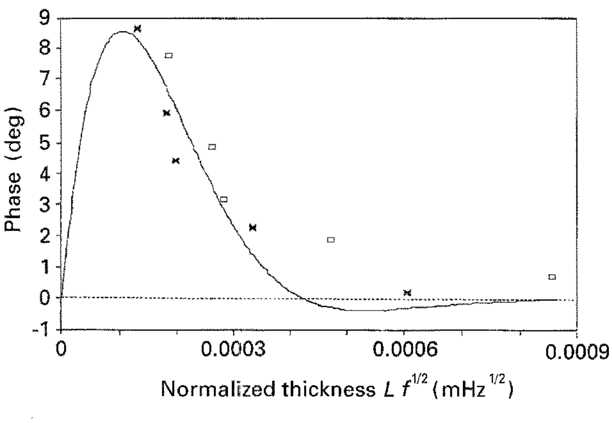

Figure 9 Measured phase of thermal wave from a test-piece of metallic graphite paint on carbon fibre composite substrate plotted against normalized thickness, $Lf^{1/2}$. The curve fitted to the data was obtained from Equation 1 using $R = -0.36$ and $\alpha = 2.0 \times 10^{-7}\ m^2 s^{-1}$. □ 20 Hz; ✖ 10 Hz.

frequencies, phase change is plotted as a function of normalized coating thickness $Lf^{1/2}$. It will be seen from Equation 1 that thermal wave interference is a function of $Lf^{1/2}$. The curves fitted to these data by using Equation 1 were generated with the values of R and α given in Table I. The value of R is related [7] to the ratio of the thermal properties of the paint and substrate used, and also to some extent the bonding condition at the interface. For a particular non-metal substrate, the value of R is greater for metallic paint, as might be expected. For the steel substrate, where R is close to unity, R may be much more sensitive to the condition of the bonding at the interface than to the type of paint itself. The value of α on the other hand indicates the type and condition of the paint. It is difficult to comment on the values obtained because no data is available at present on paint coating thermal properties. However, the values obtained are consistent with the type of paint used and independent of the type of substrate.

TABLE I Fitted parameters from Equation 1 for black paint (and metallic graphite paint in parentheses) on the given substrae

Substrate	Mild steel	Polyester	Carbon	Phenolic resin
$\|R\|$	0.99 (0.99)	0.08 (0.13)	0.23 (0.36)	– (0.17)
$\alpha/(10^{-7}\ m^2 s^{-1})$	2.2 (2.0)	2.3 (2.0)	2.3 (2.0)	– (1.95)

4. Conclusions

It is clear from this work that the thermal wave interference in coatings of paint is modelled well by the Bennett and Patty equation. The work confirms, as shown by others [3, 4], that the thermal wave technique can be used to assess paint thickness on both metallic and nonmetallic composite substrates. In addition it appears that the fitted parameters (i.e. R and α) can be used as indicators of the paint coating and bonding quality and also may be used for monitoring the progress of coating deterioration. Further work is now being planned to monitor paint degradation by using an accelerated weathering sample.

Acknowledgements

We (MMM) thank the Malaysian Government and Universiti Pertanian Malaysia for research support through IRPA and study leave.

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Received 14 April and accepted 4 October 1994