DETECTION OF COATING ADHESION DEFECTS USING FAST INFRARED

SCANNING TECHNIQUE

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INTRODUCTION

In the past ten years a variety of thermal wave nondestructive measurement systems have been developed but most of them are too slow, fragile or expensive in order to be applied in industry. The standard approach to increase the measurement speed has been to apply a uniform heat pulse and to monitor the surface temperature with an infrared camera [1]. However, in many practical situations the full speed of an infrared camera is not really needed and thus a moving line source can be used for heating and the surface temperature rise can be detected with a one dimensional infrared scanner without a significant increase in inspection time. This approach has several benefits including:

- simple and inexpensive hardware,
- no dead time between heat pulse and temperature detection,
- peak heating power can be reduced by an order of magnitude compared to area heating and so simple and cheap heating system can be used, and
- readily applicable to the on-line inspection of moving samples.

In this paper we describe such a measurement system that was designed with four goals in mind: the new measurement system should be fast, simple, easy-to-use and inexpensive.

THEORETICAL BACKGROUND

A schematic diagram of the measurement principle is shown in Fig.1. The sample is heated with a line source like a laser beam focused on a line and the resulting temperature rise is monitored with an infrared scanner.The temperature distribution in the sample can be computed from the diffusion equation

$$\rho_i c_i \frac{\partial T_i}{\partial t} = K_i \nabla^2 T_i \, , \tag{1}$$

where T is the temperature, ρ is the density, c is the specific heat and K is the thermal conductivity of the sample. The subscript i refers to the coating and the substrate. There is no generation term in Eq. (1) because the optical absorption coefficient is assumed to be large and consequently the heating can be taken into account as a boundary condition. Temperature and heat flow must be continuous across each interface so the boundary conditions are

$$T_1(x,z=d,t) = T_2(x,z=d,t) \quad \text{and} \tag{2}$$

$$K_1 \frac{\partial T_1(x,z=d,t)}{\partial z} = K_2 \frac{\partial T(x,z=d,t)}{\partial z} \quad , \tag{3}$$

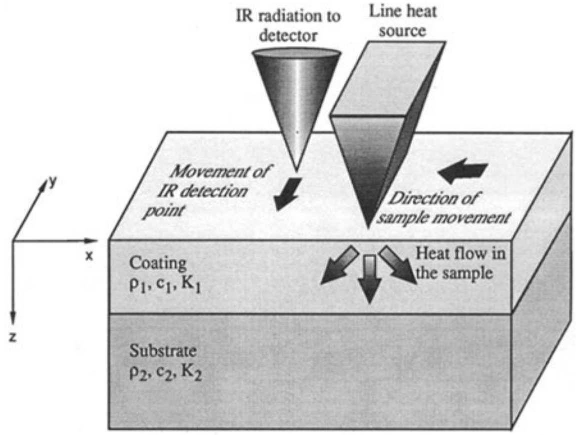

Figure 1. The measurement principle.

where d is the coating thickness. However, if the adhesion between the coating and the substrate is weak, there is thermal contact resistance at the interface and so the boundary conditions (2) must be replaced by

$$T_1(x,z=d,t) - T_2(x,z=d,t) = R\Phi \tag{4}$$

where R is thermal contact resistance and Φ is the heat flow through the interface.

If a laser beam focused on line is used for heating, the boundary condition at the front surface can be approximated with

$$K_1\frac{\partial T_1(x,z=0,t)}{\partial z} = -\frac{P}{\sqrt{\pi}aL}\exp\left(-\left(x-x_o-v_xt\right)^2/a^2\right), \tag{5}$$

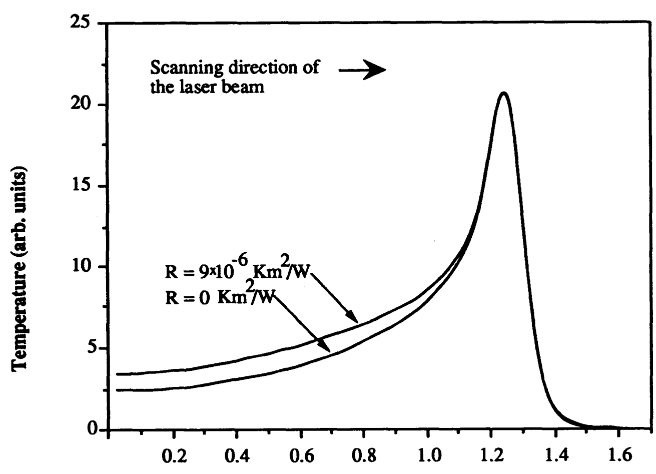

Figure 2. An example of the numerically computed temperature profiles along the x-axis when a line heat source parallel to the y-axis is moved to the positive x direction. The numeric values used in computations are: ρ_1 = 5210 kg/m^3, ρ_2 = 7860 kg/m^3, c_1 = 781 J/kgK, c_2 = 450 J/kgK, κ_1 = 10 W/Km, and κ_2 = 10 W/Km. The coating thickness is 200 μm, the heating beam width is 200 μm, and the scanning speed in the x direction is 5 cm/s.

where P is the power of the heating beam, L is the length of the beam, a is half of the beam width in the x-direction and x_0 is the position of the heating beam at t=0. In order to solve the heat diffusion equation with appropriate boundary conditions, we usually have to resort to numerical methods especially if the finite sample size has to be considered. An example of the numerical results is shown in Fig. 2.

The numeric values used in the computations correspond to a typical plasma spray coated steel sample. The surface temperature profile was computed in two cases: in the first example there was no thermal contact resistance between the coating and the substrate and in the second example weak adhesion was simulated with the contact resistance value of $9x10^{-6}$ Km^2/W. At the leading edge the temperature profiles are practically identical and the differences between the samples emerge first at the trailing edge of the temperature profile. This delay is the time it takes for a heat pulse to propagate from the front surface through the coating and back to the surface. The length of the delay depends on the thickness and the thermal diffusivity $\alpha_1 = K_1/\rho_1 c_1$ of the coating.

MEASUREMENT SYSTEM

A schematic diagram of the measurement system is shown in Fig. 3. The sample is heated with either hot air jet or a laser beam. A liquid nitrogen cooled HgCdTe detector is focused on the sample surface via a deflection mirror and so the image point of the detector is moved in the y-direction while the sample is moved in the x-direction. The measurement system is controlled by a microcomputer that is also used for processing measurement data and displaying photothermal images. The measurement software includes basic image processing functions like median averaging and histogram equalization but images can be exported to commercial image processing programs for further analysis. Images can also be exported to page layout programs.

As mentioned before, three different heating methods can be used. Hot air jet [2] directed to the sample surface through a long and narrow nozzle is cheap and simple heating method but the width of the heated area is on the order of several millimeters. This results in long heating pulses and for this reason hot air can be

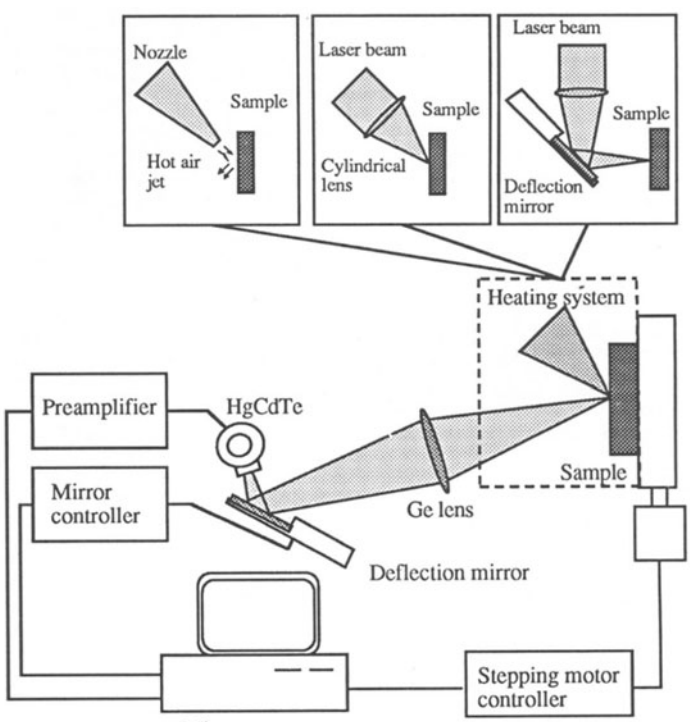

Figure 3. A diagram of the measurement system.

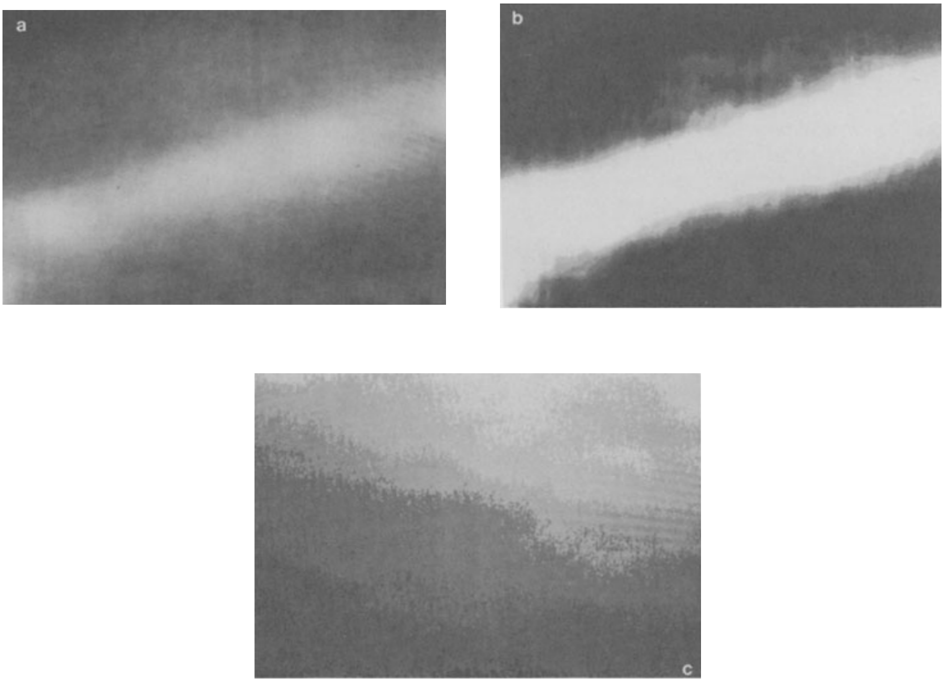

Figure 4. (a) The original and (b) the enhanced photothermal image of an adhesion defect in a plasma sprayed chromium oxide coating on steel substrate. (c) The optical image of the measured area. The size of the measured area is 4x5 mm^2.

used only with samples that have low thermal diffusivity. On the other hand, the width of a laser beam focused on a line [3] can be easily made far narrower than one millimeter and so the length of heat pulses is on the same order of magnitude as in video thermography where powerful flash lamps are used for heating. The mirror [4,5]. This way heat pulses as short as 30 μs can be produced and for this reason this heating method is useful for inspection of thin coatings. However, if the scanning velocity of the laser beam is far faster in y-direction than in x-direction, the scanning produces essentially line heating and so this technique can be used also with plasma-sprayed coatings. The laser spot has also the extra benefit that the light scattered from the sample can be measured with a photodiode and so an optical image of the sample can be formed in addition to the thermal one. Optical image provides complementary information to thermal data and thus it facilitates the interpretation of measurement results.

The most severe problem with the laser heating is the nonuniformity of the heating that causes artifacts in the final image. This problem can be partially solved by using an image of a faultless area as a reference and dividing the measured image by the reference image. In addition, further image processing is often needed to enhance contrast between defective and faultless sample areas. An example of the significance of the image processing is shown in Fig. 4. The sample was a plasma spray coated steel sample that had artificial adhesion defects in the coating. In the original photothermal image there the defective area can hardly be seen but in the final image the defect is clearly visible. The image processing is an integral part of the measurement system.

Images can be averaged in order to improve the signal to noise ratio and the total measurement time naturally depends how many images are averaged. Typical measurement time for a single photothermal image is 6 s and slightly less than 12 s if an optical image is formed simultaneously.

CONCLUSIONS

We have demonstrated an effective photothermal measurement system for the inspection of coating adhesion defects. The measurement system is simple so it can be easily modified for various situations requiring different heat pulse lengths or scanning velocities. Because of the short measurement times, the presented system offers an inexpensive alternative to videothermography when the full power of an infrared camera cannot be fully exploited.

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