DELAMINATION AND CRACK DETECTION BY THE SYNCHRONOUS HEATING METHOD: THEORETICAL ASPECTS

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INTRODUCTION

In recent years a variety of NDT techniques utilizing an IR camera have been developed (for example [1-4]). In the synchronous heating method [3] an IR camera is used for detecting the surface temperature rise caused by a scanning laser beam. The movement of the heating beam is synchronized with the deflection mirror of the IR camera so the distance between the object point of the camera and the heating point remains constant. This measurement set-up allows rapid inspection of thin coatings that are otherwise problematic from the NDT point of view. In this paper we have computed numerically the temperature profile produced by a laser beam when it is scanned over the surface of a defective sample.

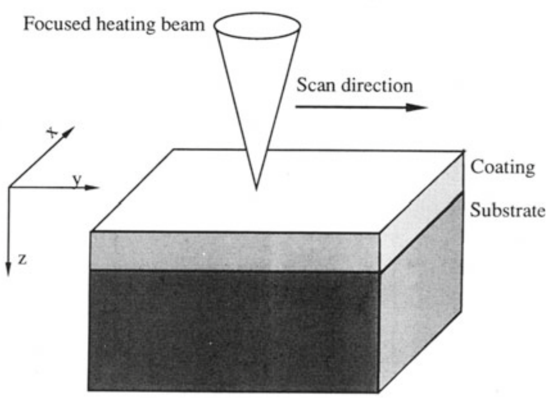

Fig. 1. Measurement geometry.

SOLUTION PRINCIPLE

The measurement geometry is shown in Fig. 1. When the sample is heated with a moving laser beam, the situation is described by the diffusion equation

$$\rho c \frac{\partial T}{\partial t} = K \nabla^2 T + Q, \tag{1}$$

where T is temperature, ρ is the density, c is the specific heat and K the thermal conductivity of the sample. Q is the heating power per unit volume and in the case of a moving Gaussian beam Q is

$$Q(r,t) = \frac{P\alpha(1-R)}{\pi a^2} e^{-[x^2+(y-vt)^2]/a^2} e^{-\alpha z}, \tag{2}$$

where P is the power and the 1/e-radius of the heating beam, v is the scanning velocity and α is the absorption coefficient and R the reflectivity of the sample.

The temperature and heat flow must be continuous at sample boundaries so the boundary conditions are

$$T_i = T_j \tag{3}$$

$$\kappa_i \nabla T_i \cdot n = \kappa_j \nabla T_j \cdot n \tag{4}$$

where n is a vector perpendicular to the boundary surface and subscripts i and j refer to the two materials in contact. Because the thermal conductivity of air is poor, we neglect the heat flow through the front surface of the sample. On the other hand, we assume that the optical absorption coefficient is large so we can neglect the generation term and take the laser heating into account in the boundary condition at the front surface

$$\kappa_1 \frac{\partial T(x,y,0,t)}{\partial z} = -\frac{P(1-R)}{\pi a^2} e^{-[x^2+(y-vt)^2]/a^2} \tag{5}$$

The other sample surfaces are assumed to be so far away from the heating point that their temperature is constant.

Weak adhesion between the coating and the substrate affects heat flow from the coating to the substrate and this can be described in terms of a contact resistance. In the presence of contact resistance temperature is no longer continuous over the interface between the coating and the substrate but

$$T_i - T_j = R\phi \tag{6}$$

where R is the contact resistance between the coating and the substrate and ϕ is the heat flow through the boundary. Contact resistance can be also used for describing the severity of a crack.

NUMERICAL METHODS

We have solved the diffusion equation using the finite difference method in space and the Crank-Nicholson method in time. Because the number of the grid points increases very rapidly as the size of the grid increases, we have used coordinate transformation

$$x' = e^{-\beta x} \text{ and } z' = e^{-\sigma z}. \tag{7}$$

This transformation allows us to have a denser grid near the heating point, where temperature changes fastest. The interface is positioned between two grid planes and the contact resistance is taken into account by introducing effective thermal conductivity κ_{eff}

$$\kappa_{eff} = \frac{2\kappa_1\kappa_2\Delta z}{2\kappa_1\kappa_2 R + \Delta z(\kappa_1 + \kappa_2)}. \tag{8}$$

The concept of effective thermal conductivity is illustrated in Fig. 2.

RESULTS

Temperature Profile in the Sample

The computed isotherms in a sample are shown in Figure 3. In this case, we used a stainless steel sample with a 5 µm thick coating on it. The interface between the coating and substrate is assumed to be ideal so there is no contact resistance. The values of the thermal properties of the coating and the substrate are listed in Table 1.

Because temperature gradient is largest below the heating beam (where its direction is perpendicular to the sample surface), the synchronous heating method is most suitable for detecting regions of

Table 1. The values of thermal properties that have been used in computations.

	$\rho(kg/m^3)$	$\kappa(W/Km)$	$c(J/kgK)$
substrate	7860	60	430
coating	5180	43	540

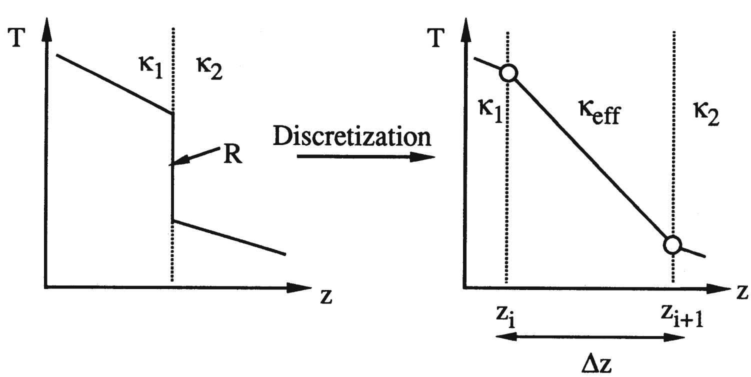

Fig. 2. The effect of thermal contact resistance on discretization.

weak adhesion. In this example the values of the thermal properties of coating are of the same order of magnitude as those of the substrate so the isotherms are smooth across the interface.

Detection of Weak Coating Adhesion

In Fig. 4 a) are shown surface temperature profiles for three test samples with different contact resistances at the coating/substrate interface. The coating thickness is again 5 μm. The differences between good and faulty samples are clearly evident and contact resistances as small as $1 10^{-7} Km^2/W$ are still detectable. When the coating thickness decreases, the maximum temperature rise in the ideal case decreases because the thermal diffusivity of the coating is

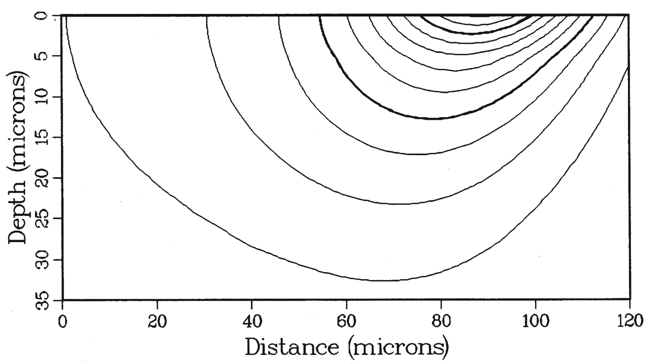

Fig. 3. Isotherms in the sample that is heated with a moving laser beam. The cross-section shown lies in the yz-plane. The 1/e-radius of the laser spot is 20 μm and its velocity is 2 m/s. It should be noted that the axes are not in the same scale.

somewhat lower than that of the substrate (Figure 4b). However, the differences between good and faulty samples are far larger because the defects are nearer the maximum heat flow area. Also the shape of the temperature profile is more symmetric in the case of thinner coating because a thin coating with weak adhesion to the substrate starts behaving like a thermally thin sample.

The detection of delaminations is not especially sensitive to the scanning velocity of the heating beam, which can be seen in Figure 5. The maximum temperature rise naturally increases when the scanning speed decreases because more heat is deposited in the sample. Also the tail of the temperature profile becomes longer, as expected, but otherwise small changes in the scanning speed do not affect the delamination detection very much.

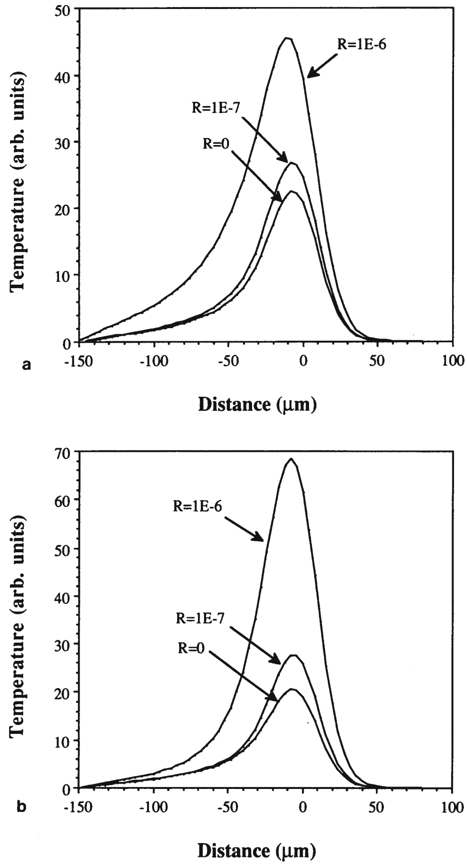

Fig. 4. a) The surface temperature profiles along y-axis for three coated samples with different contact resistance values $(0.0, 1\,10^{-7}$ and $1\,10^{-6}\,Km^2/W)$. The scan velocity is 2 m/s, the beam radius 20 μm and the coating thickness is 5 μm; b) As a) but the coating thickness is 2 μm.

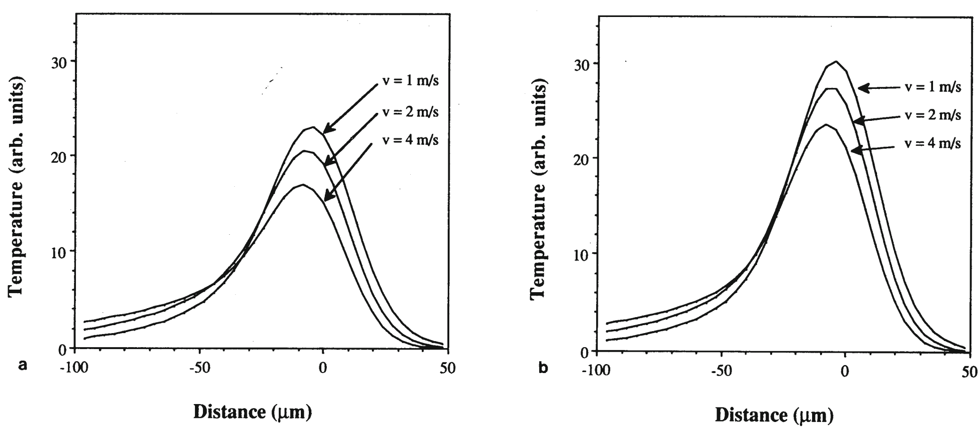

Fig. 5. The surface temperature profiles along y-axis for a) a good sample and b) a faulty sample (contact resistance $1\,10^{-7}\,Km^2/W$ with three different scanning velocities. The heating beam radius is 20 μm and the coating thickness is 2 μm.

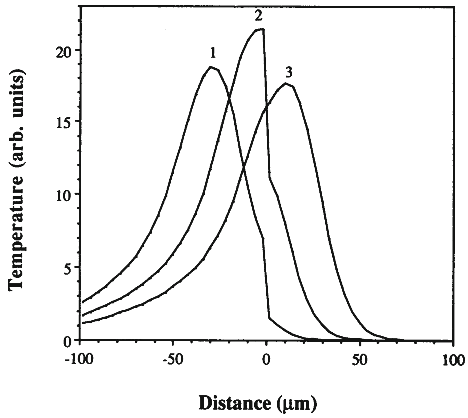

Fig. 6. Surface temperature profile along y-axis when the position of the center of the heating beam is $-22\mu m(1), -2\mu m(2) \wedge 18\mu m(3)$ relative to the semi-infinite vertical crack. The radius of the heating beam is $20\mu m$ and its velocity is 2 m/s. The crack is simulated by the thermal contact resistance of $1\,10^{-4} Km^2/W$.

Detection of Cracks

The synchronous heating method can be used also for crack detection. Three temperature profiles corresponding three different heating beam positions relative to the crack are shown in Figure 6. The sample is of stainless steel and it has a semi-infinite vertical crack along x-axis.

When the heating beam approaches the crack, the crack appears in the temperature profile as a threshold. The maximum temperature rise also increases when the heating beam is quite near the crack because the heat flow is hindered in one direction. On the other hand, there is only small heat flow through the crack after the heating beam has passed the defect point. For this reason the crack does not affect the tail of the surface temperature profile significantly.

The surface temperature profiles along y-axis for three different defective samples are shown in Figure 7. Because heat flow parallel to the sample surface is smaller than perpendicular to the surface, differences between good and faulty samples are not as large as in the case of delaminations and cracks must correspond to larger thermal contact resistances in order to be detectable. Also the temperature changes to different directions on different sides of the crack. On the other hand, the infrared detector of an IR camera averages signal over a certain area and this averaging may make the crack again undetectable.

Because the sample is heated locally, the synchronous heating method can be used for detecting short or shallow cracks, which can be seen in Fig. 8.

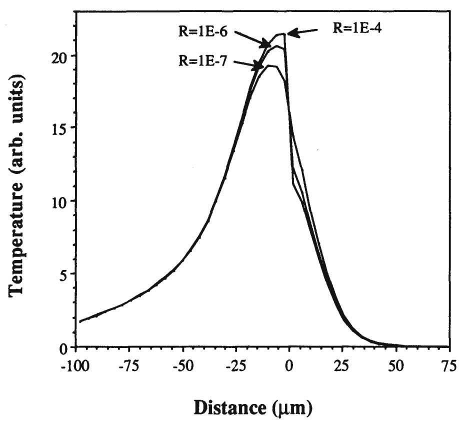

Fig. 7. Temperature profiles along y-axis for three different samples with a semi-infinite crack. Thermal contact resistances across the crack are $1 10^{-4}, 1 10^{-6}$ and $1 10^{-7} Km^2/W$. The radius of the heating beam is 20 μm, the scanning velocity is 2 m/s and the position of the center of the heating beam is $-2\mu m$ relative to the crack.

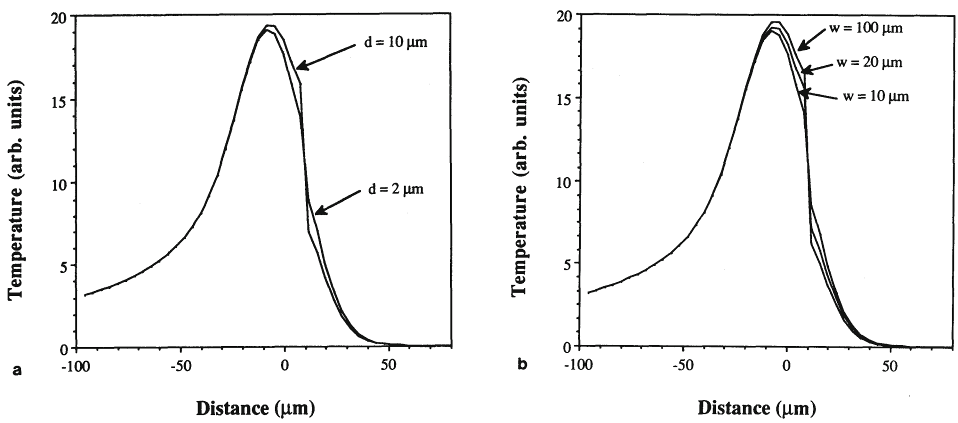

Fig. 8. The surface temperature profile along y-axis when the heating beam is scanned across a sample with a) a 2 and 10 μm deep (indefinitely long) crack b) a 10, 20 and 100 μm long (indefinitely deep) crack. In both cases the contact resistance due to the crack is $1 10^{-5} Km^2/W$, the heating beam radius is 20 μm and the scan velocity is 2 m/s.

Already a 10 μm deep crack can be considered deep in this method and deeper cracks affect the surface temperature profile essentially in the same way. On the other hand, the temperature profile of the sample with a 2 μm crack is almost identical to that of faultless sample. Also the length of the crack has only modest effect on the surface temperature profile. As the width of the crack becomes smaller than the diameter of the heating beam, differences between good and faulty samples disappear.

CONCLUSIONS

The synchronous heating method is a powerful NDT technique. It is most sensitive in detecting regions of weak adhesion of thin coatings but it can also be used for detection of cracks with good spatial resolution. Because of the infrared camera, high scanning speed can be used but the method gives information only from a thin surface layer. Also the correct alignment of the infrared detector is critical.

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