N87-27211

MEASUREMENT OF OPAQUE FILM THICKNESS

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INTRODUCTION

We describe the theoretical and experimental framework[1-6] for thickness measurements of thin metal films by low-frequency thermal waves. Although we assume that the films are opaque and the substrates are comparatively poor thermal conductors, the theory is easily extended to other cases of technological interest. We begin with a brief description of thermal waves and the experimental arrangement and parameters. Next we illustrate the usefulness of the technique for making absolute measurements (based on measurements of length and time) of the thermal diffusivities of isotropic substrate materials. This measurement on pure elemental solids provides a check on our three-dimensional theory in the limiting case of zero film thickness. The theoretical framework is then presented, along with numerical calculations and corresponding experimental results for the case of copper films on a glass substrate.

DESCRIPTION OF THERMAL WAVES AND EXPERIMENTAL TECHNIQUE

The elements of thermal wave propagation are illustrated by considering the one-dimensional heat equation, presented along with its solution in Fig. 1. Here k is the thermal conductivity, ρ is the mass density, c the specific heat capacity, and ω is the angular frequency of the (assumed) periodic heat source. By inspection, one sees that the solution is a wave whose wave vector is complex, and has equal real and imaginary parts. A sketch of the spatial variation of the real part (see Fig. 1) emphasizes an important aspect of thermal wave propagation - these waves are nearly completely damped out after propagating one thermal wavelength. Both the thermal wavelength and the proportional quantity, μ_s, the thermal diffusion length of the solid, are seen to be inversely proportional to the square root of the heat source frequency. At the typical ranges of thermal properties and experimental frequencies, diffusion lengths range from a few micrometers to a few millimeters.

The arrangement for the thermal wave measurements described here is shown in Fig. 2. The heating beam is an intensity-modulated Ar+ ion laser, focussed to a few micrometer diameter spot on the sample surface. For the present measurements, frequencies are typically below 1 kHz, such that the thermal diffusion lengths in the Cu films are much greater than their thicknesses. The time-varying temperature distribution in the air just

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above the coating is monitored phase-coherently by means of a vector lock-in amplifier, which measures the time-varying deflection of a HeNe probe laser beam skimming the surface of the coating (see Figs. 2-4, illustrating the use of the mirage effect in the heated air). In this experiment, the probe beam is fixed in position and the heating beam spot is scanned (transverse offset) across the surface beneath the probe beam and at right angles to it. Figure 5 shows the resulting in-phase component of the transverse probe beam deflection (i.e. the deflection component in a plane parallel to that of the sample surface) during such a scan. Note that the transverse deflection is zero as the heated spot passes directly beneath the probe beam, and that its sign changes at that point. The length measurement for determining both the film thickness and (accompanied by the frequency measurement) the thermal diffusivity of the substrate, is the quantity x_0 in Fig. 5, namely, the separation between the two non-central zero crossings of the in-phase signal.

THERMAL DIFFUSIVITY OF AN ISOTROPIC SOLID

A plot of x_0 versus the reciprocal of the square root of the frequency should yield the thermal diffusivity, $\alpha = k/\rho c$. Experimental verification of this fact for pure elemental solids is given in Figs. 6 and 7. Here, the nominal diffusivity is determined from the Handbook of Chemistry and Physics values for k, ρ and c.

The length measurements used in the preceding figures employed only a few data points from the scan. As a further check on the reliability of the theory, we plot the in-phase component of the transverse deflection versus the quadrature component of that deflection, during the scan of transverse offset (see Fig. 8). The resulting comparison between theory and experiment for the case of silver (see Fig. 9) uses no adjustable parameters (the Handbook value for diffusivity is assumed), and shows excellent agreement.

THEORETICAL FRAMEWORK FOR THIN FILM CALCULATIONS

The geometry for the thin film experiment is given in Fig. 10. The thickness of the film is a, the radius of the heating beam is b, that of the probe beam is c, the height of the probe beam is h_0, the transverse offset is y_0, and κ, with its appropriate subscript, is the thermal conductivity. The thermal conductivity of the air is assumed to be negligible compared to those of the film or substrate. The theoretical equation is given in Fig. 11. A detailed description of this theory is found elsewhere.[1]

NUMERICAL CALCULATIONS AND EXPERIMENTAL RESULTS: Cu FILM ON GLASS

Numerical calculations of x_0 as a function of inverse root frequency for Cu films (1000 A to 5000 A) on glass are shown in Fig. 12, and the corresponding experimental measurements are shown in Fig. 13. Theory and experiment are in excellent agreement. Figure 14 shows the theoretically predicted dependence of x_0 on coating thickness for three different frequencies. The film thicknesses were also measured independently by means of Rutherford backscattering of alpha particles. The two measurements agree to within a combined uncertainty of about 10%.

SUMMARY AND CONCLUSIONS

We have described a thermal wave technique which is capable of determining the thicknesses of opaque metal films on substrates whose thermal diffusivities are small compared to those of the films. The method is based on measuring the transverse deflection of an optical probe beam, due to the mirage effect in the air above the sample, as a function of the transverse probe beam distance from a localized ac surface heat source. The measurement is carried out in the frequency range below 1 kHz. by fitting the data to the theory of Kuo et al.[1], without prior knowledge of the diffusivities or the conductivities of the coating or the substrate, one can determine the thickness of the film as well as the thermal diffusivity of the substrate. We have applied this method to copper films on glass. The thicknesses of these films were between 1000 A and 5000 A. We find agreement between the thicknesses determined by our method and by measurements of the Rutherford backscattering of alpha partices, carried out in this laboratory, to within a combined uncertainty of approximately 10%.

ACKNOWLEDGEMENTS

This work was supported in part by ARO under Contract No. DAAG 29-84-K-0173, and in part by the Center for Advanced Nondestructive Evaluation, operated by the Ames Laboratory, USDOE, for the Air Force Wright Aeronautical Laboratories/Materials Laboratory under Contract No. W-7405-ENG-82 with Iowa State University. J. Jaarinen also acknowledges the support of Finland's Cultural Foundation.

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THERMAL DIFFUSION WITH A PERIODIC SOURCE
(ONE-DIMENSIONAL PICTURE)

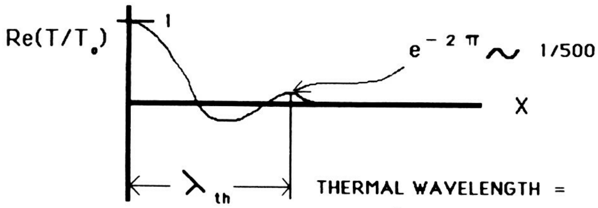
DIFFUSION EQUATION

$$k \frac{d^2T}{dx^2} = \rho c \frac{\partial T}{\partial t}$$

SOLUTION:

$$T = T_0 \exp[i(qx - \omega t)], \text{where}$$

$$q = \frac{1+i}{\sqrt{2}} \sqrt{\frac{\omega \rho c}{k}}$$



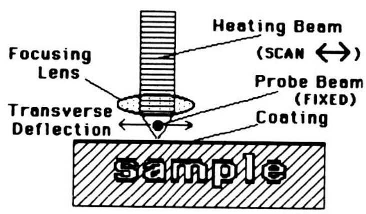
THERMAL WAVELENGTH = $2\pi\mu_s$

$$\mu_s = \sqrt{\frac{2K}{\omega \rho c}} \propto f^{-1/2}$$

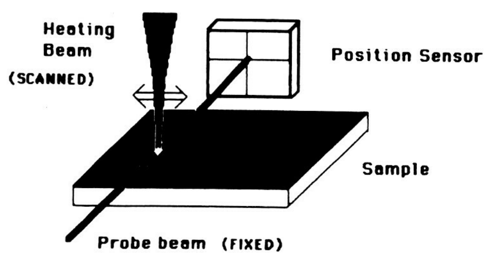
THERMAL DIFFUSION LENGTH

Figure 1

ARRANGEMENT FOR THERMAL WAVE SCAN OF A COATING



SIDE VIEW



PERSPECTIVE

Figure 2

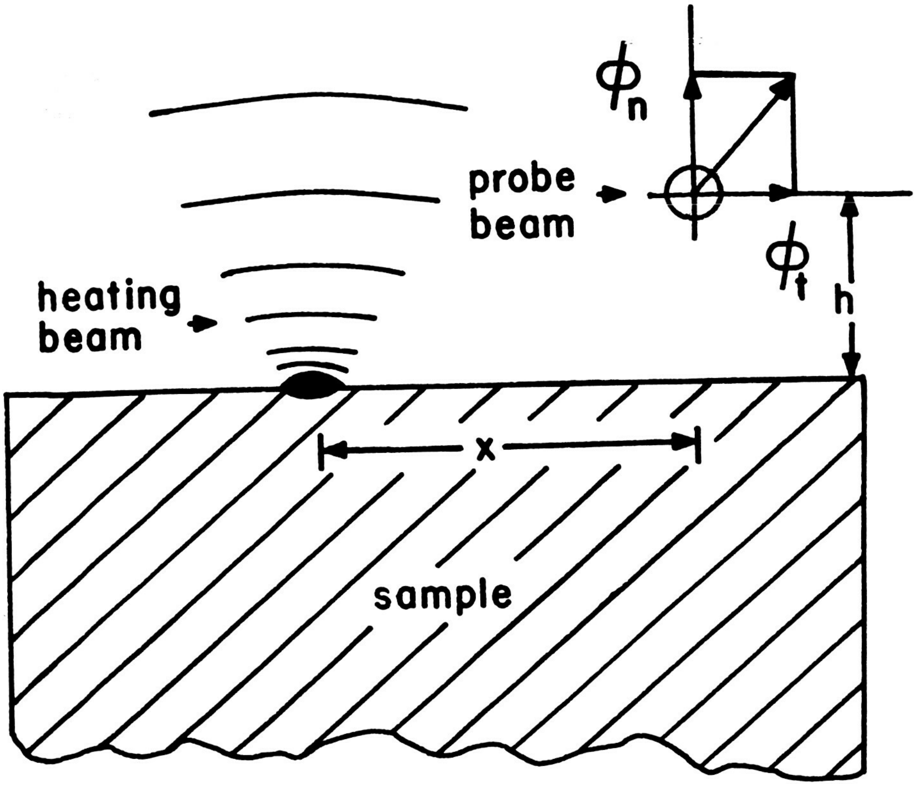
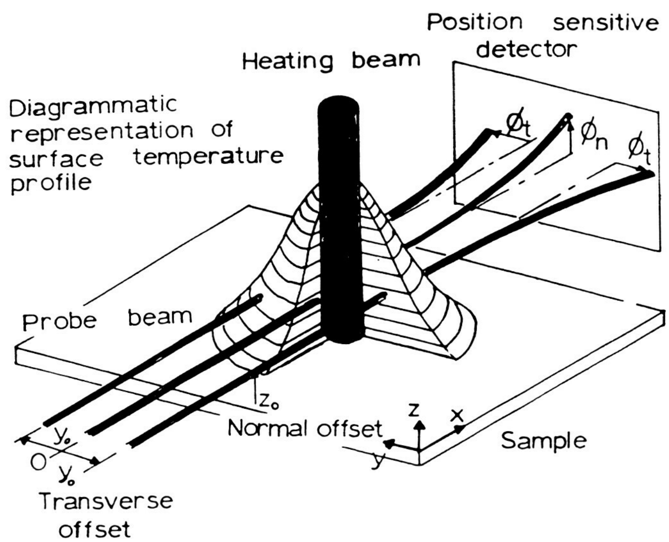


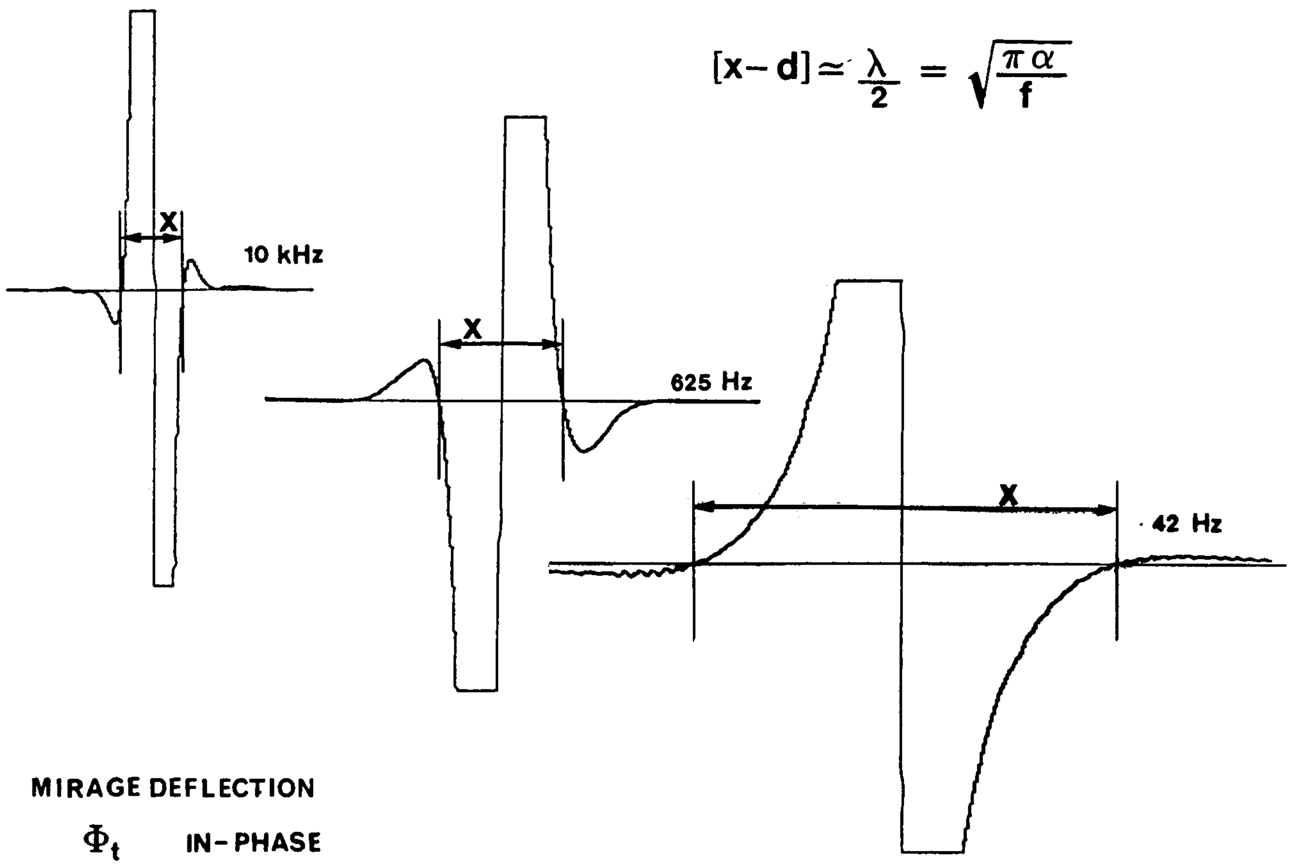
Figure 3

Mirage Effect (Optical Beam Deflection) Detection



After L.C. Aamodt and J.C. Murphy, J.Appl Phys. 54 581 (1983).

Figure 4



InSb

Figure 5

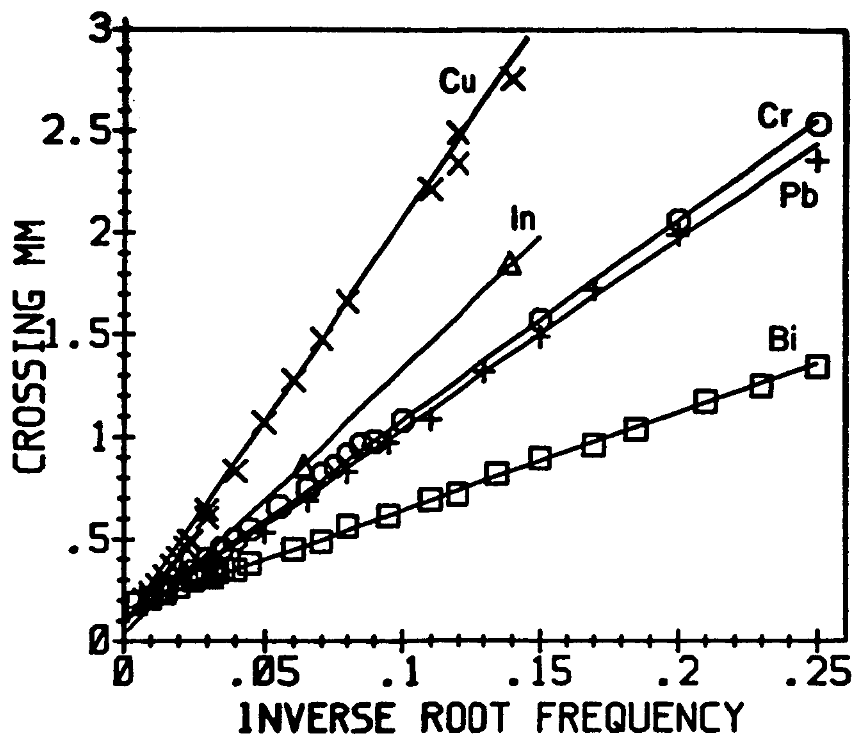


Figure 6

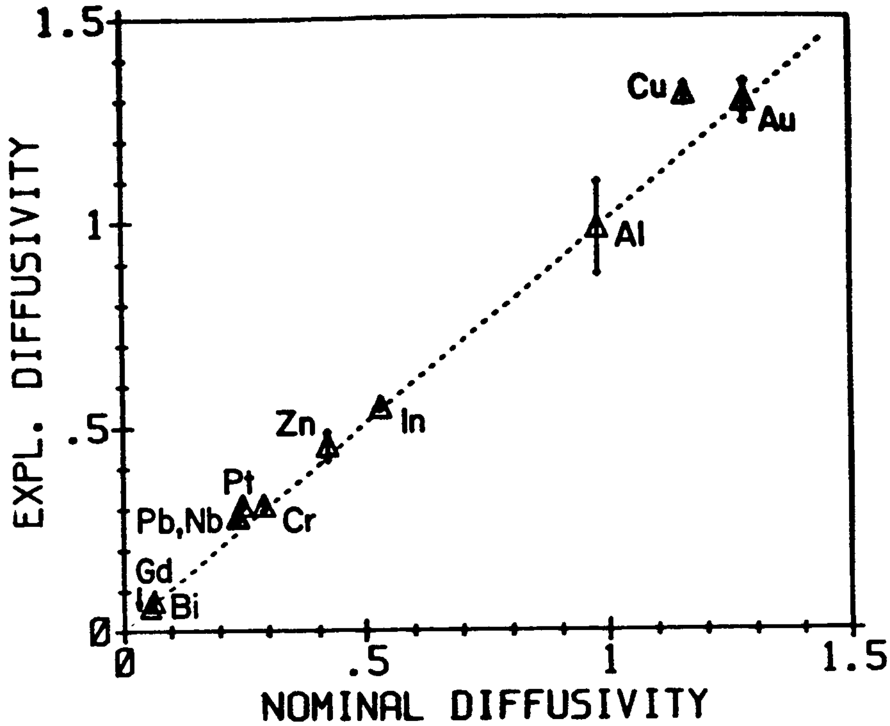


Figure 7

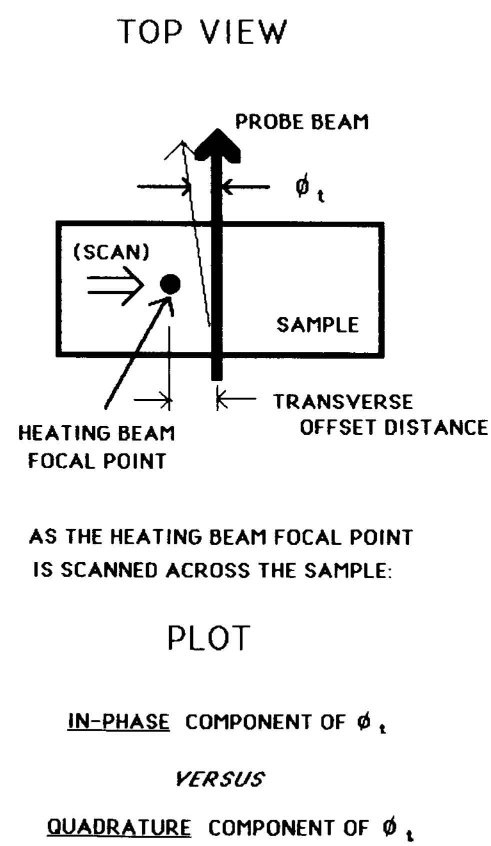


Figure 8

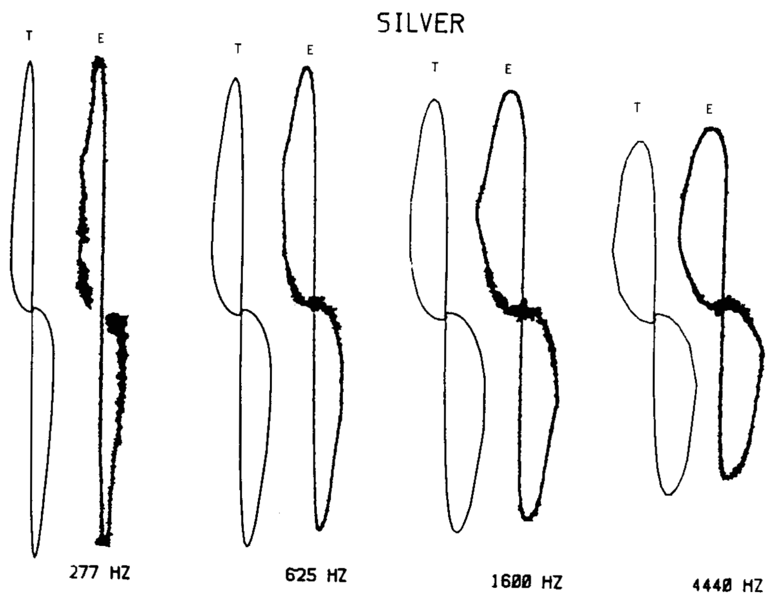


Figure 9

GEOMETRY

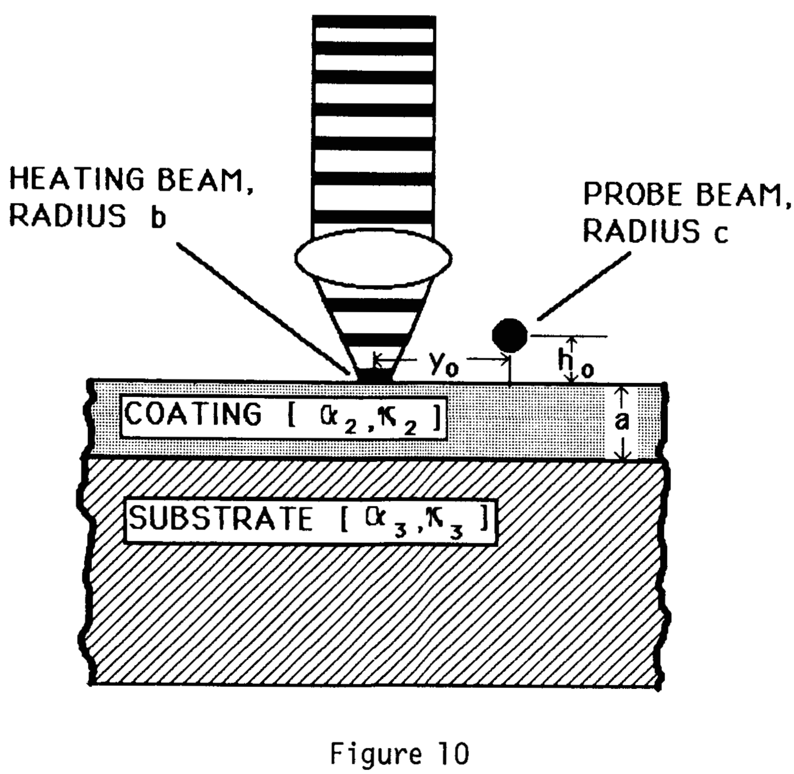


Figure 10

THEORY FOR THE MIRAGE TRANSVERSE DEFLECTION SIGNAL (S)

$$S(y_0, h_0) = \frac{1}{c^2}\left[\frac{-i\omega c^2}{4\alpha_1}\right] \bullet$$

$$\bullet \int_0^\infty \frac{k\,dk}{\sqrt{k^2 - \frac{i\omega}{\alpha_2}}} \sin k y_0 \exp\left\{-\frac{k^2 b^2}{4} - h_0\sqrt{k^2 - \frac{i\omega}{\alpha_1}}\right\} \bullet$$

$\bullet$ F (k) , where

b = Gaussian beam radius of heating beam

c = Gaussian beam radius of probe beam

α_1 = Thermal diffusivity of gas (region 1)

α_2 = Thermal diffusivity of coating (region 2)

α_3 = Thermal diffusivity of substrate (region 3)

$$F(k) = \frac{1+R}{1-R}, \quad R = \frac{1-R'}{1+R'} \exp\left[-2a\sqrt{k^2 - \frac{i\omega}{\alpha_3}}\right],$$

$$R' = \frac{\kappa_3\sqrt{k^2 - \frac{i\omega}{\alpha_3}}}{\kappa_2\sqrt{k^2 - \frac{i\omega}{\alpha_2}}}$$; κ = Thermal Conductivity, a = Film Thickness

Figure 11

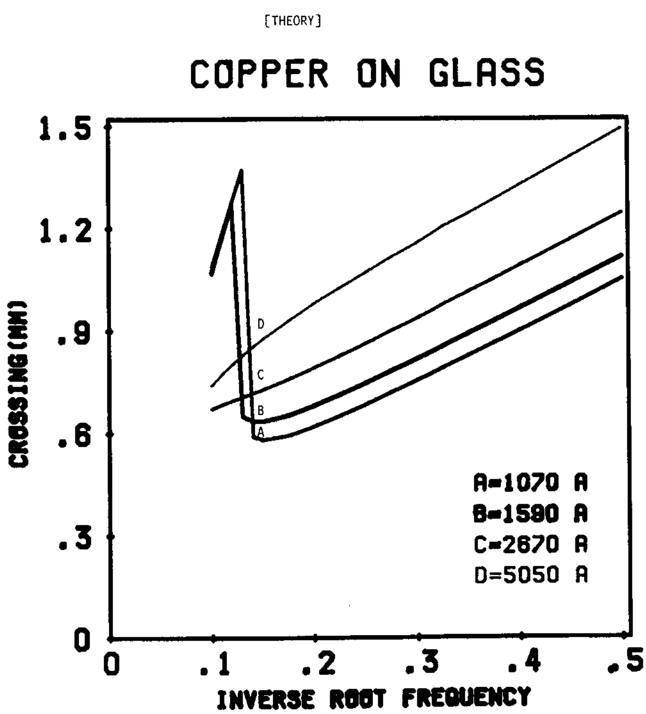


Figure 12

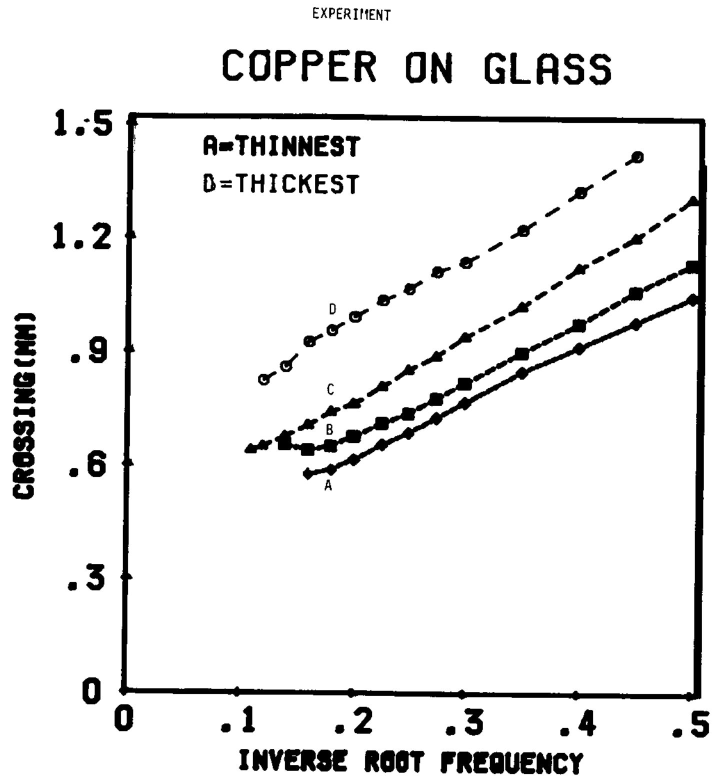


Figure 13

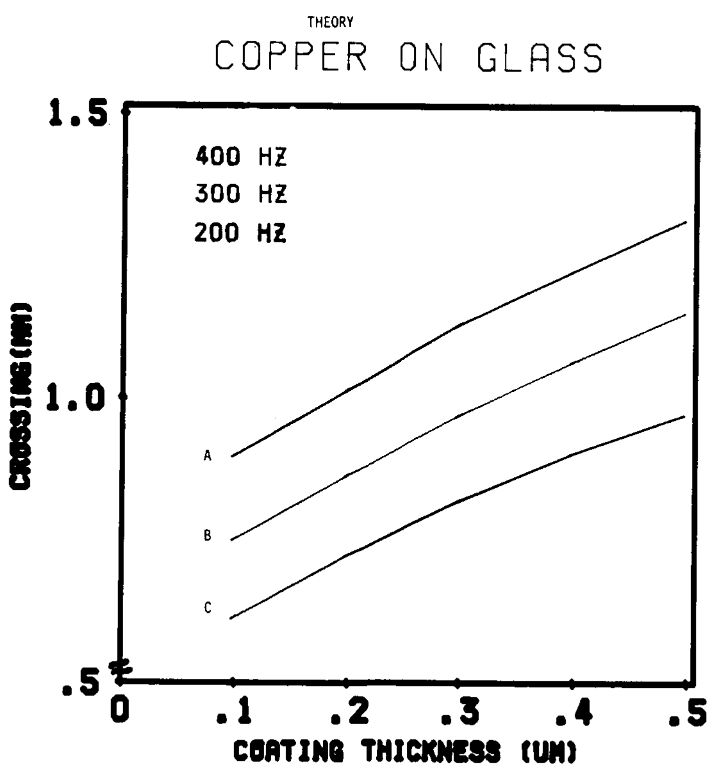


Figure 14