Bonding, density, and thickness of coatings have a vital effect on their performance in many applications. Pioneering development work by the author on thermal wave nondestructive evaluation (NDE) methods during the past 25 years has resulted in an array of useful techniques for performing bonding, density, and thickness measurements in a practical shop environment. The most useful thermal wave methods for this purpose are based on thermal wave surface impedance measurement or scanning. A pulse of heat from either a thermal transducer or a hot gas pulse is projected onto the surface, and the resulting temperature response is analyzed to unfold the bonding, density, and thickness of the coating. An advanced emissivity independent infrared method has been applied to detect the temperature response. These methods have recently been completely computerized and can automatically provide information on coating quality in near real-time using the proper equipment. Complex shapes such as turbine blades can be scanned. Microscopic inhomogeneities such as microstructural differences and small, normal, isolated voids do not cause problems but are seen as slight differences in the bulk thermal properties. Test objects with rough surfaces can be effectively nondestructively evaluated using proper thermal surface impedance methods. No contact with the test object is required, and no couplants or other contaminants are used. Thermal wave NDE might be called a "Wave of the Future", as well as a "Wave at the Past". Recent work done on thermal wave NDE by independent groups in the U.S., as well as abroad, has confirmed the potential of some of these methods for practical coating NDE applications. Some of the basic principles involved, as well as metallographic results illustrating the ability of the thermal wave surface impedance method to detect natural nonbonds under a two-layer thermally sprayed coating, will be presented in this paper.
COUPLANT: RADIATION, GAS, OR FLUID.

POWER INPUT

THERMAL TRANSUDER

LOW FREQUENCY THERMAL WAVE (DEEP PENETRATION)

HIGH FREQUENCY THERMAL WAVE (SHALLOW PENETRATION)

CIRCUIT FOR DISPLAYING THERMAL IMPEDANCE OF SAMPLE

1st LAYER 2nd LAYER

Figure 1.

FOR SINUSOIDAL $\bar{q}$ AND $\bar{t}$, THE THERMAL SURFACE IMPEDANCE IS DEFINED AS

$$Z = \begin{bmatrix} \bar{t} \\ \bar{q} \end{bmatrix}_{x=0}$$

Figure 2.

Heat Flow, $q = C e^{-(1-j)x/\delta}$ (1)

Penetration Depth, $\delta = \sqrt{\frac{K}{\pi 15 \rho}}$ (2)

Surface Thermal Impedance, $Z = [T/q]_{x=0}$ (3)

Figure 3.

140
FIRST LAYER
ON DUCTANCE
LAYERS
SECOND LAYER
BOUNDARY CONDITIONS
lim x = 0
\phi = \frac{\phi_1 + \phi_2}{2}
\frac{\partial \phi}{\partial x} = \frac{\phi_1 - \phi_2}{2h}

THERMAL SURFACE IMPEDANCE FOR A
LAYER IN GOOD CONTACT WITH A
SEM-INFINITE SECOND LAYER

Figure 4.

Figure 5.
COLD PLATE AT CONSTANT TEMPERATURE (ASSUME 0°C)

HEAT INPUT (q) → TEMPERATURE (T) → THERMAL RESISTANCE (1/K)

SURFACE THERMAL IMPEDANCE (Z)

SAMPLE

PHYSICAL ARRANGEMENT

ELECTRICAL ANALOG

Figure 6.

RELATIONSHIP BETWEEN THERMAL INPUT IMPEDANCE OF TRANSDUCER, AND THERMAL SURFACE IMPEDANCE OF SAMPLE

\[
\frac{1}{Z_X} = \frac{1}{R_C} + \frac{1}{R_G + Z}
\]

HENCE

\[
Z = \frac{R_C Z_X}{R_C - Z_X} - R_G
\]

AND

\[
Z_X = \frac{R_C(R_G + Z)}{R_C + R_G + Z}
\]

Figure 7.
Block Diagram of the Sinusoidal Thermal Wave Tester

- Oscillator
- Differential Amplifier
- Output
- Multiplier
- Phase and Amplitude
- Automatic
- Data Interpreter
- Alarm
- Process Control

Sample

Figure 8.

Figure 9.
Figure 10.

Figure 11.
Then, from the definition of the Laplace transform,

\[ \mathcal{L}\{f(t)\} = \int_0^\infty e^{-pt} f(t) dt \]

\[ \mathcal{L}\{y(t)\} = \int_0^\infty e^{-pt} y(t) dt \]

When \( f(t) \) and \( y(t) \) converge so that these two integrals are bounded after replacing \( p \) by \( j\omega \), we can write:

\[ \mathcal{L}\{f(t)\} = \int_0^\infty e^{-j\omega t} f(t) dt \]

\[ = \int_0^\infty f(t) \cos \omega t dt - j\int_0^\infty f(t) \sin \omega t dt \]

And

\[ \mathcal{L}\{y(t)\} = \int_0^\infty e^{-j\omega t} y(t) dt \]

\[ = \int_0^\infty y(t) \cos \omega t dt - j\int_0^\infty y(t) \sin \omega t dt \]

And hence,

\[ Z(j\omega) = \frac{\int_0^\infty f(t) \cos \omega t dt - j\int_0^\infty f(t) \sin \omega t dt}{\int_0^\infty y(t) \cos \omega t dt - j\int_0^\infty y(t) \sin \omega t dt} \]
Figure 16.

130 alumina-titania/444 stainless bond coat/steel

1100 aluminum corrosion coat/steel

Metcoloy #2 arc spray/steel

447 Mo-Ni-Al bond coat/steel

130 alumina-titania/447 Mo-Ni-Al bond coat/steel

105 white alumina/447 Mo-Ni-Al bond coat/aluminum

Ampcotrode #46/steel

70 S-4/steel

ORIGINAL PAGE IS OF POOR QUALITY
EMISSIVITY INDEPENDENT INFRARED- THERMAL SCAN RESULT SHOWING
ALL NONBONDS ON SIDE 11 OF PSNS CYLINDRICAL THERMAL SPRAYED TEST
SPECIMEN #11.

Figure 17.

ORDINARY EMISSIVITY DEPENDENT INFRARED- THERMAL SCAN RESULTS ON
SIDE 11 OF PSNS CYLINDRICAL THERMAL SPRAYED TEST SPECIMEN #11.
NOTE THAT MOST 1/8 INCH DIAMETER NON-BOND INDICATIONS ARE HIDDEN
IN THE BACKGROUND EMISSIVITY VARIATIONS.

Figure 18.
50X DEFECT "A"

START OF DEFECT

STEEL SUBSTRATE

STAINLESS COMPOSITE BOND COAT

Al₄O₃-TiO₂ CERAMIC OVERCOAT

Figure 20.
DEFECT "C"
LENGTH 0.085 in.

Figure 22.