Non-Contact Thickness Sensor for Thermal Barrier Coatings using Thermal Wave Interferometry

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Abstract: As plasma sprayed thermal barrier coatings continue to enhance the design of many turbine and diesel engine components, the need for a technique for on-line process control of coating thickness continues to grow. An experiment is proposed using the thermal wave interferometry technique for the determination of thermal barrier coating thickness.

Introduction: Thermal Barrier Coatings (TBC) are being widely developed as a means of improving the performance of gas turbine and diesel engines. These ceramic coatings are typically deposited using a plasma spray process onto engine components such as turbine blades and pistons. The approximately 1mm thick coatings improve the efficiency of such engines in one of two ways: by enabling the engine to run at higher temperatures or by reducing the need for cooling[1-2].

The plasma spray process basically consists of the spraying of molten material onto a cooling surface where the build up of solidified particles produces a coating. In this process a ceramic powder is injected into a very high temperature plasma flame where it is heated and accelerated toward the substrate[3].

Plasma spraying is a line-of-sight process where the deposition of uniform coatings of a desired thickness is difficult. Test coupons placed near the component during the spray process and later analyzed by microscopy are typically used to determine the thickness of the ceramic coatings. This, however, is a labor-intensive process that is not always an accurate indication of the coating thickness on the actual component[4].

Recent developments in Thermal Wave Interferometry suggest that the technique proves very promising for the non-contact determination of coating thickness[5-6]. Because of its non-contact and single-sided nature, the possibility exists for the development of this technique into an on-line process control sensor for determining coating thickness.

Theory: Thermal Wave Interferometry is based on the propagation of planar thermal waves through a coating-substrate structure. A detailed description of the technique can be found in Almond and Patel[7]. In short, thermal waves are a diffuse, heavily damped wave that exhibit most of the usual wave properties. Generated by the temporal modulation of a heat source at an angular frequency, \( \omega \), thermal waves propagate into the coating-substrate structure.
Upon reaching a coating-substrate interface, a thermal mismatch is encountered. The thermal mismatch causes reflection of the thermal wave to occur. The degree to which this reflection occurs is determined by the reflection coefficient $R$.

$$ R = \frac{1-b}{1+b}, \quad (1) $$

$b$ is the ratio of the substrate $s$ and coating $c$ thermal effusivities:

$$ b = \frac{\sqrt{(\rho c_p k)_s}}{\sqrt{(\rho c_p k)_c}}, \quad (2) $$

and $\rho$ is the bulk density, $c_p$ is the specific heat, and $k$ is the thermal conductivity.

Due to the coherence of both primary and reflected thermal waves, interference occurs. This interference leads to the modification of both the phase and the amplitude of the surface temperature.

Bennett and Patty [8] were the first to derive an interference expression for surface generated thermal waves in a thin coating by summing the contribution of both primary and reflected waves. For a coating of thickness $L$, and complex thermal wave number $\sigma_c$, the complex interference expression $T$ is:

$$ T = \frac{I_o}{2\sigma_c k_c} \left[ \frac{1-R \exp(-2\sigma_c L)}{1+R \exp(-2\sigma_c L)} \right], \quad (3) $$

where $I_o$ is the intensity of absorbed light converted to heat. The complex thermal wave number $\sigma_c$ is:

$$ \sigma_c = \frac{(1+i)}{\mu}. \quad (4) $$

Thermal waves are critically damped in a distance $\mu$, known as the thermal diffusion length [$\mu = (2\alpha/\omega)^{1/2}$]. This length is a function of the thermal wave diffusivity $\alpha$, and the angular modulation frequency $\omega$. Consequently, by adjusting the frequency of the heat source, the thermal diffusion length $\mu$ can be maximized for different coating thickness.

The complex thermal wave interference expression $T$, as defined by equation (3), can be manipulated so as to express the amplitude and phase of the surface temperature in polar coordinates. An example of the calculated phase change as a function of coating thickness is show in figure 1.

![Phase Variation](image)

**Figure 1:** Normalized phase angle variation with normalized coating thickness for various coating/substrate reflection coefficients (-0.9, -0.7, -0.5, 0.5, 0.7, 0.9).

After calibration, the thickness of a coating can be determined from experimental data by observing the change in phase caused by the reflection of thermal waves.

**Experiment:** The experimental apparatus for producing and detecting thermal waves is currently under development. The apparatus will consist
of an excitation source, a detector, and a recorder as shown in figure 2.

![Schematic diagram of the experimental test system.](image)

Thermal waves are typically generated using cw lasers which are temporally modulated by mechanical choppers. Recent developments in high-power semiconductor diode lasers make them the excitation source of choice for thermal wave interferometry. The advantage of diode lasers over conventional lasers is their reduced size and their ability to be directly modulated.

Detection of thermal waves can be accomplished in many ways but the most common and direct way is by photothermal radiometry. Using an infrared camera, the temperature of virtually any surface can be assessed by monitoring the emission of electromagnetic radiation. This method has the advantage of being non-contact, single-sided, and insensitive to surface roughness and vibrations. The use of a germanium filter in front of the camera may be required to filter scattered light from the laser.

A computer will be used for triggering the experiment and recording the data obtained by the IR camera. Phase-sensitive detection (lock-in amplification) and other processing techniques may be required for obtaining the desired signal.

Upon completion of the experimental apparatus, coatings of known thickness will be used to calibrate the system. A series of tests will then be conducted to determine the reliability of thermal wave interferometry for use in an industrial environment as a process control sensor.

References


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