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Evaluation of coating thickness by thermal wave imaging: A comparative study of pulsed and lock-in infrared thermography – Part I: Simulation

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HIGHLIGHTS

- Coating is used in modern industries to prolong the life of components.
- FEM was used to simulate the infrared thermography experimental procedures.
- Fourier transform was used to extract phase angle from the thermal sequences.
- Polynomial fitting was adopted to correlate the coating thickness and phase angle.
- The evaluation accuracy of PT and LIT was estimated and found satisfactory.

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ABSTRACT

This paper investigates the possibilities of evaluating non-uniform coating thickness using thermal wave imaging method. A comparative study of pulsed thermography (PT) and lock-in thermography (LIT) based on evaluating the accuracy of predicted coating thickness is presented. In this study, a transient thermal finite element model was created in ANSYS 15. A single square pulse heating for PT and a sinusoidal heating at different modulation frequencies for LIT were used to stimulate the sample according to the experimental procedures. The response of thermally excited surface was recorded and data processing with Fourier transform was carried out to obtain the phase angle. Then calculated phase angle was correlated with the coating thickness. The method demonstrated potential in the evaluation of coating thickness and was successfully applied to measure the non-uniform top layers ranging from 0.1 mm to 0.6 mm; within an accuracy of 0.0003–0.0023 mm for PT and 0.0003–0.0067 mm for LIT. The simulation model enabled a better understanding of PT and LIT and provided a means of establishing the required experimental set-up parameters. This also led to optimization of experimental configurations, thus limiting the number of physical tests necessary.

1. Introduction

Various type of coatings such as Thermal Barrier Coating (TBC), Functional Coating, Anti-Corrosion Coating, Biochemical Protection Coating, Microwave Absorption Coating have been widely used in modern industries and applications to prolong the life of components. TBC refers to a refractory-oxide ceramic coating deposited on the metal surface. TBC provides insulation to the base part and is widely used in aviation, power generation and automotive industries to improve the service life of components being exposed to high-temperatures. TBC is commonly used in aircraft engines, rocket nozzles, gas turbine blades, advanced aero engines to protect the components from wear, erosion and high-temperature degradation [1–4]. A typical TBC consists of a nickel based superalloy as a substrate material, intermetallic material as a bond coat, thermally grown oxide (TGO) and a ceramic top coat. The bond coat is usually made of MCrAlY alloys (M = Co, Ni, or Co/Ni) and provides a good adherence between the substrate material and top coat as well as oxidation resistance and tolerance against thermal expansion mismatch. TGO is formed during the deposition and starts to grow with high- temperature oxidation and spallation of top coat occurs from the bond coat. The topcoat is usually made of Yttria stabilized zirconia (YSZ) featuring superior mechanical, chemical and excellent thermal barrier performance. The topcoat thickness is an important parameter which determines the thermal insulation characteristics, and is important for performance evaluation. Therefore, there is a need for nondestructive testing (NDT) techniques to evaluate the coating thickness for uniformity [5–7].

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Among the NDT technologies, thermal wave imaging (TWI) often known as infrared thermography (IRT) deals with the acquisition and analysis of thermal information from non-contact, fast speed thermal imaging devices. IRT involves two classes, passive thermography and active thermography. Based on the heating methods, active thermography could be further subdivided into pulsed thermography (PT), lock-in thermography (LIT), step heating and vibrothermography. In the active approach, PT and LIT are most commonly used. PT and LIT make use of highly sensitive thermal imaging devices (IR Camera) and are carried out in either transmission or reflection mode. In transmission mode, the heat source is on the opposite side of the sample to the IR camera, whereas in reflection mode the heat source and the IR camera are on the same side of the sample [8–11]. IRT has been used in the inspection of thermo-physical properties, discontinuities, sub-surface defects and features, hidden corrosion and coating thickness [12–18].

This paper presents the comparative study of PT and LIT techniques in reflection mode for the evaluation of TBC thickness deposited on Ni-based superalloy. A transient finite element model (FEM) was developed and stimulated by a flow of heat to simulate PT and LIT which allow experimental parameters to be tailored without the need for extensive, time consuming and potentially expensive preliminary experiments. The thermal variation of the material at this excitation was recorded which depends on different parameters of the material such as thermal conductivity, diffusivity, emissivity, and specific heat as well as the excitation used as the input. By analyzing the thermal responses during heating and cooling process, the variation in thickness of the TBC was evaluated.

2. Thermal wave imaging (TWI)

When a sample surface is heated, highly attenuated and disperse waves are found inside the material which are called thermal waves. TWI is based on the propagation of thermal waves within an object and the consequent analysis of the thermal response to time dependent radiation. Fig. 1 shows the basic principle for the evaluation of coating thickness using TWI. When thermal heat energy is applied to top of the coating surface, the presence of difference in the thickness of the coating interrupts the propagation of thermal waves affecting the temperature distribution of the object as a function of time. The difference in temperature distribution is the key parameter for the evaluation of coating and the quantitative information about the coating thickness can be acquired by processing of thermal data [19–22].

2.1. Pulsed thermography (PT)

PT is one of the most popular thermal excitation methods in IRT due to the quickness of the test relying on a short and high power thermal excitation pulse to the sample surface. When a short and high energy light pulse impinges on the sample surface, the surface absorbs the light energy and its temperature increases instantaneously. Thermal waves propagate inside the material causing decrease in surface temperature. The variation in the thermal decay rate across the surface is indicative of a variation of component configuration [23–26].

To simulate the nature of pulse heating, a square heat flux was used on the front surface of the sample to be inspected and expressed as Eq. (1) [27].

$$Q = \frac{Q_{\max}}{2}(1 - sign(t - t_p)) \tag{1}$$

with

$$sign(t - t_p) = \begin{cases} -1 & 0 \leqslant t < t_p \\ 0 & t = t_p \\ 1 & t > t_p \end{cases} \tag{2}$$

where, Q is the incident heat flux, $Q_{\max}$ is the peak value of pulsed heat flow, t_p is the pulsed heating time and t is the total time.

2.2. Lock-in thermography (LIT)

In LIT, the sample surface is periodically heated to inject a thermal wave into it. The thermographic system is coherently coupled to stimulate thermal wave source and a continuous temperature modulation on the inspected sample is recorded. The system collects a series of images and compares the modulated heating with the measured temperatures by extracting the sinusoidal wave pattern at each point of the images [19,20,23,28].

To simulate the nature of sinusoidal heat flux, the thermal excitation source is expressed as Eq. (3) [29–31],

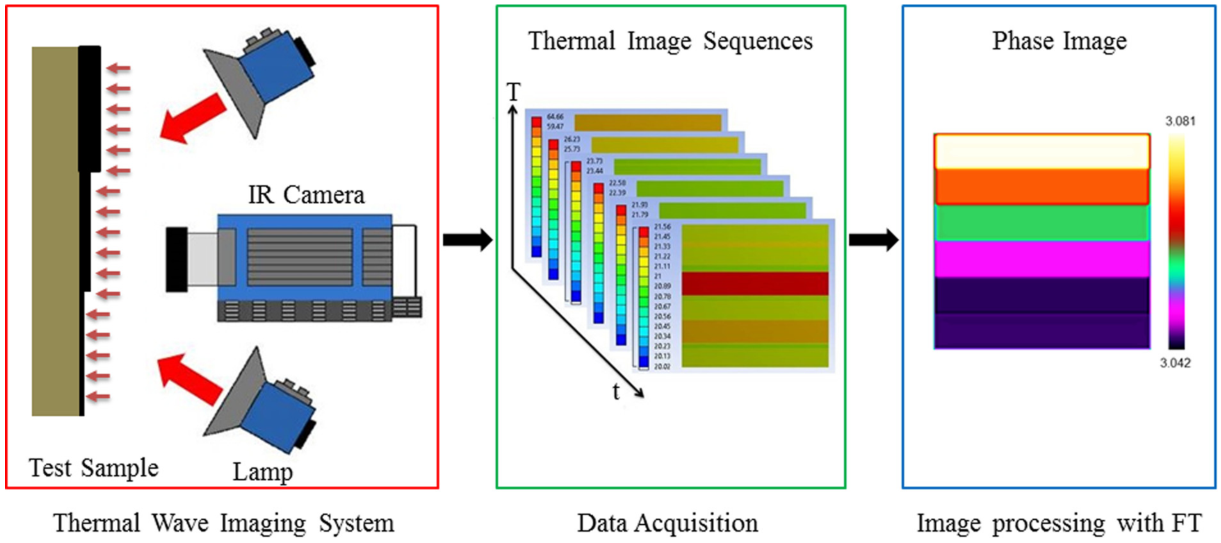

Fig. 1. Principle of evaluation of coating thickness with TWI.