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# A new measurement method of coatings thickness based on lock-in thermography

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## HIGHLIGHTS

- Proposed a set of precision thermal wave nondestructive measurement method for coatings.
- A new wide range coating thickness formula is proposed.
- A new calibration method for measuring of coating thickness is proposed.
- A group of coating specimen was successfully tested.

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ABSTRACT

Coatings have been widely used in modern industry and it plays an important role. Coatings thickness is directly related to the performance of the functional coatings, therefore, rapid and accurate coatings thickness inspection has great significance. Existing coatings thickness measurement method is difficult to achieve fast and accurate on-site non-destructive coatings inspection due to cost, accuracy, destruction during inspection and other reasons. This paper starts from the introduction of the principle of lock-in thermography, and then performs an in-depth study on the application of lock-in thermography in coatings inspection through numerical modeling and analysis. The numerical analysis helps explore the relationship between coatings thickness and phase, and the relationship lays the foundation for accurate calculation of coatings thickness. The author sets up a lock-in thermography inspection system and uses thermal barrier coatings specimens to conduct an experiment. The specimen coatings thickness is measured and calibrated to verify the quantitative inspection. Experiment results show that the lock-in thermography method can perform fast coatings inspection and the inspection accuracy is about 95%. Therefore, the method can meet the field testing requirements for engineering projects.



## 1. Introduction

Thermal barrier coatings, anticorrosion coatings, microwave absorption coatings, biochemical protection coatings and other special functional coatings have been widely used in modern weapon equipments [1–4]. For example, high temperature corrosion-resistant coatings used on missile launch pad, insulation coatings is applied on rocket engine nozzle, stealthy coatings improves aircraft's penetration ability, and etc. The coatings plays a very important role in improving the weaponry's survivability, penetration ability and operational performance. The coatings thickness is not only a parameter of the geometrical property of the coatings itself, but also an important indicator for evaluating the coatings' quality, performance and service life. Therefore, effective non-destructive testing of the coatings thickness is of great significance for the performance of the weapon equipments. There are a variety of methods such as ultrasound, ray and eddy, to inspect the thickness of the coatings. However, they all have certain limitation [5–7]. Infrared thermal wave inspection technology becomes a research hotspot in recent years as it has unique advantages over other inspection methods. Pulse infrared thermal wave inspection was the most mature and the most widely used technique among thermal wave inspection techniques [8–12]. However, this pulse method has the disadvantage that the measurement accuracy is low and the requirement of the thermal imaging equipment is high [9–11]. Therefore, researchers turn to the lock-in thermography. Compared with the pulse method, the lock-in thermography has a number of merits – low requirement on the intensity of heating excitation, less sensitive to the uneven heating and surface emission rate changes, high resistant to surface reflection interference, low requirement on surface anti-reflection processing, good adaptability to curvature surface, etc. [13].

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Especially, Lock-in Thermography has many merits such as big detection area, high efficiency, more coatings materials and good safety over X-ray Fluorescence, Eddy-Current, magnetic induction and Beta backscatter methods. Lock-in thermography could be the ideal method for coatings thickness inspection.

The lock-in thermography was proposed by Professor G. Busse from University of Stuttgart in 1992 [14]. It used thermal wave's phase difference between defective area and normal area to achieve the purpose of inspection. In the same year, G. Busse proposed the ultrasonic phase locked thermal imaging technology [15]. The advantage of ultrasonic excitation is that it only heats up the defective area, but this advantage limits the inspection area. In 2000, Singaporean scholar Bai and Wong [16], after comparing the low frequency modulation and high frequency modulation to detect specimen's defects, found that the high frequency modulation provided higher resolution for defects, i.e. it could inspect smaller defects. In 2001, Weimin Bai established new single layer and multi-layer thermal wave model [17] for lock-in thermography, which overcame the limitation of the original model's application in the experiment material with finite thickness. In 2003, Poland scholar Waldemar Swiderski used lock-in thermography in the composite material defect inspection for a military project [18]. This expanded the application scope of infrared phase-locked technology. Waldemar also pointed out that the second radiation has almost no effect on the amplitude and phase diagram of any point on the specimen's surface, and the phase diagram is also not affected by the illumination's uneven radiation or the influence of surface emissivity. The advantage of lock-in thermography was further validated. In 2006, Sargent used lock-in thermography in wet paint film thickness measurement and accurately predicted the film thickness when the paint film dried. Good results have been achieved in Sargent's application [19].

The above researches have made great achievements in the development of thermal wave testing theory and its applications, but the researches in thermal wave testing theory and experiment particular to coatings thickness are obviously inadequate. Although some scholars adopted lock-in thermography for simulation and experiment to inspect defects and they proved the advantage of phase-locked method for defect inspection, the method is difficult to be directly applied in coatings inspection as a quantitative relation has not been defined to determine defect's depth. Sargent et al. [19] firstly introduced an equation which is derived from one dimensional thermal conduction equation. However, its application is limited. To solve this problem, this paper focused on researching the coatings thickness measurement method. The second section introduces the coatings thickness measurement modeling and the numerical simulation of the model, and then discusses the basic theory of coatings thickness measurement. The third section introduces the experimental system set up and the design of the specimens. The fourth section shows the experimental results followed by discussion, and the last section is the summary.

## 2. The principle and method of coatings thickness measurement

The mechanism of lock-in thermography for coatings thickness inspection is shown in Fig. 1. A sinusoidal heat flux is used to generate external excitation onto the coatings surface. The thermal excitation form is as Eq. (1).

$$q(t) = q_0(1 - \cos(2\pi f_e t)) \tag{1}$$

$q(t)$ is the instantaneous density of the sinusoidal heat flux, $q_0$ is heating power of the heat source, $f_e$ is the excitation loading frequency of the heat source.

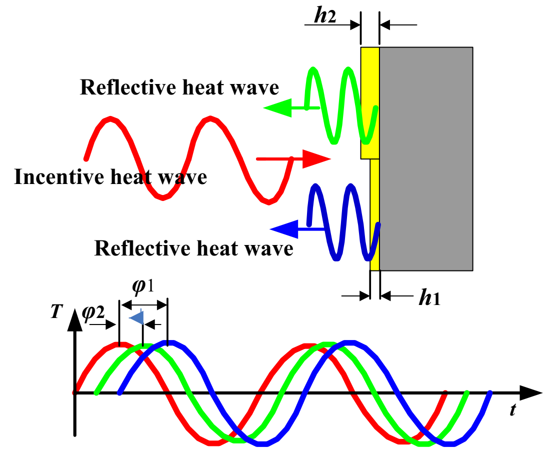


**Fig. 1.** The theory of lock-in thermography.

When the thermal wave reaches the coatings surface, part of the incident energy will be absorbed by the coatings and converted into heat energy. The heat energy forms a local heat flow field which changes periodically in the coatings. Heat energy propagates in a similar form of mechanical wave within the coatings, and the propagation process is dependent of the modulation frequency of heat source and thermal property of the coatings. When the thermal wave further arrive the interface of the coatings and substrate, it will be scattered or reflected due to the abrupt change of the propagation medium's thermal property. When the reflected thermal wave returns to the coatings surface, it changes the temperature distribution on the surface of the coatings. The process of temperature change on the coatings surface can be recorded by an infrared thermal imager. Adopting 'digital phase lock' signal processing technology, the useful signal can be separated from the noise signal and then the phase diagram and amplitude diagram which describe the temperature on the coatings surface. Since the excitation heat source's intensity is sinusoidal, the temperature change on coatings surface is sinusoidal with the same frequency. The phase of the temperature change varies due to different thermal wave propagation distance when the coatings thickness changes. The coatings thickness $L$ can be expressed as a function of phase, $L = f(\varphi)$.

The principle of coatings thickness inspection using lock-in thermography method looks simple, but the problem is very difficult to solve because the mathematical expression of the heat flow propagation in the coatings are three dimensional heat conduction differential equation which is very difficult to find the analytical solution. Therefore, it is necessary to use a simplified model to solve the problem.

### 2.1. The simplified thermal wave coatings model

Generally, coatings thickness used in an engineering project is within 3 mm, and the thinnest coatings can be a few microns. The coatings thickness is far smaller than the substrate's thickness; meanwhile, the coatings thickness is much smaller than its size. Therefore, when the heat flux propagates within the coatings, the influence of lateral and transversal conduction to the thermal wave signal on coatings surface can be ignored. So the process of heat flux's propagation within the coatings can be simplified as a one-dimensional heat conduction process, and the heat conduction model is:

$$k\frac{\partial^2 T(X,Y,Z,t)}{\partial Z^2} = \rho c\frac{\partial T(X,Y,Z,t)}{\partial t} \tag{2}$$