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Research Paper

Quantitative detection of thermal barrier coating thickness based on simulated annealing algorithm using pulsed infrared thermography technology

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HIGHLIGHTS

- Quantitative detection of TBC thickness has been carried out.
- The model of heat conduction inverse problem was built.
- The basic principle and implementation process of SA algorithm was described.

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ABSTRACT

Quantitative detection of thermal barrier coating thickness based on simulated annealing (SA) algorithm has been carried out using pulsed infrared thermography technology. The principle of quantitative detection of thermal barrier coating thickness was given, and the model of inverse heat conduction problem was built. The basic principle and implementation process of SA algorithm was described. The specimen with uneven coating thickness was detected using pulsed infrared thermography system, and the coating thickness was calculated using SA algorithm. Results show that when the coating thickness is 45~130 μm, compared with eddy current testing results, the relative error is less than 10%, which proves the effectiveness of the coating thickness detection method proposed in this paper.

1. Introduction

Thermal barrier coating (TBC) structure is widely used in hot end components such as combustion chamber and turbine blades of aviation turbine engines [1,2]. The integrity of TBC structure is the basic guarantee for the normal operation of the components, so it is necessary to carry out nondestructive testing and evaluation of the internal defects of TBC. Pulsed infrared thermal wave nondestructive detection technology has the advantages of large detection area, fast speed, non-contact, safe and easy to operate, etc [3–7]. How to measure the quantitative information of defects accurately, such as the defects' depth and size, coating thickness distribution uniformity, and get transformation from qualitative detection to quantitative evaluation, is an urgent task in pulsed infrared thermal wave nondestructive detection field. Grzegorz Ptaszek *et al.* investigated the effects of uneven discolouration of the surface and of IR translucency on the thermal responses, and results showed that unpainted TBC systems can be inspected reliably by using higher power flash heating equipment assembled with an IR glass filter and a long wave length IR camera [8]. Minoru Aoyagi *et al.* evaluated uneven painting on various substrates using thermographic observation of dynamic changes in surface temperature following exposure to a high-energy light flash [9]. Steven M. Shepard *et al.* carried out thermographic measurement of thermal barrier coating thickness using pulsed thermography technique, and the 1st derivative inflection points or negative 2nd derivative peaks of the thermographic signal was used to create highly accurate maps of TBC thickness [10].

In this paper, quantitative detection of TBC thickness was realized by using the inverse heat conduction problem theory and optimization algorithm. The paper is organized as follows: section 2 describes the principle of quantitative detection of TBC thickness; in section 3, the quantitative inversion results and discussion are presented; finally, the conclusion is given.

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2. The principle of quantitative detection of thermal barrier coating thickness

The thermal conduction process and surface temperature distribution under optical pulse excitation is closely related to coating thickness distribution. So, the problem of coating thickness detection can be reduced to inverse heat conduction problem. Therefore, this paper proposes a coating thickness quantitative inversion method by establishing and solving the inverse heat conduction problem model. The basic principle of quantitative detection of thermal barrier coating thickness is shown in Fig. 1. Infrared image sequences and the surface temperature signals can be captured by pulsed infrared thermography detection system. According to theoretical model of heat conduction and inverse heat problem, combining with optimization algorithm, the inverse heat problem can be solved and thus the coating thickness distribution can be arrived.

2.1. The model of inverse heat conduction problem

The positive heat conduction can provide temperature value and the calculation model of the measuring points for inverse heat conduction problem. In the positive problem, the temperature values of the measuring points are obtained by theoretical and experimental method. In the inverse problem, inverse variables are processed as the optimization variables, residuals between the calculated and the measured temperature values as the optimization objective function values, solved numerically by minimizing the objective function.

In the inverse heat conduction problem of coating thickness detection using pulsed infrared thermal wave testing, the value of coating thickness is unknown, with other conditions are same as that of positive heat conduction problem. The additional information needed is the surface temperature field distribution of measuring points, which can be captured by an infrared camera. The optimization objective function corresponding to inverse problem can be expressed as Eq. (1)

$$F(x_1, x_2, \ldots, x_N) = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(t_i^* - t_i(x_1, x_2, \ldots, x_N))^2} \tag{1}$$

where M means the number of measuring points; $x = (x_1, x_2, \ldots, x_N)$ is the parameter to be estimated; N is the number of inversion parameters, here $N = 1$; t_i^* and t_i are the measured and calculated temperature, respectively; and $i = 1 \sim M$, which is the same number of the selected frames of infrared image sequences.

In the practical application, parameters to be estimated have a certain range. Then the coating thickness inversion problem can be transformed into a minimum optimization problem with constraints.

$$\left.\begin{aligned} &\min F(x_1, x_2, \ldots, x_N) = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(t_i^* - t_i(x_1, x_2, \ldots, x_N))^2} \\ &\text{s.t.} \qquad x_1^{low} \le x_1 \le x_1^{up} \\ &\qquad\qquad \cdots \\ &\qquad\qquad x_N^{low} \le x_N \le x_N^{up} \end{aligned}\right\} \tag{2}$$

where x_i^{up} and x_i^{low} are the upper and lower limit values for the parameters $x_{i\in(1,2,\cdots,N)}$ to be estimated.

2.2. The solving algorithm selection and realization of inverse heat conduction problem

2.2.1. The solving algorithm selection

Inverse heat conduction problem is often ill-posed, which is characterized by the solution with non uniqueness and instability [11,12].

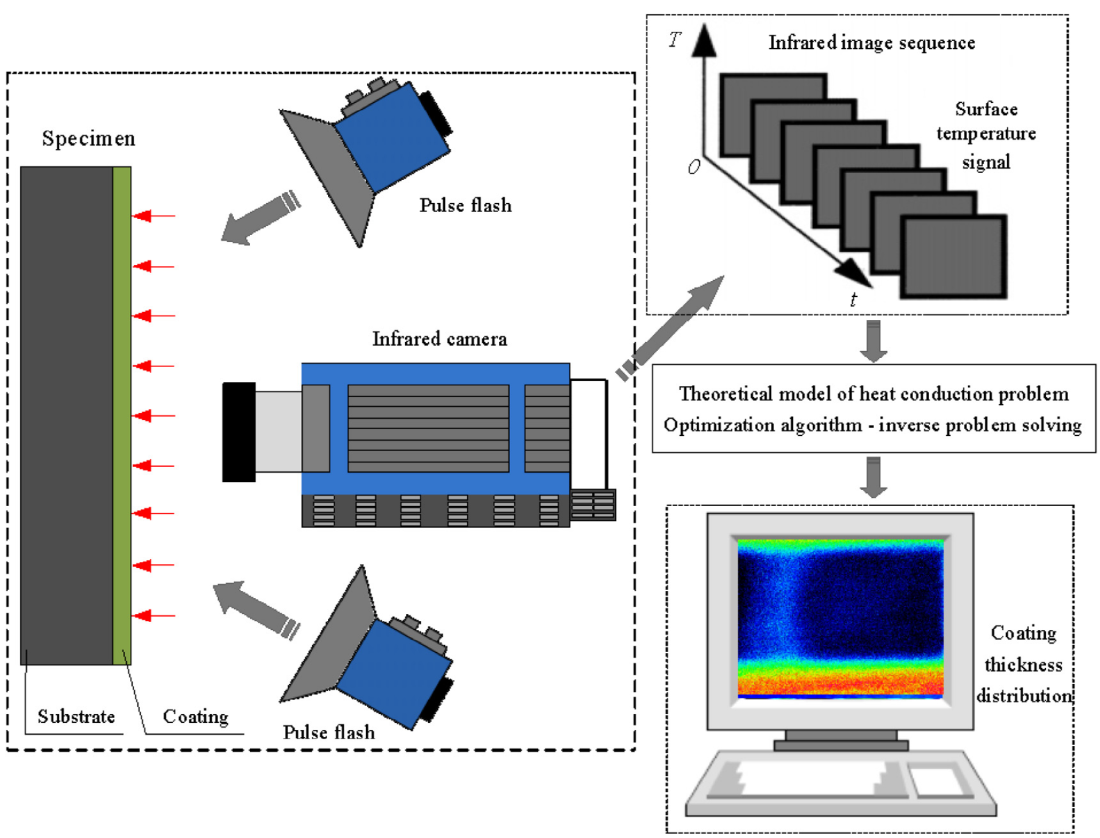

Fig. 1. Basic Principle of coating thickness quantitative inversion.