

Study of under Coating Recognition by Pulse Thermography

Da-Peng CHEN^{1,a,*}, Xiao-Li LI^{2,b}, Xiao-Long ZHANG¹, Jia GUO³ and Guang ZHANG¹

¹Science and technology on optical radiation laboratory, Beijing, 100854, China

²Department of Physics, Capital Normal University, Beijing, 100048, China

³Unit 91550, Dalian, 116023, China

^app.2002@163.com, ^blixiaoli.127@163.com

*Corresponding author

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Abstract. Pulse thermography has been proved an effective method for the quality testing of coating materials. Surface temperature variations not only reveal the shape and position of the defect, but also reflect the property of the second layer. In this paper, the relationship between surface temperature and the property of the second layer is obtained by analyzing the one-dimensional theoretical model of transient heat conduction in a double-layer structure under an instantaneous plane source, which establish the theoretical basis of the recognition by infrared time depend characteristic; typical materials painted the same coating are manufactured as the specimens for the recognition study; pulse light stimulation is adopted, and an IR camera is used to record the temperature varies of the surface. Different materials can be distinguished by comparing the log temperature vs. time curves, furthermore the theoretical log T-t curves are also shown as a comparison, and the errors are analyzed.

Introduction

Coating technology has an increasing applications in the field of mechanical engineering, information technology, microelectronic technology and optical information science, et al. The quality of the coating is an important effect of the product application. Though there are several methods for the qualitative testing of coating product, each has its limitations. Pulse thermography is a new non-destructive technology, which has the advantages of fast, non-contact and no pollution, compared with the traditional methods. And it has been proved an effective method for the quality testing of coating materials according to various of reports^[1]. Furthermore, the heat conduction characteristic between the coating and the substrate by pulse thermography has become a hot research topic^[1].

In 90's, The United States began to focus on the study of Infrared Thermal Imaging Nondestructive Testing Technology, such as Wayne State university used pulse thermography to detect defects and damages in the fuselage coating, wings, landing gear and other parts of the aircraft^[2]. Airbus used three thermal excitation methods to detect fluid ingress in composites of tails: heating blanket, oven and fridge^[3]. Laval university applied PPT method to detect composite structure, and show the damages and defects in phase images^[4]. In Russia, liquid ingress in glass-fiber, aluminum and carbon-fiber honeycomb structures were experimental studied using thermography with several kinds of light source (halogen tube heater, high-power pulsed heater and normal light with reflectors)^[5]. In Germany, University of Stuttgart, periodic and frequency controlled heat excitation was applied on the objects, and the thermal response of internal structure according to the periodic temperature changes was studied, and then the internal structure was shown in the phase images by time-frequency transformation^[8]. Furthermore, many reports show that the UK, France, Japan, et al. are also focus on this technique^[6-8].

In China, this technique is developed in ten of years. Beihang University, Harbin university, Capital Normal University and several aerospace institutes are the main research institutions of this technology and it has mainly used in the field of aerospace, wind power, military industry, automobile manufacturing. Some reports are related to quality testing of thermal barrier, and

thickness measurement of radar wave absorbing coatings[9-11], however, there is no relevant report on the under coating recognition according to physical properties variation of the substrates. Therefore, in this paper, a new method for detection and recognition of under coating material by pulse thermography is proposed. Typical materials painted the same coating are manufactured as the specimens for the recognition study; pulse light stimulation is adopted, and the characteristic of surface infrared radiation variations analyzed. A recognition algorithm is proposed by the analyzing of heat conduction equation of double-layer structure under an instantaneous plane source, and realized the recognition of under coating materials.

Theory

The principle of the pulse thermography is shown in Figure 1, the surface of the detected specimen is heated with a short pulse of light. The generated heat at front surface propagates to the interior of the sample, and leads to a continuous decrease of the surface temperature.

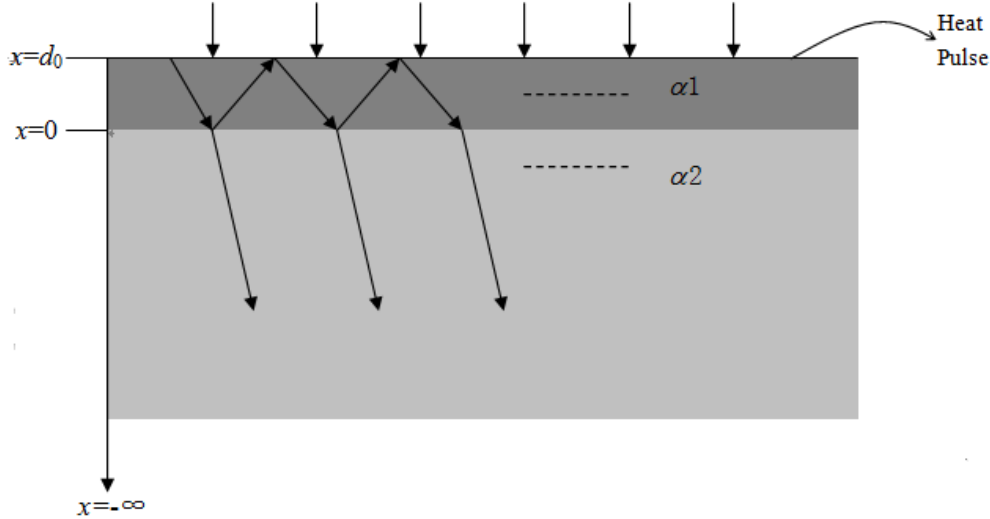


Fig. 1. Sketch map of the principle of pulse thermography

As Figure 1 shown, $0 < x < d_0$ is of one medium and $x < 0$ is of another. We write $k_1, \alpha_1, \rho_1, c_1$, and T_1 for conductivity, diffusivity, density, specific heat, and temperature in the region $x > 0$, and $k_2, \alpha_2, \rho_2, c_2, T_2$ for the corresponding quantities in $x < 0$. Consider a unit instantaneous plane source at $t=0$ at x' in the region $x > 0$, the temperature expression can be given as Eq. (1)[12-13]:

$$T_{1x} = \frac{C}{2\sqrt{\pi\alpha_1 t}} \left[e^{-(x-x')^2/4\alpha_1 t} + \sum_{n=1}^{\infty} R^n (e^{-(x+(2n-1)d_0)^2/4\alpha_1 t} + e^{-(-x+(2n+1)d_0)^2/4\alpha_1 t}) \right] \quad (1)$$

We assume that, $R = \frac{k_1\sqrt{\alpha_2} - k_2\sqrt{\alpha_1}}{k_1\sqrt{\alpha_2} + k_2\sqrt{\alpha_1}}$ which can be seen as the thermal reflection coefficient at the

interface between the two materials.

The instantaneous heat source is applied on the surface $x'=d_0$, then the surface temperature $x=d_0$ can be given as:

$$T_{lsurf} = \frac{C}{2\sqrt{\pi\alpha_1 t}} (1 + 2 \sum_{n=1}^{\infty} R^n e^{-n^2 d_0^2 / \alpha_1 t}) \quad (2)$$

This is the mathematical expression of surface temperature for double-layer structure (the thickness is d_0 of one medium and infinite of another) under the instantaneous plane source. For practical testing, effective algorithm should be developed base on Eq. (2), and then thermal

reflective coefficient can be calculated to get the thermal property of the second layer and realize the recognition of the substrate materials.

Specimens

Five kinds of materials including glass fiber, steel, aluminum, carbon fiber, and hard plastic are manufactured as the substrates, as the photo shown in Figure 2. The size of each one is $80\text{mm} \times 50\text{mm} \times 6\text{mm}$.



Fig. 2. Photo of the substrates

Table 1 shows the thermal conductivity and thermal diffusion coefficient of the substrate materials, which is measured by the TCi Thermal Conductivity Analyzer.

Table 1. Testing results of the heat physical parameters

Materials	Coating	Aluminum	Steel	CFRP	GFRP	Plastic
Heat conductivity (W/(m·K))	10.5	30	17	7	5.3	1.7
Heat diffusivity (m ² /s)	5.4×10^{-6}	1.2×10^{-5}	4.7×10^{-6}	3.6×10^{-6}	1.79×10^{-6}	1.01×10^{-6}

Black washable krylon paint is applied on the surface of the substrates to simulate the similar coatings as well as to increase its absorption of visible lights from the flash lamps.

Experiments

An infrared camera is used to capture temperature variations of surface, the sampling frequency is fixed at 60Hz. Infrared thermal images at different times are shown in Figure 3. Different substrates has similar appearance in the infrared images. Recognition method should be obtained by analyzing the characteristic of surface temperature decreasing data.

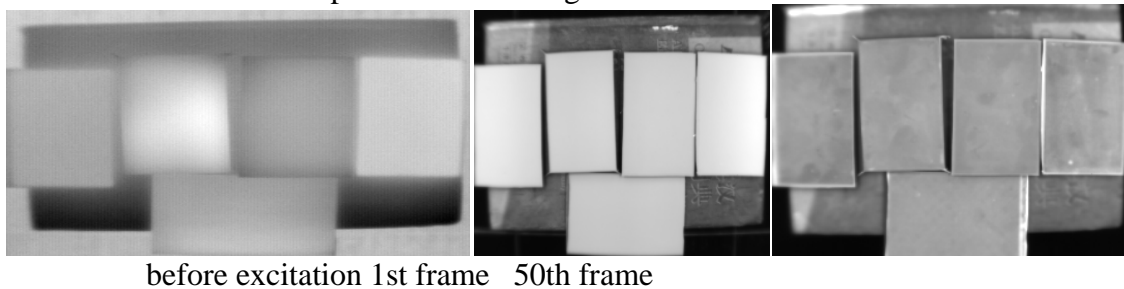


Fig. 3. Thermal images of experimental results

The original surface temperature vs. time curves are shown in Figure. 4, it can be seen that different substrate has different T-t curves, because of the thermal property variation of the substrates, which can be used as one of the basis for recognition. However, the signal to noise level of the original T-t curves is too low to be directly used for the recognition. Effective algorithm should be developed to process the original T-t data and improve the signal to noise level.

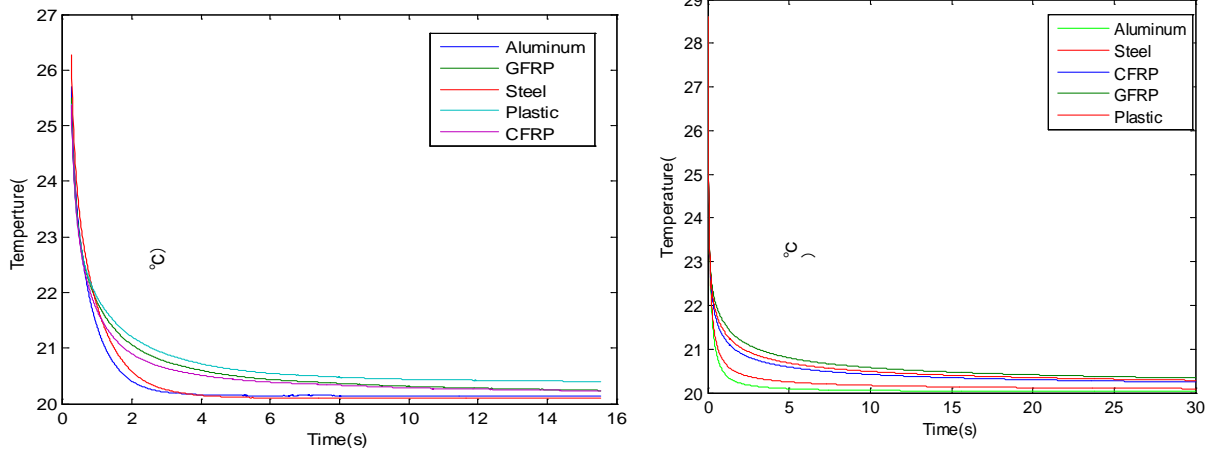


Fig. 4. Original temperature vs. time curves Fig. 5 Theoretical temperature vs. time curves

According to the thermal property parameters of the coating and substrates, the theoretical simulated T-t curves based on the Eq. (2) are also shown in Figure 5 as a comparison. It is found that the theoretical T-t curves coincide with the experimental curves.

The error generated mainly because the simulated results are based on one-dimensional heat conduction, while the heat conduction in the experiments are 3-dimension. Another reason is that the pulse in the experiment has a width of 2ms, while it is an ideal instantaneous heat source in the theoretical simulation.

Data Processing

For pulse thermography, the surface temperature decreasing fast and achieve the heat equilibrium in a very short time. Near surface signals tend to focus on the initial dozens of frames after excitation, and in addition, the initial surface temperature is not uniform. So it is difficult to identify different substrates through the original cooling curves. Therefore, developing data processing method is necessary: the cooling data is normalized at the peak value, and then adopt logarithm to the normalized data. The cooling signal at early time can be amplified by the logarithmic T-t curves, and the characteristic of different substrates can be revealed.

In theory, the logarithmic cooling equation for a semi infinite medium can be given as [13]:

$$\ln T_0 = -\frac{1}{2} \ln(t) + b \quad (3)$$

Where b is a constant, Eq.(3) shows that the logarithmic cooling curve of semi-infinite medium under pulse heat source is a straight line with a slope of $-1/2$.

According to situation of the double layer, as Eq. (2) shown, neglect the higher order ($n > 1$) reflection, the logarithmic T-t expression can be written as:

$$\ln T_{surf} = -\frac{1}{2} \ln t + b + \ln(1 + 2Re^{-\frac{d_0^2}{\alpha t}}) \quad (4)$$

The equation above indicates that the logarithmic temperature depends time curve is no longer a straight line with a slope of $-1/2$. When the thermal parameters of the coating is a constant, the deviation time with the straight line is proportional to the square depth of the second medium, and the degree of deviation is related to the thermal physical properties of the second media, which can be applied to the recognition of the substrates. The theoretical logarithmic T-t curves are shown in Figure 6.

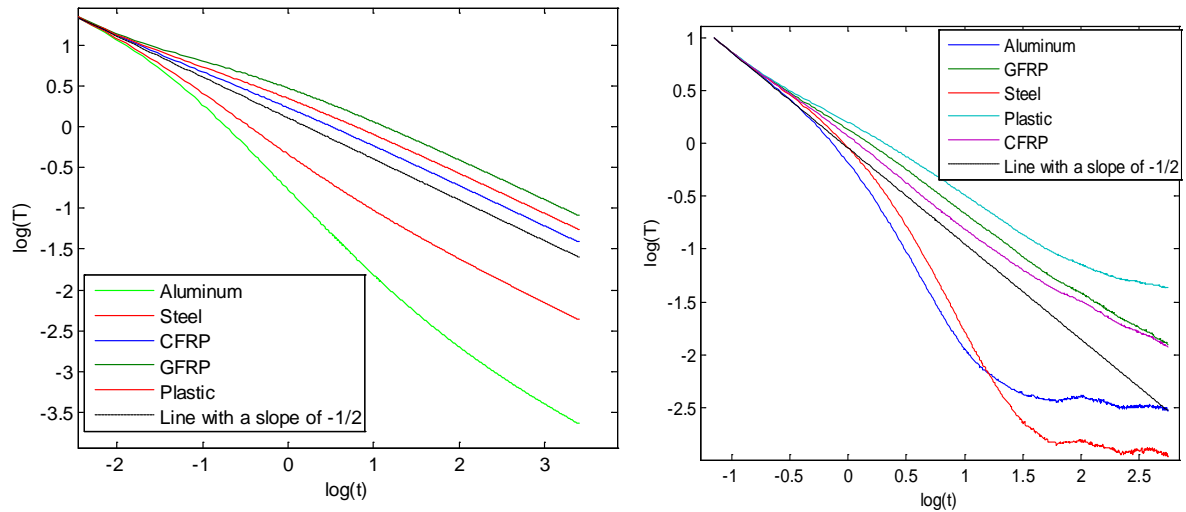


Fig. 6.Theoretical simulated Log T-t curves Fig. 7. Experimental Log T-t curves

The experimental data is processed with background subtracted, peak value normalized, then get the logarithmic curves as shown in Figure 7. As can be seen from Figure 7, though the logarithmic curve of different substrates separated at a certain time, they are coincident at the beginning. It can be considered the heat transfer takes place only in the first layer (coating) at the beginning and is not influenced by the thermal reflection of the second layer (substrates). Thus, the reference data (straight line with a slope of $-1/2$) can be obtained by linear fitting the beginning points of the logarithmic curve.

Figure 7 shows the logarithmic curve and the fitted reference for the coating specimens. As compared with the theoretical simulated logarithmic curve in Figure 6. The overall trends of curves with the same material in Figures 6 and 7 are the same except at the later parts because the experimental data is influenced by 3D heat conduction.

For practical application, separation degree with reference straight line can be used for the distinguish of the different substrates with similar coating. As shown in Figure 7, the logarithmic curves under the reference, which on behalf of aluminum and steel, have the negative reflective coefficients, however, for the logarithmic curves above the reference, have the positive reflective coefficients. Therefore, for the recognition of two kinds of materials whose thermal properties has a big difference, such as steel and wood, it can be easily distinguished by comparing the relative position of their logarithmic curves with the reference straight line. Furthermore, for the recognition with small difference in thermal properties, standard specimen is needed to establish the relationship database of the logarithmic relative position between reference line and the substrates. Then the recognition of the unknown substrate can be realized by comparing with the database.

For practical application, a $\ln(t)$ value can be chosen and then calculate the corresponding values of $\ln(T)$ as the characteristic values of different substrates, and set thresholds. Then applied logarithmic processing on every point in the thermal sequence images, different gray in the image can represent different substrates by using the threshold for image segmentation, and realize the visual image recognition.

Conclusion

Coating material has an increasing applications in many fields, such as mechanical engineering, microelectronic technology and aerospace, et al. The quality of the coating plays an important role in the reliability and safety of the products, however, traditional non-destructive methods have many limitations for the coating and under coating detection, therefore, new non-destructive methods emerge end to end. This paper presents a new method for the detection and recognition of under coating materials by pulse thermography, which is described in theory, experiments and data analysis:

Theoretical model of transient heat conduction of double-layer medium under an instantaneous heat source is analyzed, which establish the theoretical basis of the recognition by pulse thermography.

Typical materials (steel, aluminum, carbon fiber, etc.) painted the same coating are manufactured as the specimens for the recognition experiments; different thermal properties of the substrates can be distinguished by comparing the log temperature vs. time curves; and furthermore, the theoretical log T-t curves are also shown as a comparison, and the generated error is analyzed.

In addition, suggestions and guidance is proposed for the practical application, it can realize visual image recognition of under coating materials by applying the proposed algorithm on every points in the thermal sequence images.

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