Laser infrared thermography detection for aviation carbon fibre composites

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Abstract. Aviation safety is the focus of aviation field. In this paper, two different heating ways of modulated lasers were used to heat the aviation carbon fibre composites with internal defects. The results show that, after expanding, the unevenness of laser energy distribution has a great influence on the detection effect. In order to solve this problem, we obtained the reference temperature information by using the defect-free surface inside the specimen. After the difference between the obtained temperature information of the internal defect surface and the internal defect-free surface, the internal defect information of the specimen was successfully presented. At the same time, it is found that compared with the square wave heating, the effect of sine wave heating on detecting the internal defects of the specimen is more obvious. There are two main advantages of using laser infrared thermography to detect aviation carbon fibre composites: (1) the detection time is short, which only need a few seconds to complete the detection process; (2) the heating area can be adjusted by the distance between the specimen and the laser, which will make the detection more flexible.

1. Introduction

Compared with metal materials, composite materials have the characteristics of light weight and corrosion resistance under the same strength. In modern aviation industry, more and more composite materials with excellent performance are widely used to replace metal materials. For example, the American commercial aircraft bombardier c-series USES 70% of the advanced materials in the whole aircraft, among which the composite materials account for an amazing 46%[1]. Composite materials are widely used not only in aerospace, but also in many other fields.

The increase of usage is followed by the increase of the frequency of material defects. In the field of aviation, material defects will seriously affect aviation safety. Therefore, it is very important to detect defects in materials when they occur. Infrared thermography for detecting internal defects in composite materials has been rapidly developed in recent years. Its detection speed is fast, at the same time, single detection area is large. There is no damage to the material and can be used as a wide range of heat sources, so more and more attention has been paid to non-destructive testing researchers[2]. Joint capital normal university in 2004, Beijing institute of aviation materials and other units established the joint laboratories, which plays a significant role in promoting the development of infrared detection technology. Traditional heat source of the infrared thermography mainly includes flash and eddy current[3-4]. The area of heating samples with flash is large, as well as the advantage of non-contact. However, while the distance between the flash and specimen, the effect of flash heating will be affected significantly. At the same time, heating specimen with flash will affect by the external environment. In the other hand, eddy current heating need contact with the specimen. And the
specimen shape structure influence on the heating effect. Laser is a kind of heat source with concentrated energy, which will be affected slightly while heating samples. At present, researches on laser are most as the point heating source and there are still few researches on laser as surface heating source for heating specimens. In the 2013, the internal defects of bio-ceramics (Al₂O₃) were detected successfully by Razvan Gabriel Dragan[5] using CO₂ laser heating. In the 2018, Masashi Ishikawa[6] successfully detected the delamination of the carbon fibre plate by laser scanning heating at a remote distance. In this paper, carbon fibre plate was heated by an expanded laser beam to detect the internal delamination. The results show that the unevenness of laser energy distribution is an important factor that affects the experimental results. At the same time, two different pulse heating modes, pulse sine wave and pulse square wave, are used to conduct experiments respectively. The results show that the pulse sine wave has better detection effect on the internal defects of the specimen when the same heating parameters are set.

2. Laser infrared thermal imaging

As the heat source of infrared thermal imaging detection method, laser has its specific advantages. For example, laser has good collimation, concentrated energy density and can be heated at a long distance. When the sample is placed in a far position, due to the good convergence performance of the laser, its heating region can grow less, so it can still maintain a high energy density in the heating region.

2.1. Laser infrared detection principle

It is well known that when an object's temperature is above absolute zero, the object itself can emit infrared radiation related to its own temperature. The detection principle of laser excitation active infrared thermal imaging technology is as follows: laser is used as the active thermal excitation to load the thermal energy on the surface of the specimen so that the temperature of the specimen rises and sufficient infrared information is radiated. When there are defects (such as delamination, debonding and inclusion) inside or on the surface of an object, the distribution of temperature on the surface of the specimen is different due to the large difference of thermal conductivity between the sound and the defects. The temperature distribution of the specimen was recorded by high resolution infrared thermal imager.

When using laser heat a plate with limited thickness and the laser heating area is much larger than the thickness of the plate, it can be considered that the heat conduction is only in the thickness direction and the transverse heat diffusion effect could be ignored. Therefore, the whole heat transfer process can be simplified into a one-dimensional heat conduction model[7]. Assuming that the periodic heat flow with energy q is used to irradiate the defective plate, the diameter of the preset circular defect in the plate is L, and d is the distance between the defect and the surface of the specimen, the temperature difference between the surface temperature of the defect area and the intact surface temperature is, according to the classical heat transfer theory[8]:

\[ \Delta T = \frac{q}{\sqrt{\pi \rho c k t}} \left\{ \exp\left(\frac{-d}{4\alpha}\right) - \exp\left[-\frac{(d + L^2 + L^2)}{4\alpha t}\right] \right\} \]  

Therefore, the larger the size of the defect is, the greater the temperature difference between the defective area and the intact area is, and the easier it is to detect the defect area. When L is much greater than d, the above equation can be simplified as:

\[ \Delta T = \frac{q}{\sqrt{\pi \rho c k t}} \exp\left(-\frac{d}{4L}\right) \]  

Therefore, the closer to the surface of the specimen, the easier it is to detect defects.
2.2. Laser infrared thermal imaging detection system
In the laser infrared thermal imaging detection system, concave lens is used to expand the laser beam irradiation area to obtain a larger detection area. The system is shown in Fig.1.

![Laser infrared thermography system](image)

2.3. Introduction of specimen
The specimen is a practical carbon fiber laminate. Number the specimen as #1. The specimen size is 180×180mm and the thickness is 2mm. The specimen is made of two carbon fiber laminated plates with a thickness of 1mm by gluing the plates together. Each laminate is preimpregnated with epoxy resin of 8 carbon fiber laminates of the same thickness, so the thickness of each laminates is about 0.125mm. The sample and its size are shown in Fig.2.

![Sample and size](image)

The defects are preset at different depths inside the laminated plate. The defects are preset as shown in Fig.3, and the diameter units of the defects are all mm.
3. Analysis of examination result

Defects were detected by using two different forms of heating - square wave heating and sine wave heating. Before heating the specimen, necessary cleaning should be carried out to reduce the poor surface quality of the specimen for influencing the defect detection.

3.1. Primary thermal image analysis of two heating forms

On the basis of a large number of preliminary experiments, the parameters of the two heating forms are set as table 1:

| Heating mode | Time of heating/s | Distance/mm | Frequency/Hz |
|--------------|-------------------|-------------|--------------|
| Pulse heating | 8                 | 700         | 50           |

Under this parameter, the diameter of laser spot on the specimen is between 7cm and 8cm. At the same time, the actual power of the laser is 60w. Since pulse heating is adopted, when the heating time is set to 8s, the actual heating time is only the initial 4s time, and another 4s is the cooling stage.

From a visual point of view, the thermal image with good selection effect in the whole heating stage was analyzed, so the thermal image at t=3.2s was selected for analysis, as shown in Fig.4.

It can be seen from the thermal image that sinusoidal wave heating can roughly publish the location information of defects, while square wave heating cannot. It can be seen that the uneven energy...
distribution after laser beam propagation seriously affects the detection effect of internal defects of the specimen.

3.2. Differential thermal image analysis

It can be known from the above analysis that the defect information caused by the laser energy distribution has been covered. Therefore, the same laser parameters were set to collect the same thermal data on the back of the specimen (without defects) again. As a reference temperature information, the difference between the temperature information on the back of the specimen and that on the back of the specimen is carried out to reduce the influence of uneven laser energy distribution. The thermal image of differential treatment obtained at the highest temperature (4 seconds) of the two heating forms is shown below.

![Differential diagrams of two heating modes](image)

Fig 5. Differential diagrams of two heating mode

It can be clearly seen from the above two points that after the differential treatment, the defect information hidden in the material due to the uneven laser energy distribution is clearly displayed.

The temperature of defect points in two different heating forms was extracted and the defect changed with time. From the perspective of the effect alone, it is more obvious to convert the time factor into the contrast between the continuous frames of the thermal image graph with the temperature, so the transformation curve of the extraction temperature with the number of frames is as follows.

![Temperature-time curve of Sinusoidal heating](image)

Fig 6. Temperature-time curve of Sinusoidal heating
Fig 7. Fig 1. Temperature-time curve of Square wave heating

It can be seen from the temperature-time curve of the two different heating forms in the temperature-fall period at the center of the defects, after the same pulse heating time, the effect of sine wave heating the specimen is better than that of square wave heating. In fact, when the specimen is heated by a sine wave, it can be seen from the original thermal image that the occurrence time of the internal defects of the specimen is also earlier than a square wave.

4. Conclusion
Two different forms of pulse heating are used to conduct laser infrared detection of internal defects of the specimen. At the same time, the difference value of the defect free surface of the specimen is used to reduce the influence of uneven laser energy distribution on the defect temperature information to a certain extent, so that the internal defects of the specimen are more obvious. At the same time, the internal defect information of the specimen is easier to be displayed by sinusoidal wave heating, and the effect of defect information is better than that of square wave heating.

References
[1] Henrique Fernandes, Hai Zhang, Alisson Fgueredo. Carbon fiber composites inspection and defect characterization using active infrared thermography: numerical simulations and experimental results
[2] Tu Jun, WEI Quan, WANG Fei. Non-destruction testing technology for honeycomb structure in aerospace products with laser and infrared means[J]. LASER & INFRARED, 2014,44(11):1220-1223.
[3] More references LIU Ying-tao, TANG Jia, GUO Xing-wang. Effects of composites translucence on flash infrared thermal detection[J]. LASER & INFRARED, 2017,47(10):1264-1270.
[4] Sun Jiwei, Feng Fuzhou, Min Qingxu. Probability of detection for fatigue crack in eddy current pulsed thermography[J]. Infrared and Laser Engineering, 2018, 47(5)
[5] Razvan Gabriel Dragan, Sam-AngKeo. Active Thermography Method Using an CO2 Laser for Thermal excitation, Applied to Defect Detection in Bioceramic Materials[J].The 4th IEEE International Conference on E-Health and Bioengineering - EHB 2013, 2013.12.
[6] Masashi Ishikawa, Masaki Ando, Masashi Koyama. Active thermographic inspection of carbon fiber reinforced plastic laminates using laser scanning heating[J]. Composite Structures, 2018.06.
[7] LIU Junyan, WANG Yang, DAI Jingmin. The study on infrared lock-in thermography technology based on image sequences processing[J]. LASER & INFRARED, 2008, 38(7).
[8] Li Ke, Zhong Anbiao, Li yujie. Research on infrared imaging detection based on hot wind heating[J]. LASER & INFRARED, 2016,46(7).