Surface crack imaging based on delayed temperature Difference at symmetric points by laser spot thermography

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Abstract: Laser spot thermography is a novel technique for the detection of surface cracks with a laser to heat sample locally and with an IR camera to record the surface temperature distribution. Common methods to characterize cracks are only suitable for the situation that the laser scanning path is vertical to the crack. But due to the randomness of cracks, when the scanning path is parallel to the crack, surface cracks cannot be detected by these methods. To tackle this problem, a method is presented which is suitable for the situation that the scanning path is parallel to crack. The main idea is to evaluate the crack-caused asymmetries of the surface temperature distribution. The effect of temperature gradient and the maximum scanning interval are analyzed by a 2D simulation. A new crack imaging technique is presented that is based on delayed temperature difference at symmetric points to characterize the crack in the thermal image. Compared well with those obtained by the spatial first derivative method, experimental results are shown to efficiently prove this method.

Key words: Laser spot thermography; Scanning path parallel to crack; Delayed temperature difference at symmetric points; Surface crack

1 Introduction

Laser spot thermography [1-2] has become the researching hot spot as a new NDT method in recent years. Compared with the conventional NDT methods for crack detection, for instance eddy current, ultrasound, dye penetration and magnetic particle testing, laser spot thermography has the advantages such as non-contact, long distance and suitable for many types of materials.

At present, the preliminary studies have mainly focused on the situation that the scanning direction is perpendicular to the crack. For example S. Hermosilla-Lara etc. presented a modified principal component analysis which separated the thermal and optical effects from the raw images when the laser scanning path was perpendicular to the crack [3-5]. S.E.BURROWS etc. used a raster scanned laser to scan the crack by combined laser spot imaging thermography and ultrasonic measurements to detect cracks [6-8]. Schlichting J etc. presented a measurement procedure to gain information about depth and angle of open surface cracks when the laser spot moved across the crack [9-12]. Li.T and Almond D. P. etc. analyzed the effects of crack geometry and system parameters on the thermal images of laser heated spots when the laser moved along a line though the spot center perpendicular to the crack [13-15]. So far only the situation that the laser scan path is vertical to the crack has been taken into account in that work, but the results are not suitable for the situation that the laser scan path is parallel to the crack.

In this paper, a method is presented which is suitable for the situation that the laser scan path is parallel to the crack. The surface sample is heated by a scanning laser source. Because of the presence of crack, the surface temperature is asymmetric. A crack detection approach is presented to evaluate the crack-caused asymmetries. This approach allows the crack to be shown its shape and location intuitively and clearly in the thermal images. The optimum scanning interval and the effect of temperature gradient is studied by MATLAB simulations. A sample containing notches is used to carry on the comparing experiment. The results show that this method can be intuitive, clearly shows the crack form, by combining the vertical method, it lays the foundation for analyzing each direction cracks.

2 Laser Spot thermography for crack qualification

2.1 Laserspot thermography system

Laserspot thermography system is shown in Fig 1. Laser probe emits a gauss beam which is Centro symmetric to perpendicular to the material surface. The sample surface is locally heated by a scanning laser source. A surface crack impedes the vertical flow of heat and produces an unsymmetrical thermal footprint in the direction perpendicular to cracks. The resulting temperature distribution is recorded with an infrared camera. The system can qualitatively detect the presence of cracks.

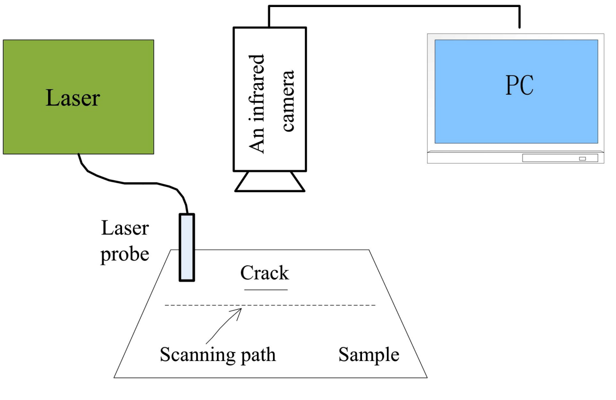


Fig. 1 Laserspot thermography system

2.2 The temperature difference of symmetry points

When thelaser scan path is parallel to the crack, because of the presence of crack, the flow of heat perpendicular to the crack is impeded, according to Fourier's Law, the heat flux density q is

$$q=-k\nabla T=-R_{th}^{-1}\nabla T \tag{1}$$

With the heat conductivity k, the temperature gradient ∇T, and the thermal resistance $R_{th}^{-1}=1/k$。

The blockage of lateralheat flow is mainly reflected in the direction perpendicular to the crack. So the heat transfer model is simplified to a one-dimensional heat conduction model, the heat flux density in the direction perpendicular to the crack is:

$$q_y=-R_{th}^{-1}\frac{dT}{dy} \tag{2}$$

The temperature distribution in the Y direction is

$$T_y=-R_{th}^{-1}q_y y+T_0 \tag{3}$$

In one-dimensional heat conduction model, theheat flux density is constant; the thermal resistance at the crack is greater than the sample's. The temperature at the symmetric points is unequal. The temperature difference at the symmetry points (TDSP) is not equal to 0.By analyzing the TDSP, we can analyze if there is crack on the sample surface. In the case of two and three dimensional heat conduction with a localized source the heat flux density is not constant and ,in addition ,affected by R_{th}, but the qualitative prediction remains valid .[16]

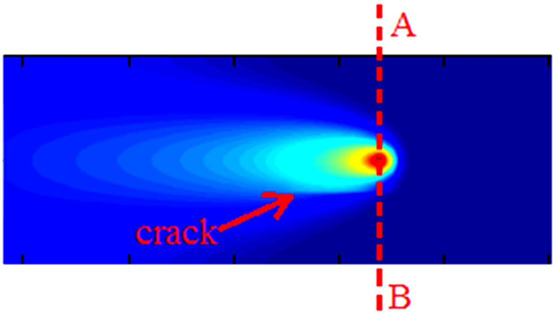
3 Laserspot thermography simulations

3.1 Modeling setup

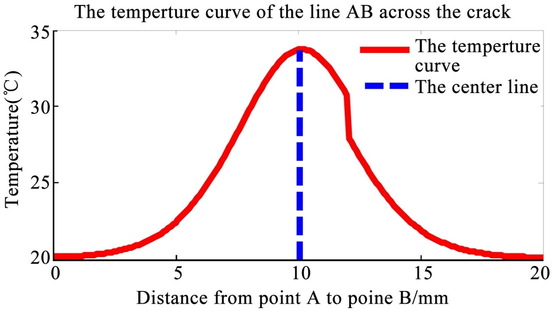
In this section, a two-dimensional model was established by MATLAB software. We chose a No. 45 steel test sample with density 7800 kg/m^3, specific heat capacity 460 J/(kg·K) and coefficient of thermal conductivity 46.5 W/(m·K).This sample had outer dimensions of 100 mm×20 mm and contained a crack with lengths 10mm and gapes 0.1 mm. The heat spot was loaded in the center of the sample and moved along with the X axis. The laser was modeled as a constant heat flow with the diameter d = 2 mm and the power P = 10^6 W/m^2. The constant laser scanning speed was 20 mm/s. The distance between the laser spot and crack is 2 mm.

When the laser spotscanned to the crack, the scanning path is 2 mm away from the crack, a red short dash line AB across the crack and the laser-spot center was obtained to present the temperature profile in Fig 2.

Fig 2(a) shows the thermal image when the laser scanned to the crack. Cracks perturbed the round vertical heat flow to make the round heat flow asymmetric. Fig 2(b) shows the temperature curve of line AB across the crack. The temperature profile relative to the center line was asymmetric. The TDSP of all the pixels at the scanning path is shown in Fig 3.



(a)A thermal image when the laser scans to the crack



(b) The temperature curve of line AB across the crack

Fig. 2 The simulation results of the laser scanning path road parallel to crack

Fig 3 shows the TDSPof the laser scanning path. With the scanning distance increasing, TDSP increases in the range from 45mm to 55 mm, in other range, TDSP is close to 0 ℃. The scope of TDSP increasing is consistent with the real location of the crack

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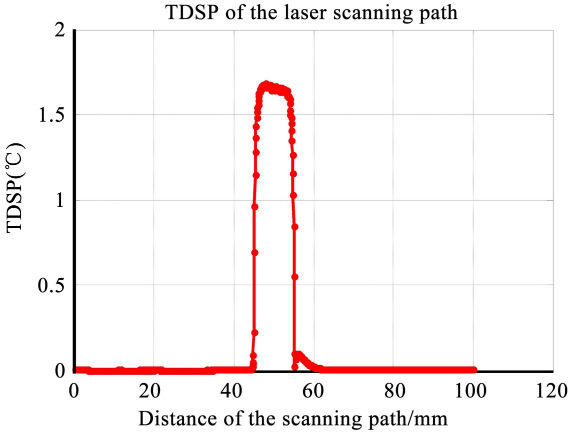
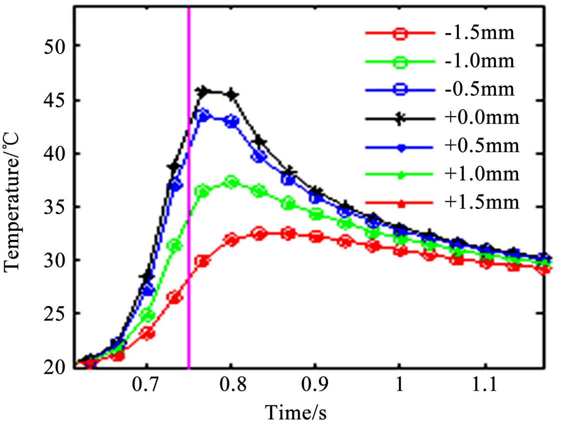


Fig. 3 The TDSP of the laser scanning path road

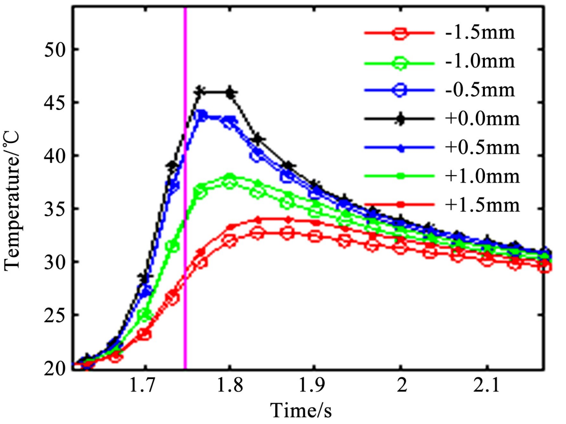
The simulation results show that when the laser scanning pathis parallel to the cracks, the temperature distribution in the direction perpendicular to the crack will be asymmetry, which can be characterized by the temperature difference between the symmetric points, so it can qualitatively judge the crack of sample surface.

3.2 The effect of temperature gradient

Laser scanning path is not strictly parallel to the X axis of the thermal imager in the process of experiment.It brings a geometric deviation at the symmetric points. Fig 4 shows the temperature of symmetry points with different distances to the crack.



(a) Far from the crack



(b) 2 mm above the crack

Fig. 4 The temperature curve of symmetry points

Fig4 shows that both the temperature curves have the same change trend 2mm above the crack or far from the crack, which are first increase then decrease when scan time increases. But the temperature of two symmetrical points away from crack keep consistent change, and temperature change of two symmetrical points 2mm above the crack is separated after 1.75s, thus appears symmetrical point temperature, and with the symmetrical spacing increases, the temperature difference between the symmetric point increase. In addition, the adjacent symmetry point temperature gradient is increased, and the variation is much larger than symmetry point. Temperature gradient (TG) 2mm above the crack and the TDSP are shown in Fig 5.

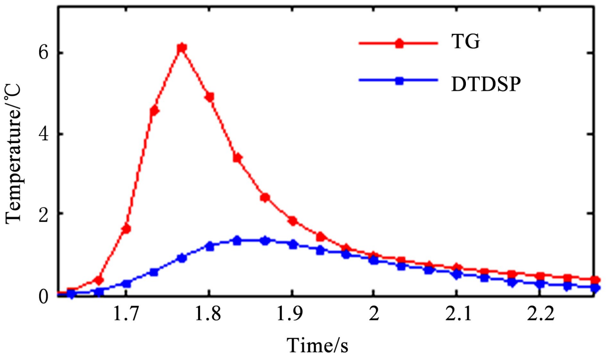


Fig. 5 The change of temperature gradient and TDSP

In Fig 5, with the scanning time increasing, the TG and TDSP first increase then decrease, and lastly tend to the same value. In addition, the time for TDSP reaching the peak lags that for TG peaking, both tend to same after 2 s.

The simulations reveal thatbetter results can be achieved by not selecting the data when the TG reaches the peak but choosing the data when the TG and TDSP reach the same value. When the TG reaches the peak, the TG is much greater than the TDSP. The TDSP would be submerged in the TG caused by a geometric deviation at the symmetric points. Hereby the effects can lead to wrong indications. But when the TG is delayed some time, the delayed temperature difference of symmetric points (DTDSP) and the TG are in good agreement. The effect of TG is reduced. Therefore, the method of DTDSP is allowed to characterize the crack.

3.3 Maximum scanning interval

To describe the relationship betweenthe scanning interval and TDSP, we assume the distance between the two scanning path as scanning interval d, the distance between the scanning path and crack is L, named interval distance. In the *i* times, the shortest distance between the scanning path and crack is *l*. In the *m* times, the distance between the scanning path and crack is

$$L_i = l + (i - m)d \quad (4)$$

Limited by the laser power and the influence of heatconduction, the interval L meets the following condition:

There is always an interval L to meet the condition that $L_{min} \leqslant L \leqslant L_{max}$。

L_{min} is the minimum distance between the laser scanning path and the crack, L_{max} is the maximum distance between the laser scanning path and the crack.

Tomeet the above conditions, the range of *d* should be:

$$d \leqslant (L_{max} - L_{min}) \quad (5)$$

To improve the efficiency of detection, and ensure thatthe laser spot can scan the cracks in the scanning process, the maximum scanning interval is $L_{max} - L_{min}$。

In thesimulation, setting the different values of L to compute the maximum TDSP, the results are shown in Fig 6.

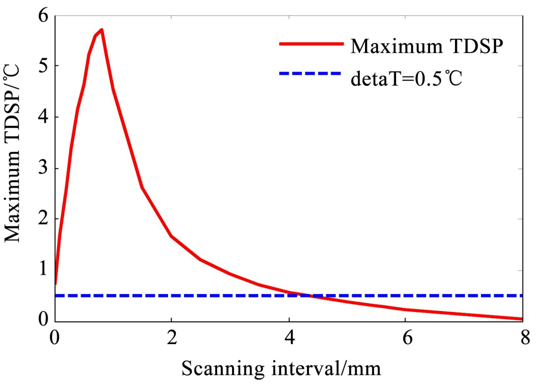


Fig. 6 The relationship between the scanning interval and TDSP

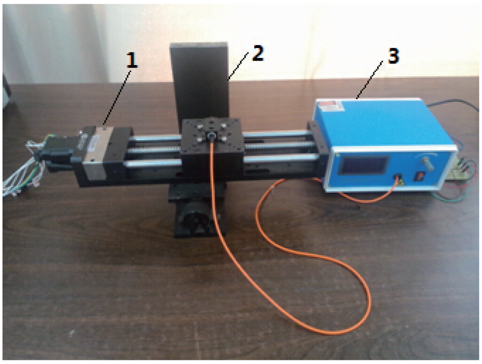
The simulations show that the maximum TDSP firstly increase and then decrease with the increase of the interval L. It reaches maximum value when the interval distance is 0.8mm. To ensure that the crack can be detected, the maximum TDSP must be more than 0℃. But in practical test, there is 0. 5℃ deviation, which is marked by a blue dash line in Fig 6. Therefore , the maximum TDSP should be more than 0.5℃, the corresponding distance L scope meets the requirements. Therefore, the range of L is 0.1 ~ 4.2mm. The maximum scanning interval is 4. 1mm.

4 Experimental for laserspot thermography

4.1 Experimentalsetup

Experiment was conducted in the indoor environment. We chose a diode laserfiber-coupled to an optical scanner (980 nm wavelength, 1W continuous wave output power, ~ 1mm spot diameter) and a DM60S infrared camera with 320×240 pixels at a frame rate of 12 kHz and spatial resolution of 0.88 mrad. Because the power of laser is low, to improve the absorption of laser, the scanning speed is reduced to 3mm/s .The temperature of the sample surface was recorded by a fixed camera at a distance of 0.5m to the sample. The experimental setup and test specimens are shown in Fig 7.

Fig7(a) shows the detection system. The laser probe is fixed on the slider which is fixed in a one dimensional motion platform. Driven by the stepper motor, the laser probe can move along the horizontal direction. The scanning direction is parallel to the crack. Fig 7 (b) shows the test specimens. The sample has outer dimensions of 200 mm×100 mm×20 mm(length×width×height) and contains a spark eroded notch with lengths of 30 mm, widths of 0.5 mm and depths of 20 mm. The sample surface is painted black to increase the absorption of laser and reduce the radiation effects of the surrounding environment.



1.A one\|dimensional motion platform
2. test specimens; 3. Laser

(a)Experimental setup

(b)Test specimens

Fig.7 The main experimental setup in the experiment

4.2 Data Procedure

MATLAB software is used to compute DTDSP in the process of each scan. The processing steps performed on the thermal images from the IR camera are as follows.

(1) Thethermal images in the process of each scanning are taken as the input signal. Compute the maximum temperature of each pixel at each scanning path to form the high temperature image.

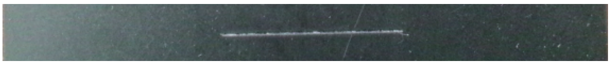
(2) Delay the high temperature image. Compute the DTDSP at each scanning path.

(3) Integrate all DTDSP collected the entire time at each scanning path. Form a composite image of all the integrated images obtained at the different scanning paths.

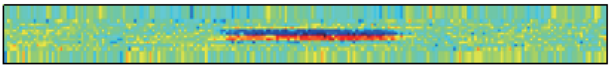
(4) A finalsummed image can be obtained by integrating all the DTDSP scanning paths to show the location and shape of cracks in the sample surface.

4.3 Results

A continuous wave laser operating at 1 W scanned across the sample. It scanned the sample 12 times in the same direction. Scanning interval was 2 mm. The thermal imager was operated to record thermal image in the process of scanning. A final summed image was obtained by computing the DTDSP in Fig 8.



(a) Physical sample figure



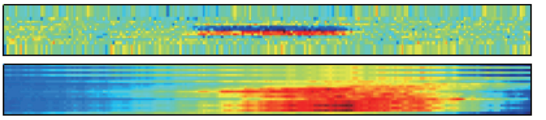
(b) The image of DTDSP

Fig.8 The detection result of the laser scanning path parallel to the crack

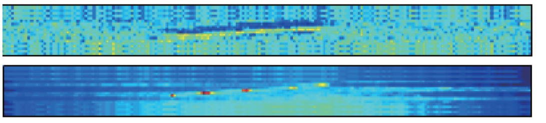
The experimental results show that the crack can be observed visually and clearly. The crack was located in the center of the image. The crack extended along the horizontal direction. The location and shape of crack in the DTDSP image was consistent with that in the physical sample figure.

The method of DTDSP is not only suitable forthe situation that the laser scanning path is parallel to crack, but also is suitable for the situation that there is an angle between the laser scanning path and cracks. Moreover, in order to show the effectiveness that the crack can be described by DTDSP compared with the method of the first spatial derivative. The results are shown in Fig 9. The left column is DTDSP thermal images, the right column is the first spatial derivative thermal images.

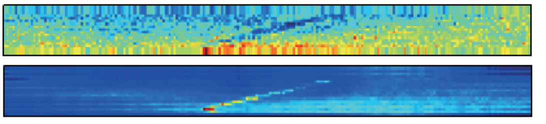
The results present thatwhen the angle between the scanning path and crack is 0°, 16° and 45°, the method of DTDSP is better than the method of the first spatial derivative. But when the scanning path is vertical to the crack, the method of DTDSP is not as good as the latter method. The method is presented in this paper can be combined with the method of the first spatial derivative thermal images to detect all cracks in all directions.



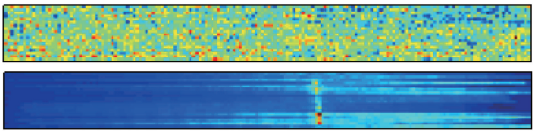
(a)The angle between the scanning path and crack is 0°



(b)The angle between the scanning path and crack is16°

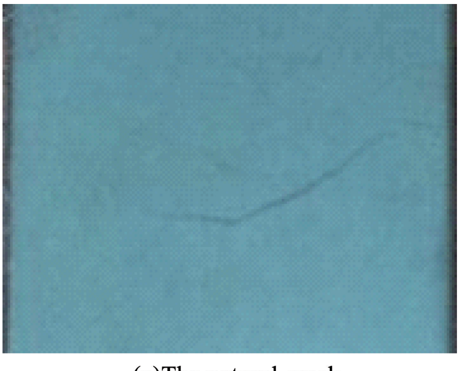


(c)The angle between the scanning path and crack is45°

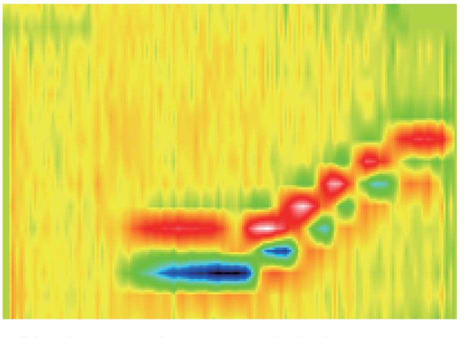


(d)The angle between the scanning path and crack is90°

Fig.9 The angle between the scanning path and crack



(a)The natural crack



(b) The crack image obtainded by DTDSP

Fig.10 Results of the natural crack-detection

Under identical experimental conditions, the method of DTDSP was used to detect the natural crack. The results are shown in Fig 10. Figure 10(a) shows a ferrite core with a surface crack. Figure 10 (b) shows a crack image obtained by the method of DTDSP. The crack image can visually and clearly show the location and shape of crack, which is consistent with that in the physical sample figure.

5 Conclusions

This paper describes a method of delayed temperature differenceat symmetric points that is suitable for the situation when the laser scanning path is parallel to crack. The Experimental results can clearly and intuitively show the crack location and morphology. The results obtained are shown as the following conclusion:

(1) The method of DTDSP succeeds in detecting the scanning surface crack.

(2) The laser scanning interval is related to the distance between the scanning path and the crack. The difference between the two distances that is the maximum and minimum distance between laser scanning path and crack is equal to the maximum scanning interval.

(3) The combination of the first spatial derivative and DTDSP can be used to detect all cracks in all directions.

Acknowledgements

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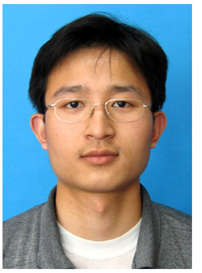

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