Detection Mechanism of Parallel Defect using Scanning Inductive Thermography

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Abstract. Aiming at the requirement of workpiece integrity for parts processing line, on-line detection using inductive heating thermography for the moving workpieces on the assembly line is studied. In this paper, the detection mechanism of pulsed eddy current thermography for moving workpieces defects is analysed. A two-dimensional model of a magnetic material (45 steel), on which there is a crack parallel to the coil is established by the finite element software named COMSOL 5.2. By analysing the changes of the temperature curves, normalized curves and the temperature difference curves, the optimal detection area for parallel cracks is proposed. The consistency of the conclusions is verified by the experimental platform. The paper can provide a theoretical guidance for quantitative detection using eddy current thermography.

1. Introduction
With the development of astronautics and new energy technology, it is more and more important to ensure the quality of products and engineering by nondestructive testing technology. Eddy Current Pulsed Thermography (ECPT) [1, 2] is a very effective nondestructive testing method. Material failures like defect, fatigue, corrosion and residual stress, etc. have been detected and evaluated using ECPT [3, 4].

In present researches, most works related to ECPT are focused on static configuration [5, 6], which lead to a low detection efficiency and cannot be directly applied to industrial production. Today, with the development of IR camera, its view is large enough for some samples. There are three kinds of Scanning configuration under research. Scanning laser spot thermography is mainly used for crack detection in metal and semi-conductor based on the lateral heat conduction [7]. Scanning Induction Thermography (SIT), which heats the sample in linear scanning style in the camera view, is more efficient and reliable[8]. The dynamic configuration, used in this paper, called Line Scanning Thermography (LST) [9, 10] patented by NASA is shown in Fig. 1.
In this paper, a two-dimensional model is established by the finite element software. The temperature curves, normalized curves and differential curves of the defect and the reference point are given to analyze and study the detection mechanism of PECT dynamic detection for parallel cracks, which lay a foundation for the quantitative identification of surface defects on workpieces.

2. Detection Mechanism

For isotropic materials, on the surface of workpieces the temperatures of points on dotted lines should be equal on account of the same distance from the coil in the ideal case as shown in Fig. 2 (a). Therefore, cracks will be detected as temperatures of fixed pixel change when the coil and the thermal camera are relatively stationary while the workpieces move.

The detection mechanism for parallel defects (such as minor cracks) is shown in Fig. 2 (b). The side that the coil first passes is defined as the front side and the one the coil passes afterwards is defined as the rear side. The heat conduction is prevented near the parallel cracks on the surface of the workpiece. Therefore, the temperature of both sides of the cracks will change and appear as "hot zone" or "cold zone" on the camera. Because parallel cracks affect only the heat diffusion and have no effect on the eddy current, they will be detected in Area II III, and IV. But with the change of the relative position between the coil and the crack, the temperatures of two sides of the crack must be equal at some time. That is, Area III may have a blind spot. Therefore, it is important to determine the optimal detection area.

To explain the mechanism for parallel defects accurately, the model was introduced at first. Secondly, the simulation results using line source move in camera view [11, 12] were done. Next, the experimental results using LST were presented. Finally, conclusions were given.
3. Numerical Studies

3.1 Simulation Model
This paper uses the finite element simulator COMSOL5.2a for the two-dimensional simulation of the eddy current field and the temperature field of 45 steel, a typical ferromagnetic material used in engineering. The temperature distribution near the crack is analyzed.

The workpiece is a 140mm × 20mm steel plate, as shown in Fig. 3. There is an artificial crack on the surface of the workpiece. The center of the crack, which is 1mm wide and 1mm deep is located at 0mm. Definition of sampling point: A is the front side of the crack that the coil passes first, B is the rear side that the coil passes afterwards, and X is the reference point representing areas with no defect. The coil is reduced to a long straight wire parallel to the crack and perpendicular to the screen. The excitation frequency is 256 kHz, and excitation current is 100A. The movement distance is 80mm, the coil moving from -40mm to 40mm at 20mm/s. The initial temperature is 293.15K. The electromagnetic and thermal parameters of the materials are shown in Table 1.

![Fig. 3. Simulation Model](image)

### Table 1. The electromagnetic and thermal parameters of the materials

| Parameters               | Steel          |
|--------------------------|----------------|
| σ/(S·m⁻¹)                | 5.4348 × 10⁶   |
| ρ/(kg·m⁻³)               | 7870           |
| a/K⁻¹                    | 1.22 × 10⁻⁵    |
| Cₚ/(J·kgK⁻¹)             | 440            |
| k/(W·mK⁻¹)               | 44.5           |
| δ(m)                     | 3.328 × 10⁻⁴   |

3.2 Analysis of Simulation
The simulation results are shown in Fig. 4 (a) when speed is 20mm/s and excitation current is 100A. The coil moving from -40mm to 40mm, the excitation time is 4s. The temperature curves change at -16 mm, so they are intercepted from -16mm to 24mm. As the distance between the coil and crack changes, three curves separate in different degrees. When the coil moves to -11mm, the temperature of A rises the fastest and becomes "hot zone"; X is the second; B rises the slowest and becomes "cool zone". Three temperature curves cross at -1mm. As the coil continues to advance, the temperature rise speed of A slows and A changes from "hot zone" to "cool zone"; B tends to be the same as X. The
normalized curve is shown in Fig. 4 (b). During temperature rise, A reaches its maximum first, X is the second, and the upward trend of B appears the latest, but the slope is maximum. During temperature drop period, A has the slowest descent rate while B and X tend to be consistent.

Compared with the non-defective areas, A cannot transfer heat to B due to the insulation of parallel cracks. A will accumulate more heat, thus presenting a higher temperature, while B presents a lower temperature because of a small amount of heat. At the end of heating period, the heat induced at B is blocked by the defect, so temperature B exceeds A’s. In the process of cooling, A cannot accumulate the heat transferred from B, thus presenting a low temperature. X is a sampling point in areas with no defect. As the surface of the workpiece is smooth and continuous, the temperature curve of X is smooth too.

To eliminate the influence of ambient temperature, A, B and X are subtracted separately and the temperature change is studied as shown in Fig. 4 (c).

\[
W_1 = T_A - T_B \\
W_2 = T_A - T_X \\
W_3 = T_B - T_X
\]
It can be seen when the coil moves to -3mm (the defect is 3mm in front of the coil), W1, W2 and W3 peak, with steep and narrow rise and fall intervals, indicating that the contrast (W1) of "hot and cold" between the two sides of the defect is the most obvious. At the same time, the temperature difference between the defective and non-directive areas (W2, W3) is maximum, so the defect profile can be revealed most clearly. At 1 mm (the defect is 1mm behind the coil), W1 and W2 peak, the fall interval of which is more moderate and larger in width. The profile of the front side of defect is more obvious now. However, W3 is approximately zero, indicating that the rear side of the defect almost overlaps the non-defective areas.

Therefore, there are two best observation moments in the defect detection of uniform velocity motion. For the detection of parallel crack under the above excitation conditions, the best detection positions are at the points when the coil is 3mm on the front side from the defect and 1.5mm on rear side from the defect, because the differences of the sampling points of the defect are large here. The detection interval is short when the coil moving to 3mm on the front side of the defect and the defect shows "hot zone" and "cold zone". The detection interval at 1.5mm at the rear side of the coil is wide, but only "cold zone" appears on the front side of the defect.

4. Analysis of Experiment
As the coil will block the vision, the experiment, different from the simulation, cannot get the full-time temperature at sampling points. Therefore, the experimental setup is shown in the Fig. 5 (a), consistent with Fig.2. The thermal camera and the excitation source remain stationary and the workpiece is moving on the chassis pushed by the slipway. The excitation source is HB-X5K from WUXI HUABO GAOPIN TECHNOLOGY COMPANY, which has an excitation power range of 0.5-5kW and a excitation frequency of 1MHz.

Fig. 5 (b) shows a thermal image, a fuzzy defect profile can be seen. Temperature curves of sampling points (M1-M5 and L1-L5) are shown in Fig. 6. The sampling interval is 1.5mm. A parallel crack is observed on the left of the coil in the picture.
Fig. 5. Experimental Image

Fig. 6. Temperature Curves of Sampling Points
Temperature curves of sampling points are shown in Fig. 6, when the moving speed is 20mm/s and excitation power is 3750W. The temperature of each sampling point is constant, unless the defect passes, which results in a low temperature. It is consistent with the results of Fig. 4 that B is less than A and X in the heating phase. On the front side of the coil, as the sampling points move closer to the coil, both the constant temperature and changes at the defect increase. On the other side of the coil, with the sampling points moving away from the coil, the constant temperature does not change monotonically. For example, the temperature of L2 is the highest but the temperature change at L1 is maximum.

In actual detection, the maximum temperature change of the workpiece is not directly below the coil. The point with the maximum temperature is not the best place to detect defects. In this experiment, defects can be identified on both sides of the coil, with the recognition capability greater on the rear side than on the front side.

5. Conclusions
The detection method is effective for the surface cracks on the moving workpieces. By analyzing the simulation and experimental data, fives are drawn:

1) The temperature of the front side of the defect increases earlier and faster, the descending process is gentler and the absolute value of temperature change is smaller. While the temperature rise of the rear side of the defect is later and the absolute value of the temperature change is bigger.

2) The maximum temperature of the workpiece is on the rear side of the coil. There are two optimal observation positions before and after the coil rather than below the coil. Experimental results show that the detection effect on the rear of the coil is better.

Acknowledgements
The work was supported by National Natural Science Foundation of China (Grant No. 61501483) and Natural Science Foundation of Hebei Province (Grant No. 51307183).

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