Research on rail crack detection technology based on magneto-optical imaging principle

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Abstract: The detection of rail top crack is of great significance in ensuring the safe operation of railway. Based on the principle of magnetic flux leakage detection and Faraday magneto-optical effect, a high-resolution and non-destructive magneto-optical imaging detection method is proposed in this paper. This paper analyse the principle of magneto-optical imaging, establishes a rail magnetic flux leakage detection experimental system based on magneto-optical effect, and detects the rail specimen with crack through experiment. The experimental results show that the change of crack width and depth will affect the magneto-optical imaging results, and the minimum crack size that can be detected by this experimental system is 0.4mm wide and 0.5mm deep. This paper realizes the detection of rail crack defects by using magneto-optical imaging method, and provides the basis for building an efficient, portable and high-resolution rail non-destructive testing equipment.

1. Introduction
Railway has become an indispensable mode of transportation in people's travel and transportation. Its use is very intensive, and China also has the largest high-speed railway network in the world. Due to the long-term contact between the train wheel set and the rail, the pressure and impact on the rail are easy to cause varying degrees of damage to the rail [1]. After the rail is subjected to the action of wheel set for a long time, the typical damage caused by rolling contact fatigue is crack. Cracks generally appear on the top surface of the rail at the initial stage of formation, and initially grow laterally to the interior of the rail over time, which poses a great threat to the performance and safety of the rail [2][3].

Magnetic flux leakage detection technology is applicable to ferromagnetic tested materials such as rail. Generally, the tested part will be magnetized and saturated by external magnetic field [4]. If there is a crack defect in the rail, due to the large magnetoresistance at the defect, some magnetic lines of force will leak into the space outside the defect surface to form a magnetic leakage field [5]. Magnetic flux leakage detection technology mainly detects this kind of magnetic flux leakage, so as to inverse and determine the defect location, size and other information, so as to help judge the damage condition of the test piece.

The existing rail flaw detection methods are mainly ultrasonic and electromagnetic. Among them, ultrasonic nondestructive testing methods have great restrictions on the detection speed [6]. The magnetic sensor method commonly used in electromagnetic nondestructive testing methods, such as hall sensor method, is limited by the size of the element itself, resulting in low resolution and non-intuitive detection effect [7][8]. Therefore, based on the principle of rail magnetic flux leakage detection and Faraday magneto-optical effect, a rail crack magnetic flux leakage detection method based on magneto-optical imaging technology is proposed in this paper. Compared with the original method, it has higher detection
resolution and more intuitive detection results. According to the characteristics that the magnetic induction intensity of the rail specimen changes suddenly at the crack defect under the external magnetization condition, this paper applies the magneto-optical imaging technology to the detection of the rail top crack. The leakage magnetic field changes the polarization angle of polarized light and displays the change of image gray in the results, so as to realize the detection of rail top crack. Compared with the traditional magnetic flux leakage detection method, it has higher detection resolution and more intuitive detection results.

2. Principle of magneto optic imaging

2.1. Faraday effect
Magneto-optical imaging is a detection technology based on Faraday magneto-optical effect. When light passes through a medium with special magneto-optical properties, if a magnetic field is applied to it along the light propagation direction, the polarization plane of light will deflect \[9\].

As shown in Fig.1, the deflection angle \(\theta\) is called Faraday magnetic rotation angle, which can be expressed as:

\[
\theta = VBL
\]  \(1\)

In the above formula, \(V\) is the Verdet constant, which is related to the wavelength of light propagating in the material and the magneto-optical characteristics of the material itself; \(B\) is the magnetic field intensity along the light propagation direction in the magneto-optical medium; \(L\) is the propagation distance of light in magneto-optical medium. When \(V\) and \(L\) are determined, the rotation angle \(\theta\) is linear with magnetic field strength \(B\).

2.2. Magnetic flux leakage defect detection of rail based on magneto-optical imaging
When the external excitation magnetic field is used to magnetize the rail specimen, the magnetic leakage field will be generated at the crack defect on the rail top. In order to make full use of the detection area of the imaging method, magneto-optical materials are often used in the form of magneto-optical sheets, which are transmissible materials, and the bottom surface is coated with a reflective film facing the interior of the material. The detection principle is shown in Fig.2.
This method mainly determines the shape and position of the defect by detecting the normal component of the leakage magnetic field. After the specimen is magnetized, the normal magnetic field intensity components on both sides of the defect will have opposite poles, which will deflect the polarization direction of the linearly polarized light clockwise and counter-clockwise respectively $\theta_r$ angle, and the magnetic field intensity at the center of the defect is 0, which is consistent with that when the specimen is not magnetized, and will not deflect the linearly polarized light \(^{10}\). Here, $l_1$, $l_2$ and $l_3$ respectively represent the projection of the light on both sides and the centre of the defect in the direction of the polarizer, then:

$$l_2 = E \cos \beta \quad (2)$$
$$l_1 = E \cos(\beta + \theta_r) \quad (3)$$
$$l_3 = E \cos(\beta - \theta_r) \quad (4)$$

Where $E$ represents the amplitude of linearly polarized light, $\beta$ indicates the included angle between polarizers.

According to Malus' law, the light intensities of the three beams after passing through the polarizer in the above formula are:

$$I_2 = E^2 \cos^2 \beta \quad (5)$$
$$I_1 = E^2 \cos^2(\beta + \theta_r) \quad (6)$$
$$I_3 = E^2 \cos^2(\beta - \theta_r) \quad (7)$$

As shown in Fig.3, the magneto-optical image intuitively displays the position information and shape of the defect. Among them, three areas can be clearly seen, and the bright and dark parts are shown on each side of the defect, with the corresponding light intensity of $I_1$ and $I_3$. The reason is that the normal leakage magnetic field intensity forms two opposite levels on both sides of the defect; The corresponding light intensity of the intermediate transition zone is $I_2$.
3. Experiment and analysis of magneto optic imaging detection of rail crack defects

In this experiment, the magnetic yoke made of ferrite is used as the DC magnetizer, and the coil is wound outside. The magnetization function can be realized by energizing the DC regulated power supply. The magneto-optical sheet is used as the magneto-optical medium, and its bottom surface is coated with a reflective film. The experiment system is shown in Fig. 4.

![Fig. 4 Experimental system](image)

The essence of leakage magnetic field is the distortion of electromagnetic field caused by defects, and the size of defects itself is directly related to the distribution and size of leakage magnetic field. With the development of computer science, the electromagnetic field theory based on Maxwell equations can gradually give the accurate distribution of leakage magnetic field in practical application by numerical method. For crack defects, the main factors affecting the distribution of leakage magnetic field are the width and depth of defects.

For approximately rectangular defects with the same width, the peak-to-peak value $B_{p}$ of the normal magnetic induction component of the leakage magnetic field on the surface perpendicular to the specimen is approximately linear with the defect depth \[5\]. In this paper, magneto-optical imaging experiments are carried out on horizontal depth cracks with different widths. Eight cracks are machined on the top surface of 1115mm rail by wire cutting method, and the cracks are at an angle of 45 ° to the train travel direction. The horizontal depth of the crack is 0.35mm, 0.5mm, 1mm, 1.5mm, 2mm, 2.7mm, 3.5mm and 5mm from left to right, and the width of the crack is 0.4mm, as shown in Fig. 5. In this experiment, the first six cracks were imaged by magneto-optical imaging.

![Fig. 5 Top view of crack specimens with different depths](image)

In order to make the defect produce leakage magnetic field as much as possible, 60V DC voltage was applied to the DC magnetizer in the experiment. The experimental results of cracks No.1~3 and No.6 are shown in Table 1. The magneto-optical imaging area of the defect is cut from the overall camera image. From the magneto-optical image, when the depth of the crack reaches more than 1mm, the human eye can clearly identify the defect position. Light and dark stripes can be obviously observed on both sides of the defect. The deeper the defect depth, the greater the contrast of the light and dark stripes.

In order to further analyse the influence of defect depth on magneto-optical imaging results, a row of pixel columns with a length of 180 was taken to draw the image (blue dotted line area), with abscissa as pixel value and ordinate as gray value. For the defect gray image with a depth of 0.35mm, the overall gray value shows a uniform change trend, there is no obvious gray peak and valley value, and the defect position cannot be observed. The gray value of the image rises evenly from left to right, which is affected
by the weak magnetic line of force in the air between the two poles of the yoke; For the defect gray image with a depth of 0.5mm, it can be observed that there is a gradient change between the abscissa of 40-60 pixels, which represents the location of the defect. With the gradual increase of defect depth, the gray values on both sides of the defect position in the gray image change suddenly, and the difference between peak and valley values of gray values is gradually obvious, which also more clearly represents the defect position.

From the perspective of detection, the maximum crack depth that this method can detect in the experiment is 0.5mm, and the defect with the depth of 0.35mm cannot be detected. Although the problem of magnetic saturation occurs in the detection of defects with a depth of 5mm, in order to ensure the detection ability of small defects, it is necessary to improve the strength of the external excitation magnetic field as much as possible to make the leakage magnetic field generated by defects as large as possible.

Table 1. Experimental results of magneto optic images of cracks with different depths

| Crack number with depths | Magneto optic images | Gray images |
|-------------------------|----------------------|-------------|
| No.1 (Depth=0.35mm)     | ![Magneto optic image](image1.png) | ![Gray image](image2.png) |
| No.2 (Depth=0.5mm)      | ![Magneto optic image](image3.png) | ![Gray image](image4.png) |
| No.3 (Depth=1mm)        | ![Magneto optic image](image5.png) | ![Gray image](image6.png) |
4. Conclusion

Based on the magnetic flux leakage detection principle of rail and Faraday magneto-optical effect, this paper applies the magneto-optical imaging method to the crack defect detection of rail top surface, which can realize high-resolution magneto-optical imaging and intuitively show the detection results. And the conclusions are obtained as below:

(1) Through the experimental analysis of crack defects on artificial rail top with different width and depth, the influence of defect size on leakage magnetic field distribution is verified. The normal component of the leakage magnetic field will form opposite peaks on both sides of the defect, and the greater the defect depth, the greater the difference between the peaks.

(2) In this experiment, the minimum rectangular crack size that can be detected by gray analysis is 0.4mm wide and 0.5mm deep, and the minimum rectangular crack size that can be clearly restored is 0.4mm wide and 1mm deep.

The research of this paper provides a theoretical and experimental basis for the design of magneto-optical Imaging Nondestructive Testing System with high resolution and visual detection of rail top crack.

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