Magneto-Optical Imaging Detection and Reconstruction of Complex-Shaped Weld Defects

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Abstract. To research the feasibility of magneto-optical imaging (MOI) in detecting small and complex defects and to explore the imaging process of MOI detection, the MOI system is used to detect defects with small and complex shapes. And the magnetic field energy accumulation of defects is simulated by Maxwell 3D. Finally, the defect profile is reconstructed according to the magnetic field distribution obtained. Research results show that the reconstructed defect images are basically consistent with the actual magneto-optical images. And there is special magnetic field energy accumulation at the intersection point, inflection point and end point of the complex-shaped defects. MOI is feasible in the detection of complex shapes, and the simulated imaging method has a certain theoretical assistance for MOI detection.

1. Introduction
Welding products can be seen everywhere in our life, such as cars, mobile phones. Welding quality plays an important role in product quality. However, in the welding process, due to the influence of factors such as welding speed, welding environment and so on, there may be cracks, pores, dents, non-fusion and other welding defects in the weld or solder joint [1]. In particular, the harm of invisible defects is great, because it is not only difficult to find, but also significantly reduce the fatigue strength of the weldment and even produce safety risks. It is of great significance to find a reliable nondestructive testing (NDT) to detect invisible defects. The conventional methods of nondestructive testing have some shortcomings for such small and invisible defects. Penetrant testing (PT) can only detect surface defects,
and the detection efficiency is low [2]. Eddy current testing (ECT) has high sensitivity to near-surface or surface defects, so it is only suitable for detecting them of weldments [3]. Ultrasonic testing (UT) can detect the defects inside the weldments, but the processing method of the received ultrasonic signal is complex and the detection method has higher requirements for operators [4]. Radiographic detection (RT) is an effective method to measure the internal defects at present, but the detection cost is high and the radiation produced is great harm to human body [5]. What’s more, the sensitivity of this method to defects tiny cracks is low. Therefore, the paper aims to explore a convenient and safe NDT, which has low requirements for operators, and can detect small and invisible defects and can image directly — magneto-optical imaging.

In this paper, taking small and complex defects as the research object, the images of magneto-optical detection are simulated three-dimensionally. And the distribution of leakage magnetic field and field energy accumulation of defects are researched. The defect images are reconstructed according to the principle of MOI.

2. Experimental Principle and Setup of Magneto-Optic Imaging

2.1. Principles of Magneto-Optic Imaging

The principle of MOI is based on Faraday magneto-optical rotation effect. When a beam of linearly polarized light propagates in a medium with a magnetic field parallel to the direction of light propagation, the polarization direction of the light rotates a Faraday rotation angle $\theta$. The angle $\theta$ can be described as

$$\theta = VBL$$  \hspace{1cm} (1)

where $\theta$ is the Faraday rotation angle of linearly polarized light (in radians), $V$ is the Verdet constant of the medium (in radians per tesla per meter); $B$ is the magnetic induction intensity in the direction of light propagation (in tesla); $L$ is the length of the magnetic medium which the light passed through (in meters). When Verdet constant and the length of medium remain constant, Faraday rotation angle is linearly related to the magnetic induction intensity.

MOI detection is to apply Faraday magneto-optical rotation effect to defect detection [6], as shown in Fig. 1. The natural light produced by LED light source is linearly polarized by the polarizer. The linearly polarized light does not deflect in the strong magnetic field without defects and deflects in the leakage magnetic field caused by defects. After passing through the mirrors and the magneto-optical film, the linearly polarized light containing defect information is detected by the polarizer and received by the CMOS camera. Finally, the magneto-optical image of defect is formed [7]. After the linearly polarized light passes through the magneto-optical film, the amplitude of the polarized light received can be described as

$$I = E \cos(\varphi + \theta)$$  \hspace{1cm} (2)

where $I$ is the projection of the linearly polarized light in the polarization direction of the analyzer, $E$ is the amplitude of linearly polarized light, $\varphi$ is the angle between the incident light and the polarization direction of the analyzer, $\theta$ is the Faraday rotation angle, and the positive and negative of $\theta$ represent different rotation directions of the angle. When the light propagates along the magnetic field direction, the polarization rotates to the right; when light propagates against the magnetic field, the polarization rotates to the left. When $\theta$ changes from positive to negative, the projection of linearly polarized light in the polarization direction of the analyzer $I$ gradually increases, which means that the intensity of light received by the analyzer is increasing.
Therefore, the principle of Faraday magneto-optical rotation effect is actually about the change of magnetic field linearly transformed into the change of light intensity. Through the detection of the change of light intensity to confirm whether the magnetic field changes, so as to confirm whether there are defects in the weldment.

When a magnetic field is applied to a weldment as shown in Fig. 2, most of the magnetic lines are inside the plate; when there is a defect, the magnetic lines change path, generating a leakage magnetic field around the defect of weldment. The magnetic induction intensity at a certain point can be divided into three components $B_x$, $B_y$ and $B_z$ in the three-dimensional coordinate axis, which can be expressed as:

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{3}$$

According to Faraday magneto-optical rotation principle, the magnetic field in the same direction with the light can deflect the polarization direction of light.

2.2. Experimental Setup
The experimental setup for MOI detection of defects is shown in Fig. 3, mainly including portal frame, base table, image acquisition and storage device, excitation regulation, electromagnet, magneto-optical sensor and industrial control computer. The turns of excitation coils are 350, and the current through the coils is 1A. The size of the weldment is 200mm×100mm×1mm (length × width × thickness), and the material of the plate is 65Mn. The acquisition resolution of the magneto-optic sensor is set to 400 pixels × 400 pixels, which means that the actual size of range detected by the magneto-optic image is 4mm × 4mm.
3. Simulation

To research the field energy accumulation of defects and the imaging process of MOI, a finite element model for detecting small defects was established. Since complex defects cannot be simply simulated by two-dimensional models, this section uses three-dimensional finite element analysis (FEA) models to simulate tiny and complex defects.

3.1. Establishment and Setting of FEA Model

The size of the weldment in this model is 200mm × 100mm × 1mm (length × width × thickness), and the material of the weldment is 65Mn. There is also an iron core, coils and air in the model. The simulation parameters of the FEA model are shown in Table 1.

Since the defect is too small for the weldment, the mesh is refined for the area of interest, which makes the mesh more reasonable. The three-dimensional model and mesh generation of the model are shown in Fig. 4.

The overall size of the defect is only 2mm×2mm×0.1mm (length × width × thickness). It presents a complex shape of X, which is formed by the vertical intersection of two rectangular grooves, as shown in Fig.5.

3.2. Simulation Results

Maxwell equation is the theoretical basis of electromagnetic field analysis, and the differential form of Maxwell equation can be expressed as (4)-(7).

\[ \nabla \cdot D = \rho \quad (4) \]
\[ \nabla \cdot B = 0 \quad (5) \]
\[ \nabla \times E = -\frac{\partial B}{\partial t} \quad (6) \]
\[ \nabla \times H = \frac{\partial D}{\partial t} + J \quad (7) \]

where \( D \) is Electric Flux Density, \( \rho \) is Electric Charge Density, \( B \) is Magnetic Flux Density, \( E \) is Magnetic field, \( \frac{\partial B}{\partial t} \) is the partial derivative of the magnetic flux density, \( \frac{\partial D}{\partial t} \) is the Displacement Current density, \( J \) is Electric Current Density [9]. The FEA model of this paper is established and calculated based on the above equation. According to the principle of MOI, the magnetic field intensity in the normal direction of the weldment is measured. The field energy accumulation is shown in Fig. 6.
Table 1  Simulation Parameters

| Parts    | Simulation Parameters |
|----------|-----------------------|
| Material | Attribute             |
| Coils    | Copper                | The number of turns is 350, the current is 1A |
| Iron core| Mn-Zn ferrite         | The relative permeability is 5500 |
| Weldment | 65Mn                  | The size is 200mm × 100mm × 1mm, the permeability is B-H curve |
| Defect   | Air                   | The relative permeability is 1 |
| Air      | Air                   | The relative permeability is 1 |

Figure 4  Mesh generation of FEA model

Figure 5  Appearance of defect
(a) I-shaped defect, (b) X-shaped defect

Figure 6  Three-dimensional magnetic induction intensity of two defects
(a) Top view of I-shaped defects, (b) Top view of X-shaped defects, (c) Axonometric drawing of I-shaped defects, (d) Axonometric drawing of X-shaped defects
Fig. 6 shows the three-dimensional magnetic field energy accumulation of two kinds of defects. It can be seen that the magnetic induction intensity of I-shaped defects with only one rectangular groove is evenly distributed. The maximum magnetic induction intensity (red part) is concentrated inside the defect, and the magnetic induction intensity around both ends of the rectangular groove is smaller than that in other areas. The magnetic induction intensity of the X-shaped defect with two rectangular grooves intersecting vertically is not significantly different from that of the I-shaped defect except for the central part. The magnetic induction intensity of the center area of the X-shaped defect is much lower than that of the other parts and is the lowest of the parts seen, which is most likely caused by the interaction of the magnetic fields between the two rectangular slots. Fig. 6 is the three-dimensional magnetic induction intensity vector diagram of two defects. When the sample has defects, the magnetic field near the defect is distorted and the magnetic field lines will bypass the defect, and the magnetic induction intensity of this part is significantly different from that of other non-defect areas.

The magnetic field distribution of leakage magnetic field was obtained through simulation of X-shaped defect, and a complete image was obtained after data processing. As shown in Fig. 8, these are the simulated image of MOI detection of I-shaped defect and X-shaped defect.

4. Experiment
An X-shaped defect with the same size as the simulated defect was made on the weldment. The weldment was tested by magneto-optical imaging with the experimental device described in the section II, and the magneto-optical image of X-shaped defect in Fig. 9(a) was obtained. Due to the acquisition and imaging of MOI, the magneto-optical image is mirror image with the actual defect. After the analysis of this figure, the three-dimensional gray distribution in Fig. 9(b) is obtained. As can be seen from Fig. 7(b) and Fig. 9, the size, shape and color distribution of the simulated image are consistent with that of the actual measured image, and are also consistent with the overall size of the actual defect. It shows that this simulation imaging can have a certain theoretical guiding significance for magneto-optical imaging, and also proves the feasibility of detecting small and complex defects in MOI.
5. Conclusion

This paper introduces a magnetic field simulation imaging method by simulating the leakage magnetic field distribution of defects and using magneto-optical imaging principle. Based on Faraday magneto-optical effect and Maxwell equation, the defect image can be reconstructed by magnetic field distribution. This method simulates the process of magneto-optical image detection. Research results show that: 1. MOI detection technology has high sensitivity and can detect small and complex defects. 2. The images reconstructed by defect are basically consistent with the magneto-optical images, which is helpful for further analysis of MOI. 3. It can obtain the magnetic field energy accumulation distribution of defects by defect simulation, and the special field energy accumulation of intersection, corner and endpoint of defects.

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