Sensors and Actuators A 172 (2011) 365–368

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

The inspection of magnetic flux leakage from metal surface cracks by magneto-optical sensors

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ARTICLE INFO

Article history:
Received 26 February 2011
Received in revised form 11 August 2011
Accepted 6 September 2011
Available online 12 September 2011

Keywords:
Magneto-optical sensors
Garnet thin films
Faraday rottaion
Magnetic flux leakage

ABSTRACT

We investigated the feasibility of using magneto-optical sensors for measuring the magnetic leakage fields in non-destructive evaluation. We used magneto-optical garnet thin films as a sensor and the effect of crack dimension on the sensor's response were investigated via a simple Faraday rotation technique. Our results show that the sensor signal displays a linear increase as the length and depth of the cracks increase however; the change in crack width does not have a significant effect on the magnetic leakage field and the sensor's signal. This technique is capable of high resolution magnetic imaging of small surface cracks and thus has great potential for application in the magnetic flux leakage test industry.

1. Introduction

The magnetic flux leakage (MFL) method is the most common and cost-effective nondestructive magnetic testing technique used in various nondestructive testing applications (NDT) [1,2]. This method is based on measuring the magnetic leakage field (MLF) over the surface of a test specimen in the vicinity of small defects such as cracks [2]. In the measurement of MFL, we need to visualize the magnetic map of the surface with good precision and sensitivity.

The most commonly used sensors for these applications are Hall and induction coil sensors [3,4]. Related to recent advances in magnetic sensor technology, for the detection of very small changes in the MFL distribution, high resolution magnetic sensors such as SQUID [5], GMR [6,7] and GMI [8,9] sensors have been introduced.

On the other hand, magneto-optic (MO) sensors appear attentive and sensitive for the visualization of magnetic map for conventional MFL in NDT applications. There are two basic modes of the MO methods [10] such as static regime detecting MFL from surface and subsurface defects [11] and eddy currents (ECs) [12,13] in metallic specimens.

The MO sensor technology is based on the combination of magnetic field and the MO Faraday effect [14–16]. These sensors are localized and miniaturized for recording the surface magnetic map applications. It is generally demanded that the sensing materials must have good MO properties of large Faraday rotation, high MO figures of merit and suitable saturation magnetic field [17,18].

In fact, sensitive equipment such as Bi substituted yttrium iron garnet (Bi: YIG) thin films are a principal part of the measuring system which determines the capability of an MO sensor. These useful materials are commonly used in new sensor structures such as monolayer, multilayer and magneto-photonic crystals [19,20]. The qualifications of these systems strongly depend on the used image recorder such as a CCD camera and image processing approach employed [21]. This makes the simple detection of micro-cracks difficult and thus there is a need to detect damages by straightforward detection systems. In this paper, in order to utilize the capabilities of MO sensors to detect cracks we used Bi: YIG thin films to measure the MLF of metal surface cracks. The effects of crack length (L), crack depth (D) and the crack width (W) on MFL response have also been investigated.

2. Experimental procedure

The principal setup for magneto-optical detection and evaluation of rectangular cracks is sketched in Fig. 1(a). The crack introduced using electro-discharge-machining at the center of a $75 \times 200 \times 1.5$ mm specimen surface that is magnetized in-plane along the x-direction (Fig. 1(b)). The measurement setup comprised of an optical path where the laser light (635 nm) passed through the polarizer, garnet thin film and analyzer before it was analyzed by silicon PIN Photodiode that was connected to the computer via an oscilloscope.

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doi:10.1016/j.sna.2011.09.010

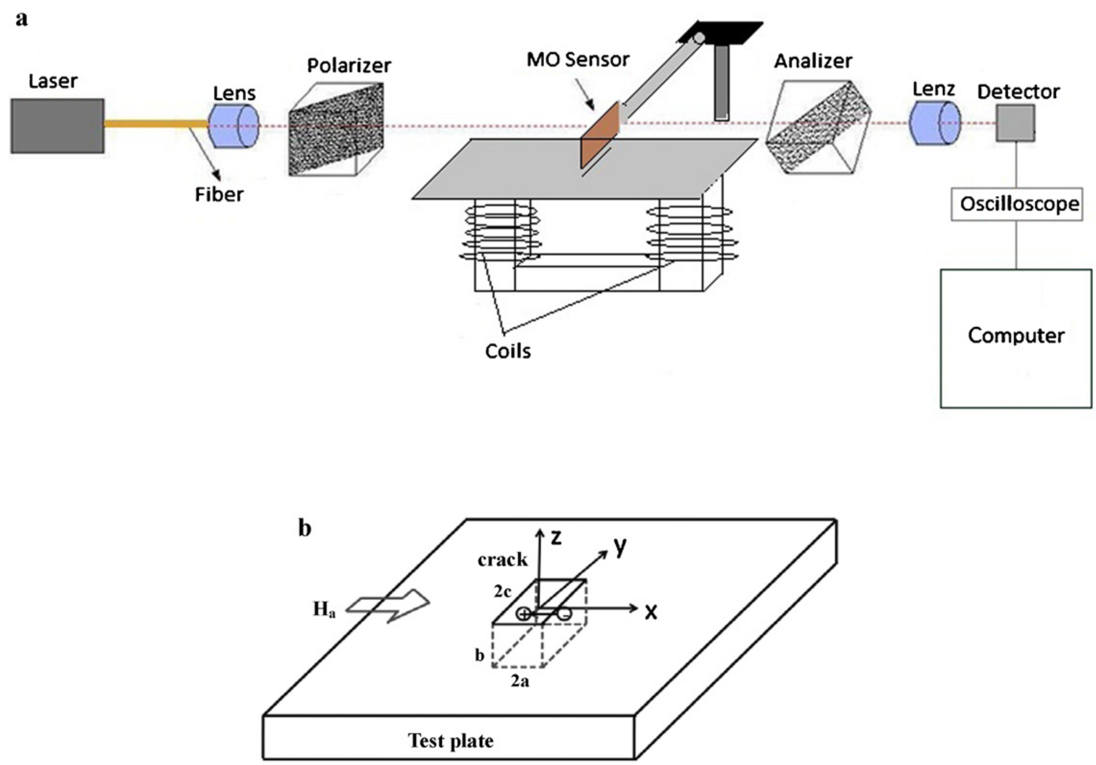

Fig. 1. (a) Schematic diagram of magneto-optical crack detection setup and (b) the size of a rectangular crack and its coordinates.

Actually, the linearly polarized light passing through the crack region and having its polarization direction changed by Faraday rotation angle, then the beam traverse a second polarizer (analyzer) and is next focused onto a photodiode which acts as an intensity recorder. In fact the change in polarization direction of the optical field due to the test magnetic field can be measured at the photo detector.

The MLF signal (B_x) of cracks has been measured by using the MO sensor which was scanned over the crack with 3 mm lift off. Distribution of the sensor signal with respect to position has been obtained after calculating the Faraday rotation angle via Malus' law. The Faraday rotations were determined by measuring the changes in intensity with respect to the field variation for a fixed polarizer and analyzer angle set at 45 degree:

$$\theta_F = \cos^{-1}\left(\frac{I_{\text{det}}}{2I_{\text{det}\,0}}\right)^{0.5} - 45 \quad (1)$$

where $I_{\text{det}0}$ and I_{det} are the intensity of light without and with magnetic field respectively.

The dynamic range of a MO sensor is determined by the saturation magnetic field which can be adjusted by chemical composition and growth conditions that can be concluded via saturation magnetic field, B_s, and maximum amount of Faraday rotation, $\theta_{\max}$, as [22]:

$$S = \frac{\theta_{\max} L}{B_s} \quad (2)$$

Thus the higher the sensitivity the lower the dynamic range and vice versa. We used a garnet thin film with sensitivity of 0.03°/mT.

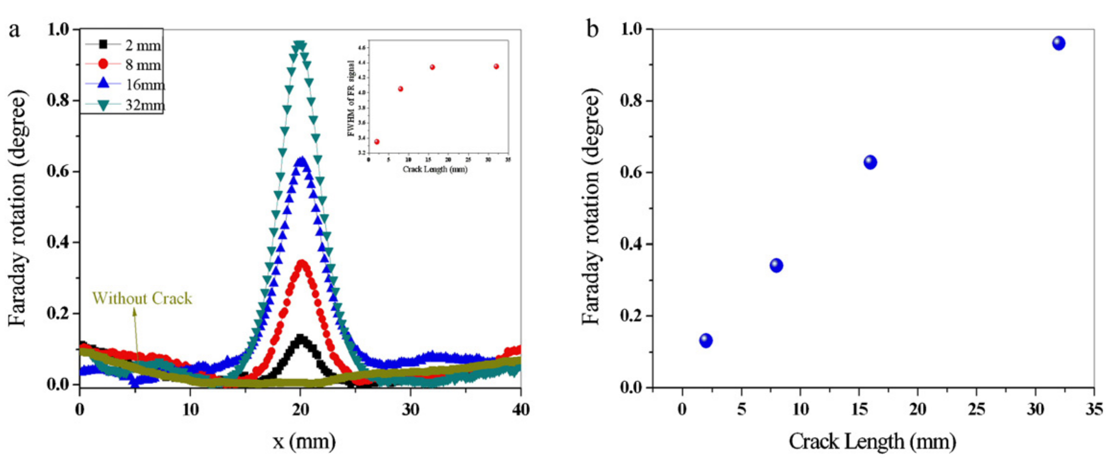

Fig. 2. (a) The distribution of the magneto-optical sensor's response for different values of crack length, 2 mm (squares), 8 mm (circles), 16 mm (up triangles) and 32 mm (down triangles)) and the sample without any cracks, the inset shows the variation of width of FR signal. (b) Change in the sensor's response as a function of crack length.

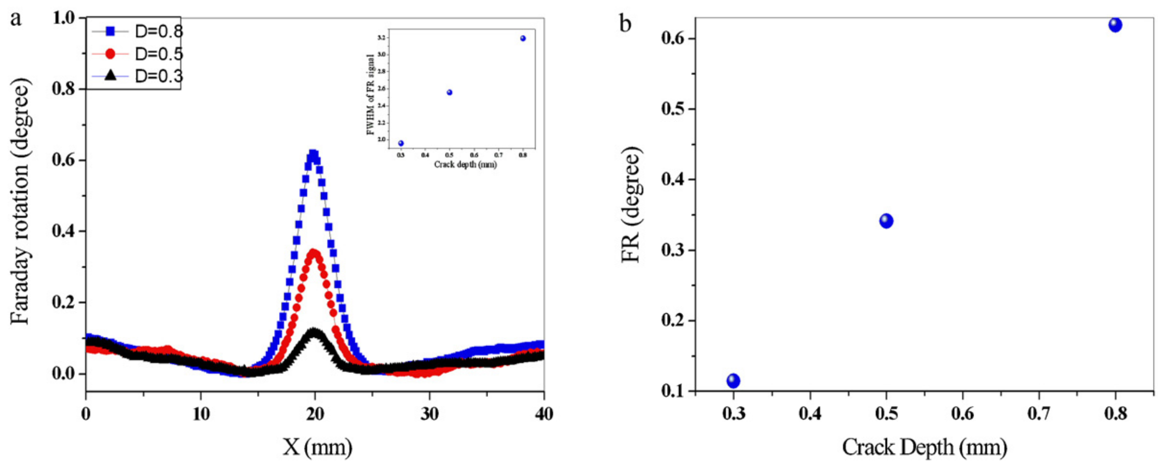

Fig. 3. (a) The distribution of the magneto-optical sensor's response for different values of crack depth, 0.3 mm (triangles), 0.5 mm (circles) and 0.8 mm (squares), the inset shows the variation of width of FR signal. (b) Change in the sensor's response as a function of crack depth.

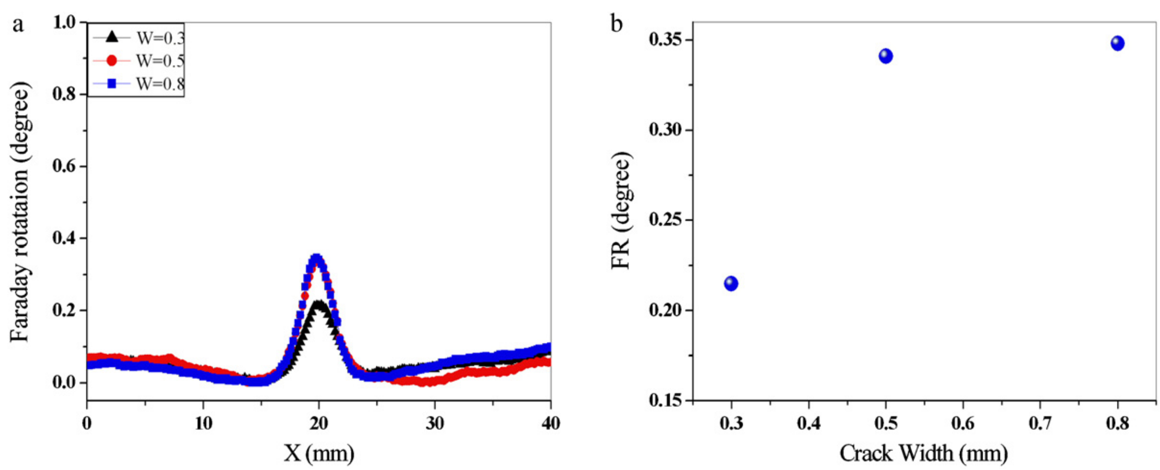

Fig. 4. (a) The distribution of the magneto-optical sensor's response for different values of crack width, 0.3 mm (triangles), 0.5 mm (circles) and 0.8 mm (squares), the inset shows the variation of width of FR signal. (b) Change in the sensor's response as a function of the crack width.

A crack induced local damage and so local MFL must be measured via MO sensor. As the angle of Faraday rotation is also proportional to the magnetic field and thus MFL signal, from a measurement of this angle, we can get the value of the former MFL. The effect of crack dimension on MFL response has been investigated with ten test specimens with different lengths, depths and widths.

3. Results and discussion

The distribution of the MO sensor's signal when increasing the crack length, L, while the crack depth and width are kept constant at 0.5 mm has been shown in Fig. 2(a). The full width at half maximum (FWHM) of these answers has been depicted in the inset of this figure. As shown in this figure, the FWHM of the MO answer has a linear increase until the crack length reaches 16 mm and after that the change is smoother. Indeed by increasing the crack length, the MO Faraday rotation and therefore; the MO answer increased linearly too (Fig. 2(b)).

As shown in this figure, while $|B_x|$ increases by scanning from one end of the crack toward the crack center until reaching its peak at the center which has the highest amount of leakage, the MO sensor's output and thus; the MO Faraday rotation maximize in the middle of the crack.

In fact, while MFL rises in the middle of the crack, the polarization rotation of linearly polarized light increase and then the MO Faraday rotation amplify too. Therefore as expected, the crack is determined by a significant increase in the sensor signal.

In order to show the sensor capability in the detection of different crack depth (D), we used a sample in which the crack width and length are kept constant at 0.5 and 8 mm, respectively.

The effect of crack depth (D) has also been depicted in Fig. 3. As shown in the figure, we have found a linear increase in the MO sensor's response and its width with crack depth.

It is worth mentioning that the lift-off distance between the MO sensor and surface of the specimen was as high as 3 mm which shows the high sensitivity of the MO sensor in leakage field sensing.

Finally, Fig. 4 depicts the sensor's distribution and MO Faraday rotation for samples with different crack width, in which the crack length and depth are fixed at 8 mm and 0.5 mm respectively.

The leakage flux first increases sharply with the crack width and reaches its peak at about 0.5 mm and then converges slowly to a certain constant level. This manner is confirmed by common sensors such as EC and GMI sensors [5,9].

4. Conclusions

A kind of flexible and useful MFL sensor based on the MO sensor is presented here. The experiment show that a MO sensing element like garnet little thin film can be utilized for design a suitable sensor for non-destructive crack detection.

We have investigated how the MO sensor can detect the surface crack with different spatial distribution and how the dimensions of the cracks influence the sensor signals. The results indicate that the sensor signal increases as the length and depth of cracks rise because increasing in the MFL distribution. The MO sensor is therefore successful in discriminating among different crack sizes with high sensitivity and low cost technique.

Now the change in Faraday rotation resulting from the MFL is easily illustrated by means of MO sensor from the point of view of change in polarization of linearly polarized incidence light. On the basis of it, the correspondence relationship between the MFL and the MO response in crack detection is analyzed.

Finally, this technique is capable of high resolution magnetic imaging of small surface cracks and thus has great potential for application in the MFL test industry.

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