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Double core giant magneto-impedance sensors for the inspection of magnetic flux leakage from metal surface cracks

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ABSTRACT

Magnetic flux leakage inspection is one of the most common nondestructive techniques used to detect crack-like defects in ferromagnetic materials. In order to improve the accuracy and reliability of crack detection, sensors based on the giant magneto-impedance (GMI) effect are suitable candidates for the magnetic sensors used in MFL detection systems. In this paper, we have introduced a double-core GMI sensor based on Co-based amorphous wires for the detection of rectangular shaped surface cracks. A theoretical method compared with experimental measurements indicates that an increase in the crack dimension is observed via an increase in the sensor signal amplitude. Magnetic imaging of different cracks shows that there is a good correlation between the size and position of cracks and the sensor signals; which can lead to improvement of the MFL test industry.

1. Introduction

The magnetic flux leakage (MFL) method is the most common and cost-effective method for magnetic nondestructive testing (MNDT) of materials used in various industries, particularly in oil and gas pipelines and oil-storage tank floors [1,2]. This method is based on measuring the magnetic leakage field (MLF) over the surface of a test specimen magnetized to near saturation. The specimen can be magnetized using different techniques which can be generally classified to DC [2], AC [3,4], pulsed [5] and residual [6,7] MFL. The MLF distribution is also highly correlated with changes in geometry and homogeneity of the test specimen in the vicinity of small defects such as cracks [2,3]. Furthermore, for a better understanding of this correlation, various mathematical models based on magnetic dipole modeling and finite element approach have been investigated [8–11].

In the measurement of MLF, accuracy and reliability depend on the sensitivity and response speed of the magnetic sensor used in the measuring system. In this system, the most commonly used sensors are Hall and induction coil sensors [12]. Related to recent advances in magnetic sensor technology, for the detection of very small changes in the MLF distribution, high resolution magnetic sensors such as SQUID [13], GMR [2,14], magneto-optical sensors [15] and giant magneto-impedance (GMI) [16] sensors have been introduced.

GMI sensors can be quite suitable due to their low cost, easy implementation, the possibility of attaining high sensitivities, fast response, good temperature stability, broad linear working range and the fact that they show low hysteresis [16–19]. The high resolution and sensitivity of GMI sensors, which are the key parameters in the measurement of very low magnetic fields [17], have particularly made them candidates for the detection of MLF from cracks. Nevertheless, length dependence of the sensor response is a restriction in the measurements of local MLF [16,20]. Following our latest research on upgrading the novel structures of GMI sensors [18,19,21–24], the GMI response turned out to be very sensitive to the composition and shape of the sensor core. For the core of these sensors, Co-based amorphous magnetic wires are promising candidate materials [17].

Using GMI sensors, new designs of MNDT systems have for flaws at a qualitatively new level allowed to be detected [25]. These sensors have been employed for the NDT micro structural characterization of ferromagnetic materials [26]. They have also been used for NDT eddy current and MFL systems to detect surface cracks [16], corrosion defects [20] and embedded flaws [27]. However, despite the advantages of GMI sensors over conventional magnetic sensors, they have not been implemented into practical MNDT systems for the characterization of cracks in the foregoing literature. In this paper, in order to utilize the capabilities of GMI sensors and to overcome the difficulties due to long length of the sensor core, a double-core GMI sensor based on Co-based amorphous magnetic wires, with reduced size and improved sensitivity has been

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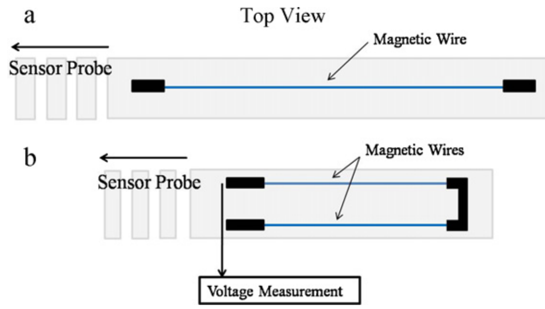

Fig. 1. Designs of (a) single core and (b) double core GMI sensors.

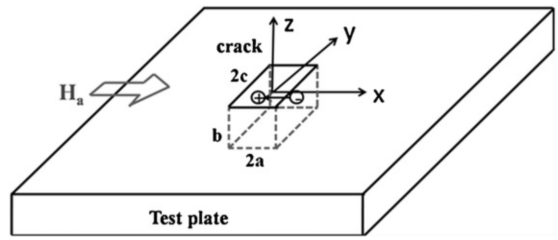

Fig. 3. The size of a rectangular crack and its coordinates.

employed to measure the MLF of metal surface cracks. The effects of crack length (L), crack depth (D) and the liftoff (LO) between the sensor and the specimen surface on MFL response have also been investigated. To confirm the validity of the experimental results, we have used magnetic dipole modeling of rectangular surface cracks to predict the tangential component of the MLF distribution.

2. Experimental details

We have used $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ amorphous magnetic wires with 125 μm diameter as the core of the GMI sensor in two different designs. The first one corresponds to a 20 mm long piece of the magnetic wire as a single sensing element (Fig. 1a). In the second configuration two 10 mm long pieces of the magnetic wire were arranged in a parallel manner and connected electrically in series to form a double core sensor as indicated in Fig. 1b. In both configurations the free ends of wires were attached to a probe. The electrical circuit of the sensor probe includes a lock-in Amplifier (7265 Perkin Elmer) which excites 14 mA_{rms}/250 kHz AC current through the magnetic wires and measures the drop of voltage between the free ends of the wires in order to evaluate the GMI effect. It is worth mentioning that this frequency is very beneficial for industrial application.

Fig. 2 shows the DC MFL measurement setup for the detection and evaluation of rectangular cracks (Fig. 3) introduced by using Electro-Discharge-Machining at the center of a 75 mm × 200 mm × 1.5 mm specimen surface magnetized in-plane along the x-direction. The MLF signal ($|B_X|$) of cracks has been measured by using the GMI sensor which was scanned over the crack. Distribution of the sensor signal with respect to position has been obtained after removing the background. In order to show the advantages of the double core GMI sensor, its output has been compared with that of the single core sensor. The effect of crack dimension on MFL response has been investigated with nine test specimens. The effect of physical lift off between the GMI sensor and the specimen surface has also been studied.

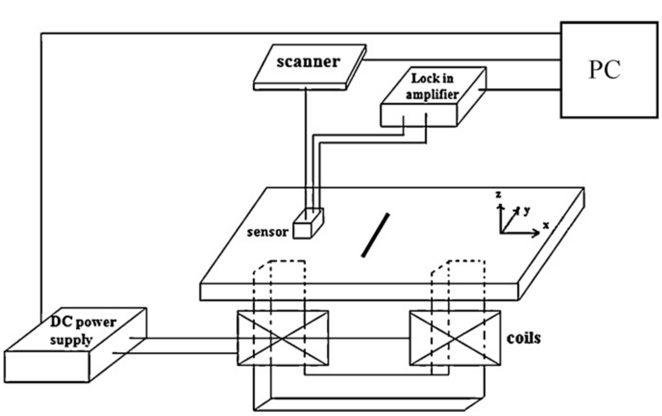

Fig. 2. The experimental setup for DC MFL inspection with a GMI sensor.

3. Results and discussions

The giant magneto-impedance (GMI) effect consists of the strong change of real and imaginary components of impedance of a soft magnetic material in the presence of static magnetic fields [19]. Change of GMI ratio defined as $\Delta Z/Z$ (%) = $[Z(H) - Z(H_{max})]/Z(H_{max}) \times 100$ (H_{max} is the maximum applied field in the GMI measurements) and the response signals of the single core and the double core GMI sensors versus parallel DC magnetic field at a frequency of 250 kHz have been presented in Fig. 4. It can be seen that the GMI response is nearly single peak with a high ratio, due to the negative and nearly zero magnetostriction constant of the magnetic wire which influences the magnetic anisotropy strength [28]. This figure also shows that the sensor signal decreases as the field intensity increases. Furthermore, as we can see the sensor is working in its linear working range far from the peak. Working far from the peak is more favorable because the peak of GMI curve is modified by the enhancement of the transverse anisotropy field due to the hard rotational process near the end of the magnetic wires [29].

As mentioned in this figure, the double core sensor has a higher sensitivity in spite of its reduced size. The significant increase of GMI effect and field sensitivity in the double core sensor mainly results from the increase of effective permeability [30] while there is no considerable change in the electrical resistance. Also, the symmetry of the sensor signal with respect to positive and negative applied magnetic fields is an important parameter for crack characterization.

In order to obtain greater understanding of the benefits of the double core sensor in crack detection, the magnetic responses of the single core and the double core GMI sensor to the x component of the MLF ($|B_x|$) of a sample with a crack 16 mm long, 0.5 mm deep and 0.5 mm wide have been shown in Fig. 5. 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 output voltage of the GMI sensor minimizes in the middle of the crack. So it is expected that the crack is determined by a significant decrease in the sensor signal output. Some undesirable behaviors such as two small minimums have been observed in the sensor signal which has been hypothesized to be due to the long length of the magnetic wire.

To prove the hypothesis we have employed an approximate theoretical method based on the dipole model of a crack to determine the distribution of MLF around a rectangular surface crack. In this method, it is assumed that the crack is filled by parallel magnetic dipoles whose density $(m(z')_{z' \subset [0,d]} = m_1 - m_2 z')$ varies linearly along the crack depth. Theses dipoles generate MLF such that its tangential (x) component for a crack with length 2c along y

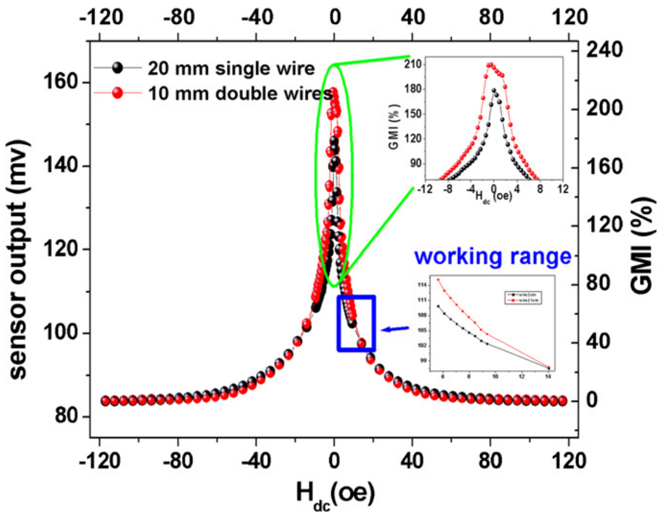

Fig. 4. The field dependence of single and double core GMI sensors signal outputs.

axis, width 2a along x axis and depth d along z axis is given by the following equation [31,32]:

$$B_X(x,y,z)=\int_{-d}^{0}\int_{-c}^{c}m(z')\left\{\frac{(x+a)dy'dz'}{\left[(x+a)^2+(y-y')^2+(z-z')^2\right]^{3/2}}-\frac{(x-a)dy'dz'}{\left[(x-a)^2+(y-y')^2+(z-z')^2\right]^{3/2}}\right\}, \quad (1)$$

As the sensor is not able to measure the local MLF due to its long length, we have added an assumption to this theory to compute the final MLF that the sensor had measured. We have assumed that in the long single core sensor, each portion of the magnetic wire has local impedance which depends on the local MLF [20]. This was supported by the results of our computation of the summation of $|B_X|$ (Eq. (1)) for the little portions which are connected in series along the length of the magnetic wire ($F(x)=\sum_{i=0}^{a}B_X(x+i)$, $a = 10, 20$). The summation has been expressed as the sensor signal in respect to x position for two sensors with 20 mm and 10 mm lengths, in Fig. 6. The theoretical results in this Figure are in good agreement with the experimental ones in Fig. 5. Therefore utilizing the double core sensor permits us to increase the sensor signal while eliminating the undesirable behaviors associated with long length. Consequently, the use of this sensor looks promising for improving crack size detection.

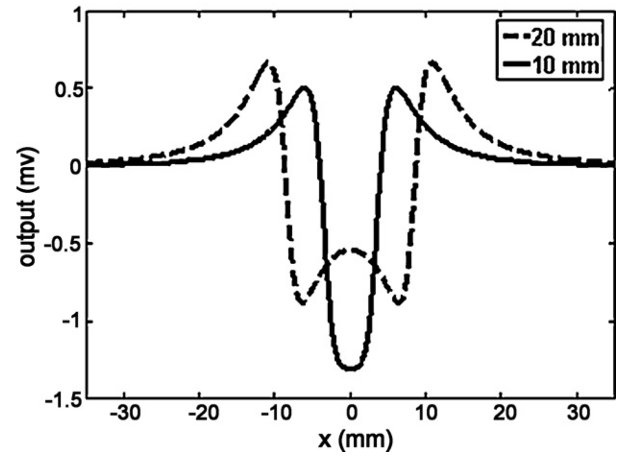

Fig. 6. Responses of 10 mm and 20 mm in length core of the sensor using theoretical model.

For most cracks associated with pipes, the crack width (W) is much smaller than its length and depth, therefore the width effect on MFL response is negligible [33]. So here, the effect of crack length and depth has been studied.

Fig. 7 shows the distribution of the sensor signal when the crack length (L) is changed, while the crack depth and width are kept constant at 0.5 mm. The figure denotes that the trough value of the sensor signal is increased noticeably when the length of the crack is increased.

By increasing the crack length, the width of the sensor signal remained constant. Thus we have utilized the first derivative of the sensor signal (Fig. 8) which is proportional to the intensity of the signal variation and thus correlates with the signal strength. The signal derivative is however more accurate for explaining the sensor signal variations. The peak to peak value of the derivative signal in respect to L has also been depicted in Fig. 9. As shown in this figure, we have found a linear increase with increasing in crack length.

Furthermore, the distribution of the x-axis sensor signal of three different cracks of varying lengths with respect to the x position has been displayed as a contour plot in Fig. 10. Colors used in

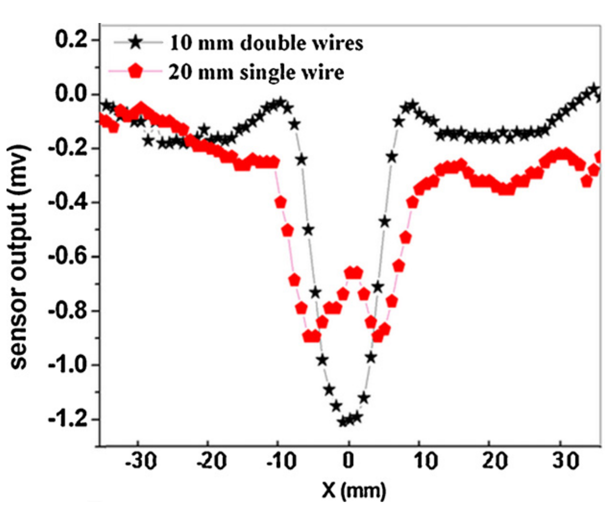

Fig. 5. Variation of the single core and double core sensor signals versus position (×).

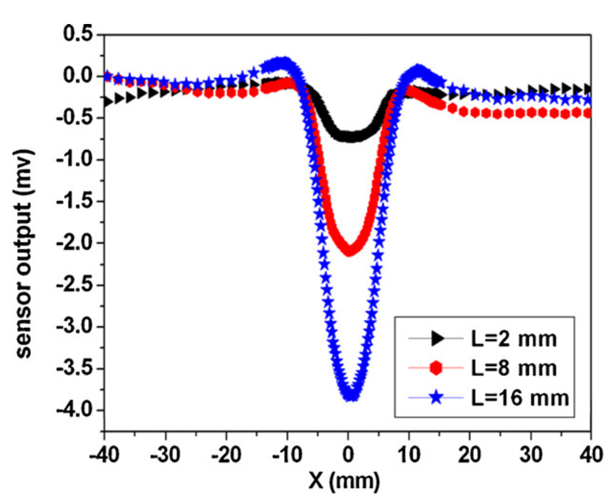

Fig. 7. The sensor response to B_x from cracks of different length as W and D = 0.5 mm and L = 2 mm, 8 mm and 16 mm.

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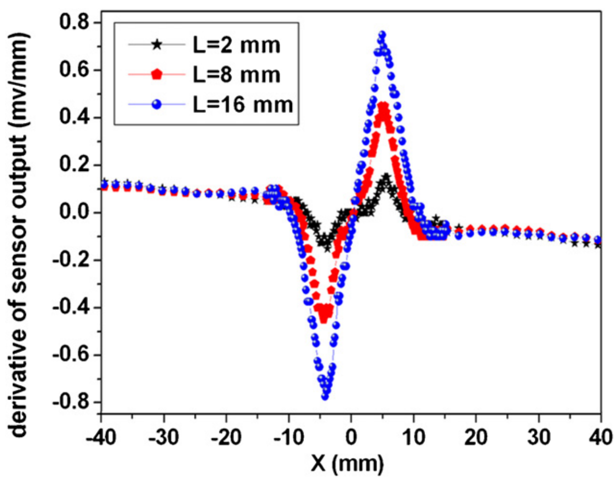

Fig. 8. Derivative of the sensor response for the three cracks of different length.

the contour plot display the sensor signal. Red is assigned to the nominal background magnetization level. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.) Increasing the flux leakage levels and therefore decreasing the sensor signal levels progresses the color from red to blue. Results show that there is a good correlation between the size and position of the cracks and the sensor signal. As $|B_x|$ shows a peak at the crack center, the sensor signal shows a trough at this position. Thus, the crack center is distinguished by dark blue in the 16 mm long crack and by decreasing the strength of MFL; the signal became orange at the 2 mm long crack. The sensor is able to discriminate different inspected cracks by using the color of the plot at the crack position. It is worth mentioning that the lift-off distance between the sensor and surface of the specimen was as high as 2 mm which shows the high sensitivity of the GMI sensor in leakage field sensing.

To examine the variation of sensor signal with increasing crack length, the theoretical method was employed for the three cracks of different lengths (Fig. 11). The figure indicates that the MLF amplitude rises due to the rise of the magnetic charge density in Eq. (1) as the crack length increases and thus, the sensor signal falls.

The effect of crack depth (D) has also been depicted in Figs. 12 and 13 while the crack width and length are kept constant at 0.5 and 16 mm, respectively. As shown in the figures we have found a linear increase with crack depth while there is no change in the signal width.

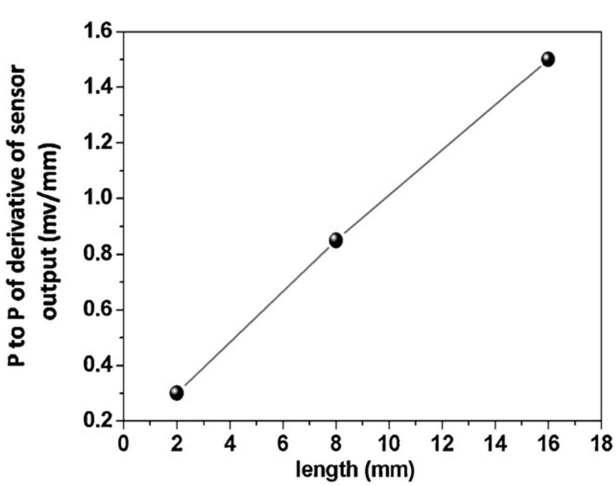

Fig. 9. Variation of peak to peak value of the sensor signal with crack length.

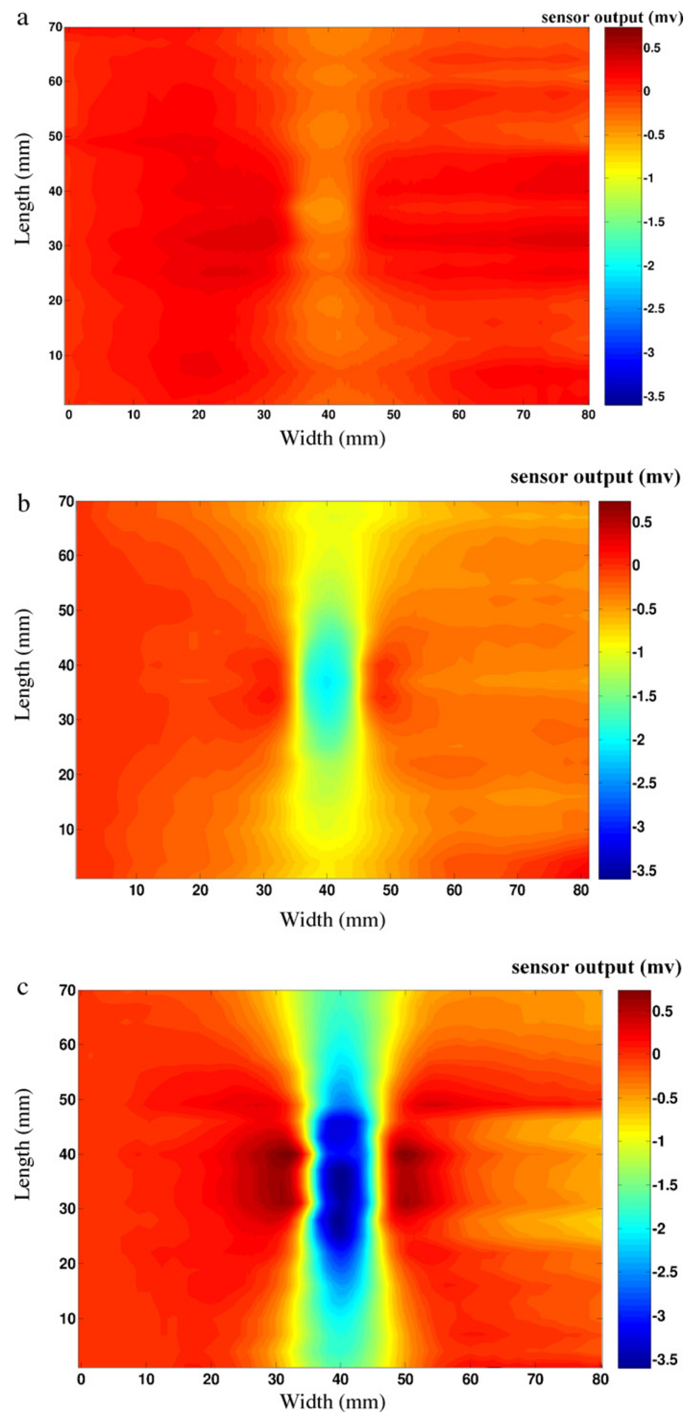

Fig. 10. Contour plots of the sensor signal on the surface of three cracked plate: W and D = 0.5 mm and (a) L = 2 mm, (b) L = 8 mm, and (c) L = 16 mm.

The contour plots of distribution of x-axis sensor signal for the three different cracks of varying depths are displayed in Fig. 14. As expected, when increasing the depth, there is an increase in the sensor signal amplitude which has been indicated with progress from yellow to blue in color at the crack center in the contour plots. Using the above theoretical hypothesis, sensor signal has also been computed for the three cracks (Fig. 15) which is in good correlation with Fig. 12.

Finally, the variation of GMI signal amplitude with physical lift-off distance for differences in crack depths has been depicted in

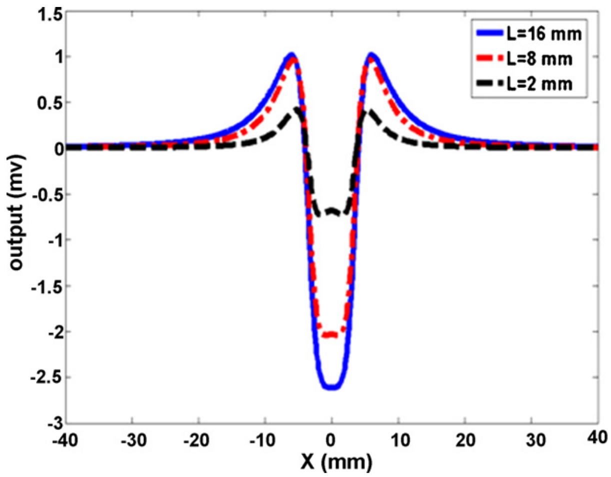

Fig. 11. The sensor signals of three cracks of different length using the theoretical model.

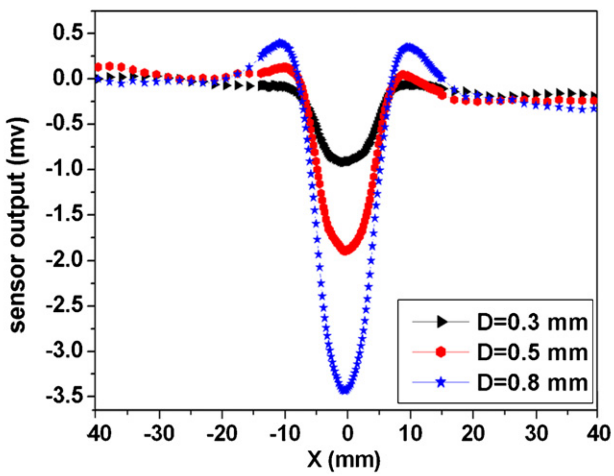

Fig. 12. The sensor response to Bx from cracks of different depth as $W = 0.5$ mm, $L = 8$ mm and $D = 0.3$ mm, 0.5 mm and 0.8 mm.

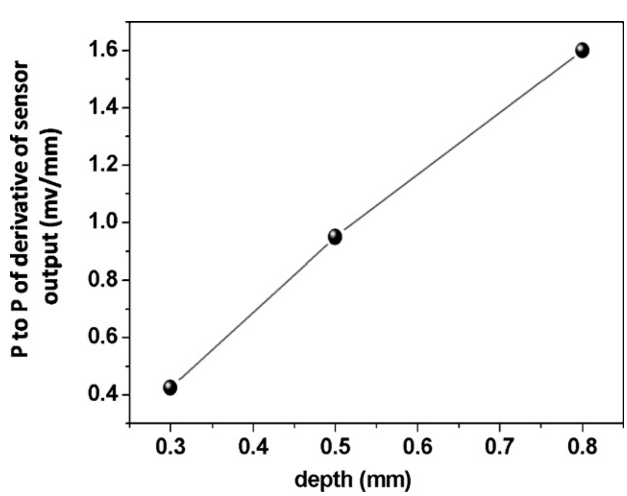

Fig. 13. Variation of peak to peak value of the sensor signal with crack depth.

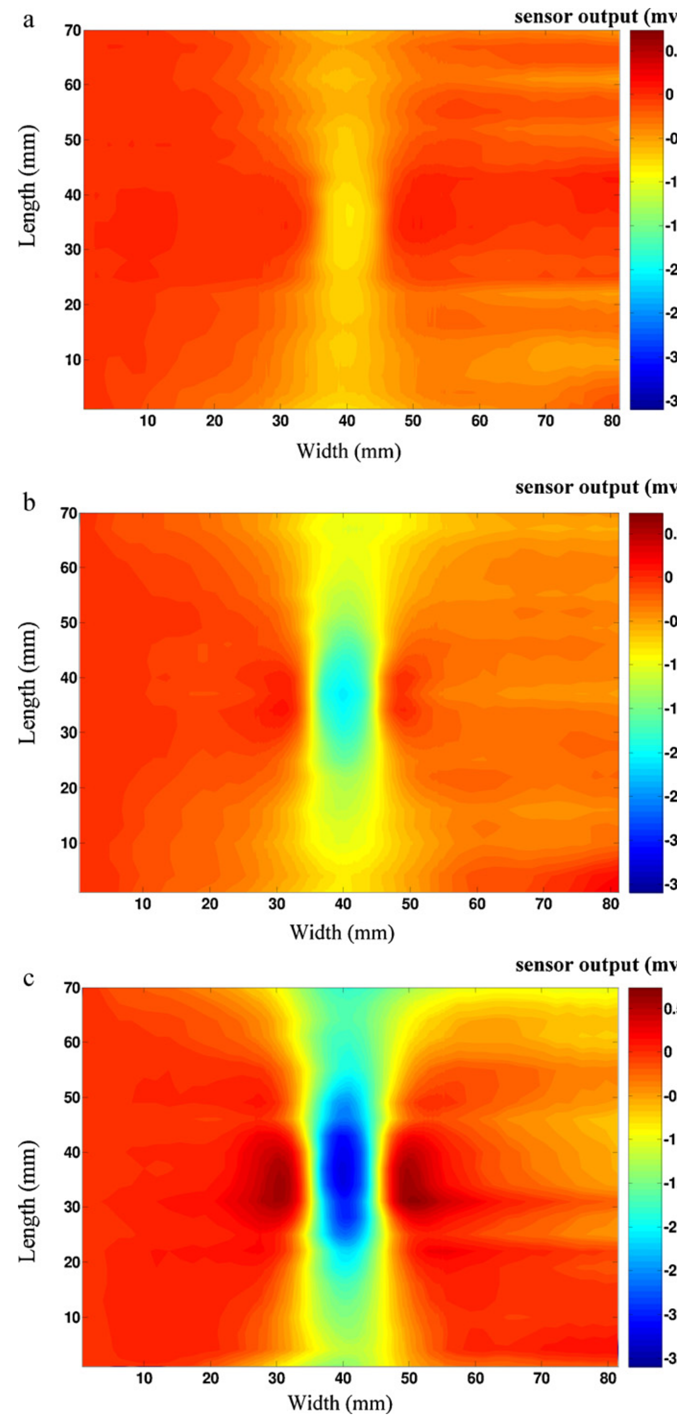

Fig. 14. Contour plots of the sensor signal on the surface of the three cracked plates: $W = 0.5$ mm, $L = 8$ mm and (a) $D = 0.3$ mm, (b) $D = 0.5$ mm, and (c) $D = 0.8$ mm.

Fig. 16. The figure indicates that increasing in lift-off distance is followed by a decrease in MFL response and also a decrease in the slope of its variation with depth, which is correlated with the reduction in the sensor sensitivity to change in crack size. It is obvious however that the double core GMI sensor is applicable at high lift-offs due to its high sensitivity.

Therefore, there is sufficient information in the GMI sensor x-axis field component to indicate the crack geometry accurately.

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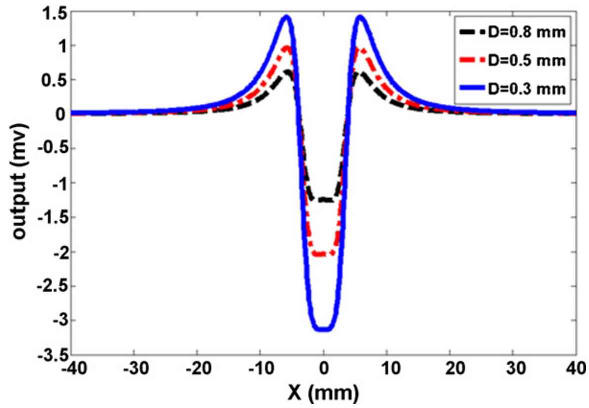

Fig. 15. The sensor signals for the three cracks of different depth using the theoretical model.

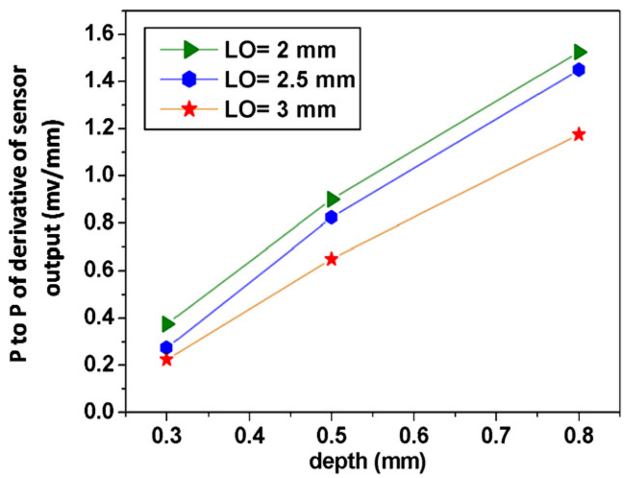

Fig. 16. The derivative of sensor signals for cracks of different depth at three different lift-off distances as 2, 2.5 and 3 mm.

4. Conclusions

Two types of structure as the core of GMI sensors, single and double sensing element of amorphous Co-based magnetic wires, have been utilized to measure the magnetic leakage field due to a rectangular crack on the surface of a magnetized ferrous plate. It has been shown that the use of the double core sensor looks promising for improving crack size detection. We have also proposed a theoretical hypothesis in the dipole model of cracks which is in good agreement with the experimental results.

We have investigated how the dimensions of cracks and lift-off distances influence the sensor signals. The results indicate that the sensor signal amplitude increases as the length and depth of cracks increase and the lift-off distance decrease. By modeling the cracks geometry and position according to their MFL intensity in contour plots, we have shown that there is a good correlation between the size and position of cracks and the sensor signals. This technique is capable of high resolution magnetic imaging of small surface cracks even at high lift-off distances and thus has great potential for application in the MFL test industry.

Acknowledgment

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