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A novel magnetic flux leakage method based on the ferromagnetic lift-off layer with through groove

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ABSTRACT

In conventional magnetic flux leakage (MFL) detection, a lift-off layer based on air or non-ferromagnetic wear-resistant material is employed to prevent magnetic sensors from wearing. However, the increase of the lift-off will lower the detection sensitivity and reduce the MFL signal amplitude. To address the issue, theoretical analysis was used to investigate the effect of the ferromagnetic lift-off layer on MFL detection in this study. Then, we put forward a new MFL detection method based on the ferromagnetic lift-off layer. A through groove is machined in the ferromagnetic lift-off layer, which creates an air gap below the sensor. The leakage magnetic field (LMF) generated by the through groove increases the local magnetization intensity around the crack on the sample, while the LMF generated by the crack increases the magnetization intensity surrounding the through groove of the lift-off layer. As a result, the magnetic sensor above the through groove detects a greater MFL signal. In addition, the effect of applied magnetization intensity, groove width, and lift-off layer thickness on the detection signal were explored by experiments. The practicality of the proposed method of detecting different size cracks of nearside and farside were studied. In summary, experiments show that the ferromagnetic steel sheet with a through groove strengthens the MFL signal of the nearside and farside cracks.

1. Introduction

Steel wire, steel pipe, drill pipes, bearing, and storage tank[1–5] are important components in the industrial sector. When these important ferromagnetic components are subjected to alternating loads, micro-cracks easily propagate, causing fracture failure, seriously affecting the safety of life and property. Therefore, it is necessary to carry out non-destructive testing (NDT) for these parts. To date, several NDT methods have been used to detect defects in ferromagnetic materials, such as magnetic flux leakage (MFL) testing, ultrasonic testing (UT), eddy current testing (ECT), etc.

MFL testing is widely used because it does not require a coupling agent and can detect internal cracks. In MFL detection, magnetic sensors are typically kept at a distance from the sample surface to protect magnetic sensors and reduce wear. The distance is referred to as lift-off value[6–8]. Similar to ECT, the lift-off value in MFL is a very important research focus[9–11]. The increase of the lift-off value causes the attenuation of the signal rapidly. Therefore, considerable research efforts dedicated to improving the sensitivity of MFL detection have been proposed, mainly from three aspects: increasing the source of the LMF, guiding or converging the LMF, and developing high-sensitivity sensors.

From the perspective of increasing the source of LMF, conventionally, a stronger LMF requires a higher magnetization intensity[12]. However, it makes the magnetizer quite bulky[13]. Sun Yanhua found that the LMF is related not only to the magnetization intensity but also to the background magnetic field near the crack. The background magnetic field can compress the distribution of the LMF and reduce the MFL signal amplitude, which is called the magnetic compression effect[14]. Based on the effect, Sun proposed a new MFL method based on near-zero background magnetic field, in which the background magnetic field was greatly reduced using a magnetic shield. It promotes the magnetic field to leak out from the sample to the air above, which significantly improves the detection sensitivity[15]. In addition, Sun Yanhua proposed a method based on magnetic field disturbance to realize the detection at a large lift-off value[16].

In terms of guiding or converging LMF, Wu Jianbo embedded a high permeability iron core in the induction coil. Due to the high permeability of iron cores, more leakage magnetic flux was guided and leaks into a larger space, which improved the sensitivity[17]. Ma Yilai, Zhang Yiqing, Jia Yinliang, and Gwan Soo Park all adopted the

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magnetic concentrating principle to gather the LMF, which could obviously improve the SNR of MFL signals and reduce the requirement of lift-off value in MFL detection[18–21]. Lee proposed a method based on "magnetic lens" and "magnetic camera". The LMF was converged in the space by the high permeability "magnetic lens", and is picked up by the "magnetic camera"[22].

In recent years, anisotropic magnetoresistance (AMR)[23], giant magnetoresistance (GMR)[24], tunnel magnetoresistance (TMR)[25], and other high-sensitivity magnetoresistors have been developed rapidly in the NDT industry[26]. Compared with the traditional Hall element and induction coil, these new magnetoresistors have a higher sensitivity and smaller spatial resolution, which is suitable for high-precision MFL detection of microcracks. In addition, the design of the sensor also helps to better pick up the leakage magnetic field signal. Jin Zhu fabricated serial MTJ-based TMR sensors and connected them to a full Wheatstone bridge circuit, which can effectively suppress white noise and improve SNR[25]. Wu Dehui detected the change rate of LMF with two sensors, which can reduce the signal instability caused by the background magnetic field and mechanical vibration[27]. However, the linear range of these high sensitivity sensors is limited, and the sensors cannot work in a strong background magnetic field[28,29].

These methods improve the sensitivity of MFL detection from different perspectives. However, the material of the lift-off layer is air or non-ferromagnetic and the attenuation of the LMF in the lift-off layer is ignored. In this paper, for the MFL testing of uncoated parts, a ferromagnetic lift-off layer is considered and a new MFL detection method based on the ferromagnetic lift-off layer with a through groove is proposed. The lift-off layer between the sensor and the sample is a ferromagnetic material, and a through groove is machined in the ferromagnetic material below the sensor. When a crack is detected, the LMF of the crack and the LMF of the through groove interact and strengthen each other. This method improves the sensitivity of MFL detection.

2. Principle

2.1. Conventional MFL detection and magnetic shielding effect

In MFL detection, the distance between the sensor and the detection surface is referred to as lift-off value. The lift-off layer is defined as the space between the sensor and the detection surface in this paper. Conventionally, the lift-off layer is non-ferromagnetic material such as stainless steel or copper as a wear-resistant layer. In the non-contact MFL detection, the sensor suspends and the lift-off layer is filled with air. When the lift-off value increases, the SNR decreases rapidly.

Due to the high permeability of ferromagnetic materials, the ferromagnetic lift-off layer is considered to avoid the attenuation of the LMF. However, it is found that the ferromagnetic lift-off layer weakens the LMF further, resulting in a *magnetic shielding effect*.

The magnetic shielding effect of the ferromagnetic lift-off layer is analyzed by a two-dimensional finite element simulation model. The magnetic source is a permanent magnet with a length of 10 mm and a thickness of 3 mm, and the residual flux density in the horizontal direction is 2 T. The dimensions of the ferromagnetic lift-off layer (steel sheet) are 100 mm × 7.5 mm (length×thickness), and the distance between the steel sheet and permanent magnet is 3 mm. The measuring point is on the vertical line of the permanent magnet, 12.5 mm away from the upper line of the permanent magnet.

Fig. 1 depicts the simulation results. When there is no steel sheet, the horizontal component of the magnetic flux density B_x at the measuring point is 53 mT. Placing a steel sheet between the magnet and the measurement point, the B_x at the measuring point is 0.13 mT. It is because the steel sheet is magnetized by the magnetic source, and the magnetic domains in the steel sheet are rearranged according to the direction of the magnetic induction line. However, the magnetic domain in the steel sheet produces an opposite magnetic field at the measuring point. Therefore, the magnetic field at the measurement point is reduced, namely, shielded by the steel sheet.

2.2. The new method based on the ferromagnetic lift-off layer with a through groove

For conventional MFL method, as displayed in Fig. 2(a), the material between the sensor and the sample is nonferromagnetic, such as copper, austenitic stainless steel, or air. The lift-off layer made of these materials has no effect on the distribution of magnetic fields, and the LMF signal of the crack $H_{\text{MFL-a}}$ is just the LMF itself $H_{\text{crack-ng}}$.

It should be noted that, to facilitate research, we simplify the crack into a rectangular notch in this paper[30]. Besides, magnetic sensors generally sense the magnetic field component in a single direction. In this paper, the horizontal component (X-direction) of the magnetic field is extracted to illustrate. The magnetic field intensity mentioned later refers to its horizontal component.

The thickness of the lift-off layer is the lift-off value of the sensor. However, with the increase of the lift-off value, the LMF decreases rapidly. Although the ferromagnetic material can converge the LMF, the ferromagnetic lift-off layer results in a magnetic shielding effect.

To avoid the magnetic shielding effect and strengthens the MFL signal, a new MFL detection method based on the ferromagnetic lift-off layer with a through groove is proposed in this paper. A steel sheet is placed between the sensor and the sample as the ferromagnetic lift-off layer. A through groove is machined in the steel

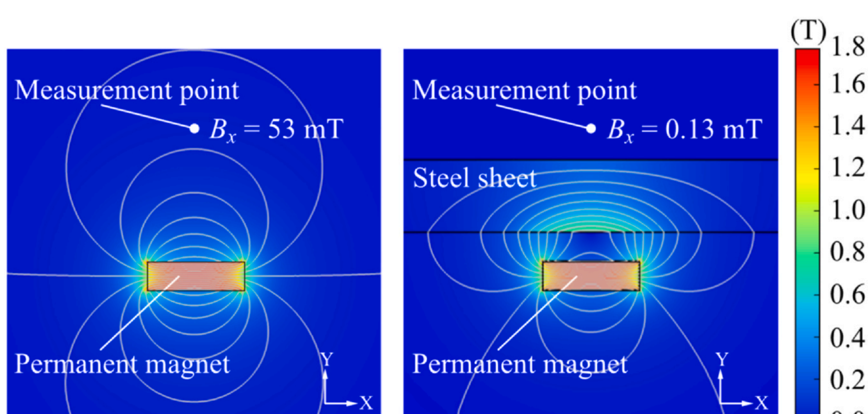

Fig. 1. The simulation results of the magnetic shielding effect of the steel sheet.

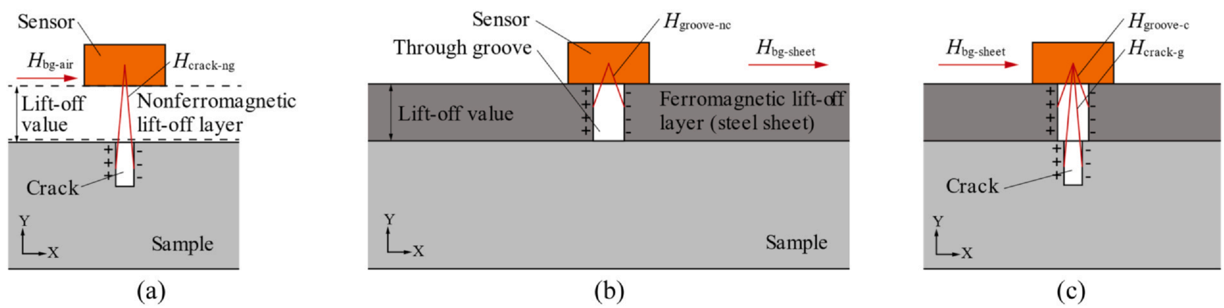

Fig. 2. Schematic diagrams of conventional method and the new MFL method: (a) The sample with a crack in conventional method; (b) The sample without a crack in the new method; (c) The sample with a crack in the new method.

sheet, which creates an air gap below the sensor. The steel sheet and the sensor scan the sample together, as shown in Fig. 2(b).

When there is no crack, the magnetic field intensity sensed by the sensor $H_{\text{sensor-nc}}$ is the sum of the LMF of the groove $H_{\text{groove-nc}}$ and the background magnetic field in the air $H_{\text{bg-sheet}}$, i.e.

$$H_{\text{sensor}-\text{nc}} = H_{\text{groove}-\text{nc}} + H_{\text{bg}-\text{sheet}} \quad (1)$$

While when the crack is detected as shown in Fig. 2(c), the magnetic field intensity sensed by the sensor $H_{\text{sensor-c}}$ is the sum of the crack LMF $H_{\text{crack-g}}$, the groove LMF $H_{\text{groove-c}}$ and the background magnetic field in the air $H_{\text{bg-sheet}}$, i.e.

$$H_{\text{sensor}-\text{c}} = H_{\text{crack}-\text{g}} + H_{\text{groove}-\text{c}} + H_{\text{bg}-\text{sheet}} \quad (2)$$

Therefore, the LMF of the crack in the new method $H_{\text{MFL}-\text{p}}$ is

$$\begin{aligned} H_{\text{MFL}-\text{p}} &= H_{\text{sensor}-\text{c}} - H_{\text{sensor}-\text{nc}} \\ &= H_{\text{crack}-\text{g}} + H_{\text{groove}-\text{c}} - H_{\text{groove}-\text{nc}}. \end{aligned} \quad (3)$$

Compared with Fig. 2(c) and (a), for the sample, when the crack is detected, the LMF generated by the groove leaks upward into the air and downward into the sample. The downward LMF strengthens the magnetization of the crack, so $H_{\text{crack-g}} > H_{\text{crack-ng}}$. Compared with Fig. 2(c) and (b), for the groove, when the crack is detected, the LMF generated by the crack also strengthens the magnetization of the steel sheet, so $H_{\text{groove-c}} > H_{\text{groove-nc}}$. That is to say, the LMF of the crack and the through groove strengthen each other.

To compare the signal amplitudes of the new method and conventional method, $H_{\text{MFL-a}}$ is subtracted from $H_{\text{MFL-p}}$.

$$\begin{aligned} & H_{\text{MFL}-\text{p}} - H_{\text{MFL}-\text{a}} \\ &= H_{\text{crack}-\text{g}} + H_{\text{groove}-\text{c}} - H_{\text{goove}-\text{nc}} - H_{\text{crack}-\text{ng}} \\ &= (H_{\text{crack}-\text{g}} - H_{\text{crack}-\text{ng}}) + (H_{\text{groove}-\text{c}} - H_{\text{goove}-\text{nc}}) \\ &= \Delta H_{\text{crack}} + \Delta H_{\text{groove}} \\ &> 0 \end{aligned} \quad (4)$$

Where ΔH_{crack} is the LMF increment caused by the magnetization strengthening effect of the crack, and ΔH_{groove} is the LMF increment caused by the magnetization strengthening effect of the groove. It is obvious that the lift-off layer of the steel sheet with a through groove enlarges the LMF of the crack.

3. Simulation and analysis

Finite element modeling (FEM) is commonly used in the study and analysis of NDT[31,32]. FEM can effectively predict the field pattern in the vicinity of a crack, which provides a good platform for researching the magnetic field distribution and the effects of each parameter on the MFL signal.

A three-dimensional finite element model was established in the COMSOL software. The model consisted of a magnetizing coil, a sample, and a steel sheet with a through groove, as shown in Fig. 3. The simulation parameter configuration is shown in Table 1.

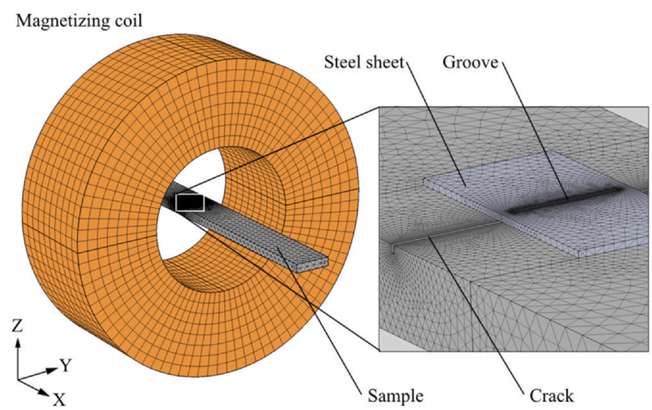

Fig. 3. FEM simulation.

Specifically, our sample and steel sheet (Q235 steel) were considered to be isotropic ferromagnetic material. The magnetization curve of Q235 steel, as shown in Fig. 4, was adopted for material properties in the simulations. The center of the coil is the coordinate origin.

Three simulation models were calculated as shown in Fig. 5. There was a groove and a crack in model I; there was a crack but no groove in model II; there was a groove but no crack in model III.

According to the previous analysis, the through groove of model I is magnetized by the crack LMF, while the through groove of model III is not. Therefore, the magnetic flux density at region A in model I should be stronger than that in model III. The simulation data were taken from the symmetry plane of the simulation model, which is plane Y = 0. The simulation results are displayed in Fig. 6. The magnetic flux density of model I is larger than that of model III near the through groove. Then the magnetic flux density of path 1 and path 2 are extracted and plotted in Fig. 8(a). It can be seen that the magnetic flux density along Path 1 is around 1.6 T, while that along Path 2 is around 1.4 T. It verifies the magnetization strengthening effect of the crack on the through groove.

For the crack, the crack in model I is magnetized by the LMF of the through groove, while the crack of model II is not. Therefore, the magnetic flux density at region B in model I should be stronger than that in model II. The simulation results are shown in Fig. 7, which depicts that the magnetic flux density of model I is larger than that of model II near the crack. The magnetic flux densities are accordingly extracted from path 3 and path 4 and plotted in Fig. 7(b). It shows that the magnetic flux density of Path 3 is approximately 1.4 T, while that of Path 4 varies greatly, but all data are less than 1.35 T. The magnetization strengthening effect of the through groove on cracks is verified.

The results of the two FEM simulations show that the through groove of the steel sheet and the crack of the sample are magnetized and strengthened with each other under the magnetization of the

Table 1
Condition of simulation.

Magnetizing coil	Inside diameter = 170 mm, Outside diameter = 370 mm, Thickness = 130 mm, Turns = 1000, Magnetizing current = 18 A;
Sample	Length = 500 mm, Width = 40 mm, Thickness= 10 mm;
Crack	Length = 40 mm, Width = 0.1 mm, Depth = 0.5 mm;
Steel sheet	Length = 30 mm, Width = 15 mm, Thickness= 0.8 mm;
Through groove	Length = 12 mm, Width = 0.1 mm;
Convergence tolerance	1.0E-5

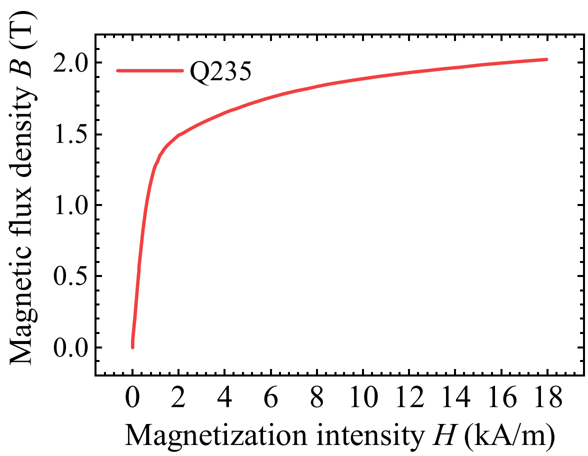

Fig. 4. The *B-H* curve of Q235 steel.

applied magnetic field. The simulation results are consistent with the analysis, which verifies the previous theoretical analysis.

As shown in Fig. 9, the distribution of LMF in path 5 which was 0.3 mm above the steel sheet, was obtained in model I, and the distribution of crack LMF under the new method was obtained by subtracting the background magnetic field in the corresponding no-crack model. Then the steel sheet in model I changed to the copper sheet, and other conditions remained unchanged. The LMF distribution in Path 6 was extracted. The crack LMF distribution under conventional method was obtained in the same way. The simulation signal is shown in Fig. 10. The simulation results show that the signal amplitude of the new method is 27.23 mT, while that of conventional method is 10.87 mT. The new method increases the signal amplitude by 2.5 times under the simulation conditions. The through groove not only avoid the magnetic shielding effect but also strengthens the MFL signal.

4. Experiment

4.1. Experiment test set-up

The schematic diagram and the picture of the experiment platform are illustrated in Fig. 11. The DC magnetization coil of 1000 turns was powered by a DC magnetization power supply. The magnetization direction was perpendicular to the crack direction. The steel sheet and copper sheet with a thickness of 0.8 mm were selected as the lift-off layer. The steel sheet was used as the ferromagnetic lift-off layer, and through grooves were machined by wire-electrode cutting. A copper sheet was used as the nonferromagnetic lift-off layer. The sensor was a Hall element (0811). The output voltage of the Hall element was acquired and displayed by an oscilloscope.

Five experimental samples were Q235 steel plates with a length of 300 mm, a width of 40 mm, and a thickness of 10 mm, as shown in Fig. 12. Each sample has five artificial rectangular cracks with the same depth and width of 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1.0 mm, respectively. The depth of cracks on the five samples are 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1.0 mm, respectively. The cracks were machined by electric discharge machining (EDM).

4.2. Analysis of influencing factors

4.2.1. Magnetization intensity

In the previous analysis, the new method strengthens the LMF by mutual magnetization between the groove and the crack. Therefore, it is necessary to study the influence of the intensity of the applied magnetization on the new method. The magnetization currents I varied from 1 A to 15 A with an interval of 1 A. The 0.8 mm thick steel sheet with an artificial crack (0.4 mm in width,1 mm in depth) was used to experiment. The Hall element was fixed on the 0.6 mm width through groove. After the steel sheet with the Hall element scanning the crack under different I, the signal amplitudes of the new method were obtained. Then the Hall element was fixed on the 0.8 mm thick copper sheet. In the same way, the signal amplitudes of the conventional method under different I were obtained. The experiment results of the two methods are shown in Fig. 13.

With the increase of magnetization current, the amplitude of conventional method increases gradually and then tends to be flat. While that of the new method increases rapidly at first, after reaching the peak, then decreases slowly. Under different magnetization currents, the MFL signal of the new method is always larger than that of conventional method. The signal strength of the new method is not limited by magnetization.

4.2.2. Groove width

The width of the through groove is an essential parameter, thus we studied the influence of the groove width on the strengthening effect in the new method. The groove width b_g was changed in the range of 0.2–1.0 mm with an interval of 0.2 mm, as displayed in Fig. 14. And the crack width b_c is changed in the range of

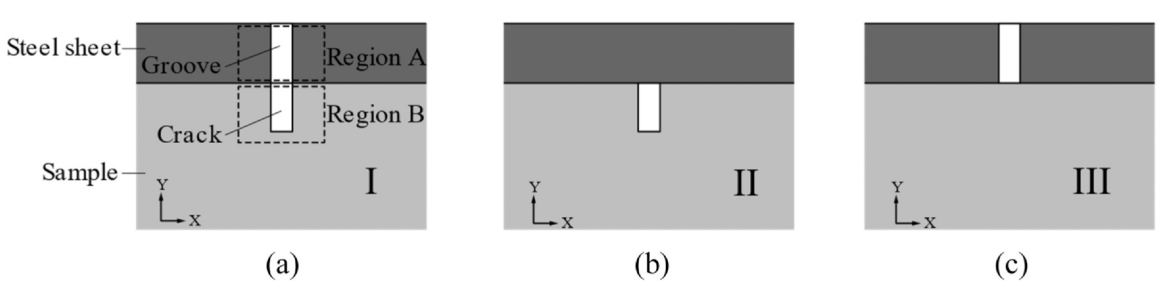

Fig. 5. Three FEM models. (a) There is a groove and a crack in model I; (b) there is a crack but no groove in model II; (c) there is a groove but no crack in model III.

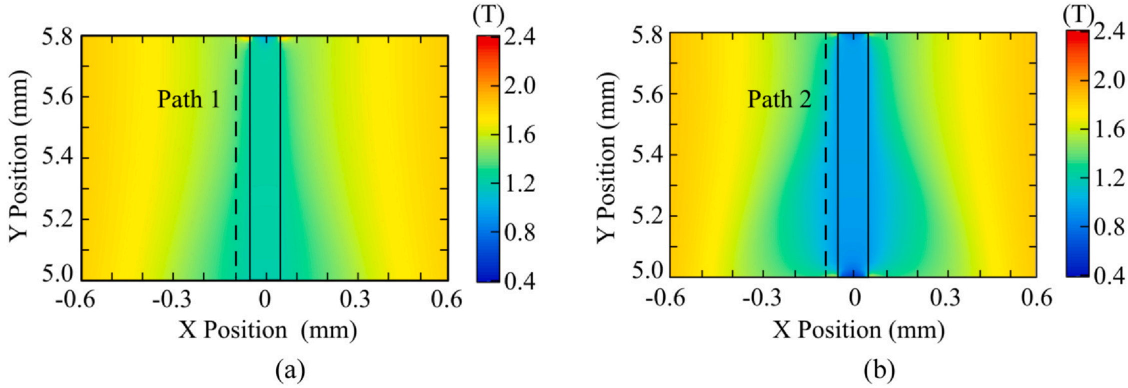

Fig. 6. Simulation results comparison of the area near the groove with or without a crack in the sample. (a) Region A in model I; (b) Region A in model III.

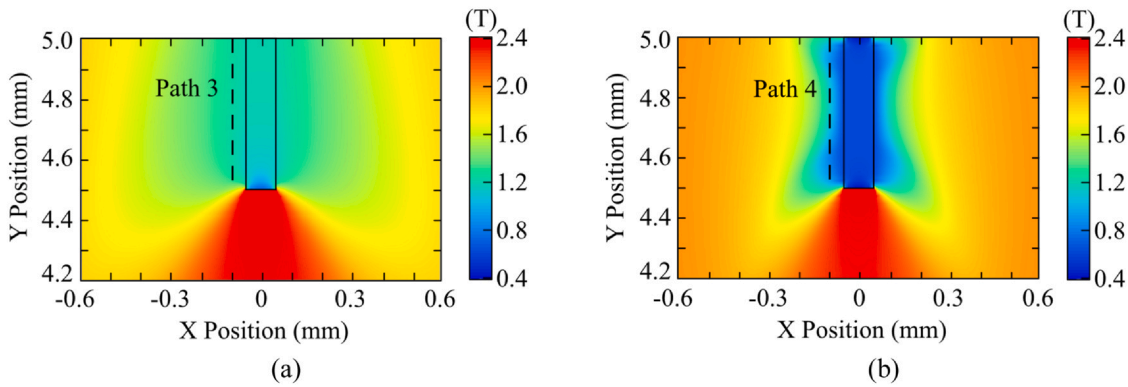

Fig. 7. Simulation results comparison of the area near the crack with or without a groove in the steel sheet. (a) Region B in model I; (b) Region B in model II.

0.2 mm~1.0 mm with an interval of 0.2 mm, as shown in Fig. 12. The magnetization currents I was 10 A.

The relationship between the amplitude of MFL signal B_x and the b_g under different b_c is obtained, as shown in Fig. 15. The experiment results show that with the increase of b_g, the LMF all increases first and then decreases. On the one hand, when b_g is small, the LMF of the groove is weak. The change of the groove LMF is also small with increasing the same magnetization, so the magnetization strengthening effect of the groove is limited. On the other hand, according to the previous analysis of the magnetic shielding effect, when the groove is small enough, the steel sheet with a through groove will be transformed into a complete steel sheet. The magnetic shielding effect is strong, and the LMF will be shielded. With the increase of b_g, the groove LMF increases. The magnetic shielding effect weakens, and the magnetization strengthening effect of the groove gradually increases. When b_g is further increased, the spatial range of the crack LMF is smaller than the b_g, and the crack LMF cannot reach the steel sheet. Therefore, the magnetization strengthening effect continues to decrease.

Meanwhile, with the increase of the b_c from 0.2 mm to 1.0 mm, the optimal b_g increases slowly from 0.4 mm to 0.6 mm. The change trend of optimum b_g with b_c is not obvious. In the range of

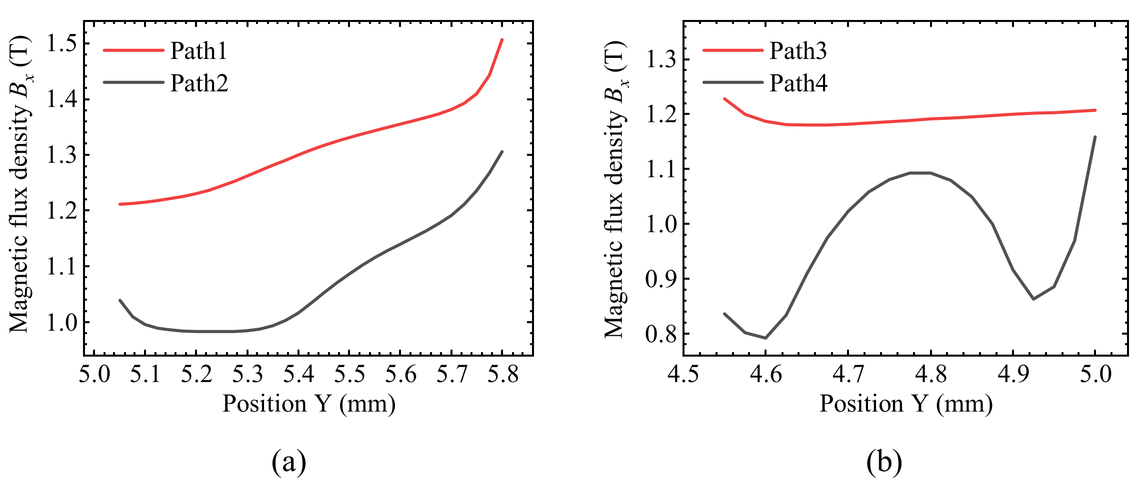

Fig. 8. Comparison of magnetization near the crack and the through groove. (a) The magnetic flux density near the crack of path 1 and path 2; (b) The magnetic flux density near the through groove of path 3 and path 4.

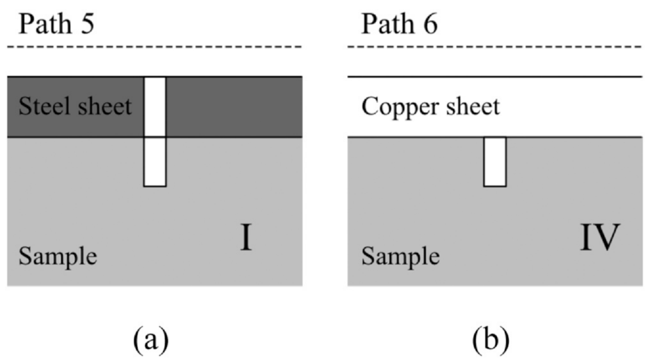

Fig. 9. Two FEM models: (a) the new method model; (b) conventional method model.

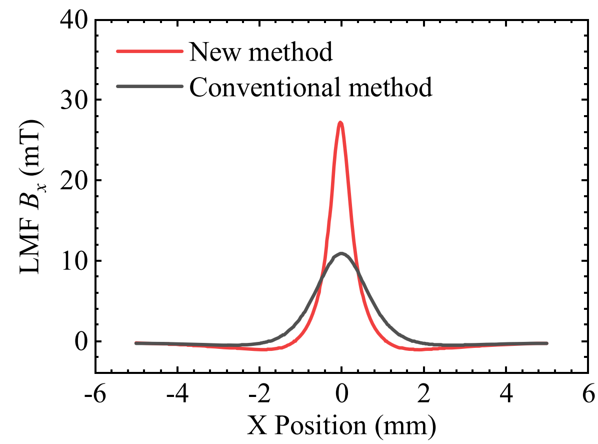

Fig. 10. The MFL signal obtained by the new method and conventional method.

experiment parameters, the optimal b_g is about 0.4–0.6 mm. Generally speaking, for the same size crack, the fluctuation of signal amplitude of different b_g grooves is in the range of 17–22%. In actual testing, when the groove width is selected within a reasonable range, the leakage signal does not vary too much.

4.2.3. Lift-off layer thickness

The thickness of the lift-off layer t is another important parameter. The range of t varied from 0.2 mm to 1.0 mm with an interval of 0.2 mm. b_c was 0.4 mm and b_g was 0.6 mm. The magnetization currents I was 10 A. The LMF amplitude of the new method at different t is obtained. Then, the lift-off layer is changed from the steel sheet to the copper sheet, and the experiments of different thick copper sheets were carried out to get the amplitude of LMF in conventional method. The two curves are plotted in Fig. 16.

It can be seen that with the increase of t, the LMF of both the new method and conventional method decreases. However, The MFL signal amplitude of the new method is always larger than that of conventional method. Then the leakage fields of the two curves were normalized separately to compare the decay rates of the two methods, as shown in Fig. 17. The curve slope of the new method is

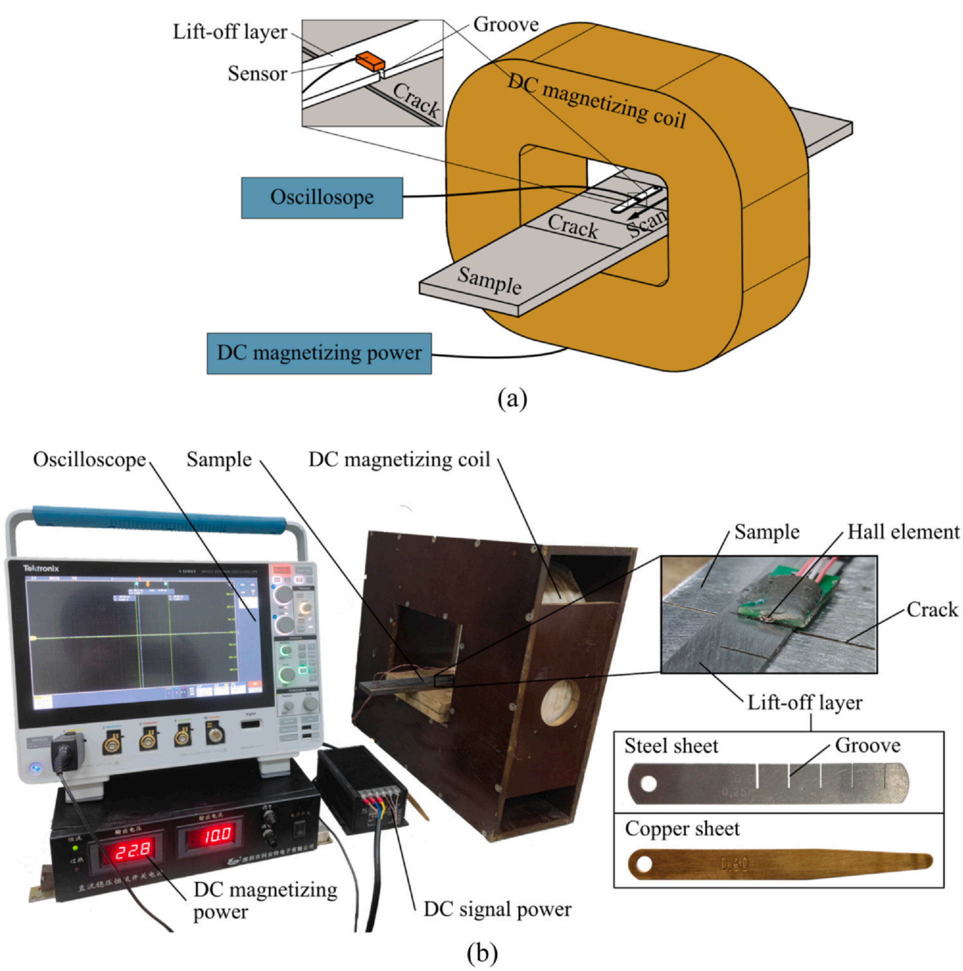

Fig. 11. The schematic diagram and the picture of the experimental system**:** (a) the schematic diagram of the experiment platform; (b) picture of the experiment platform.

Fig. 12. The picture of the five experiment samples.

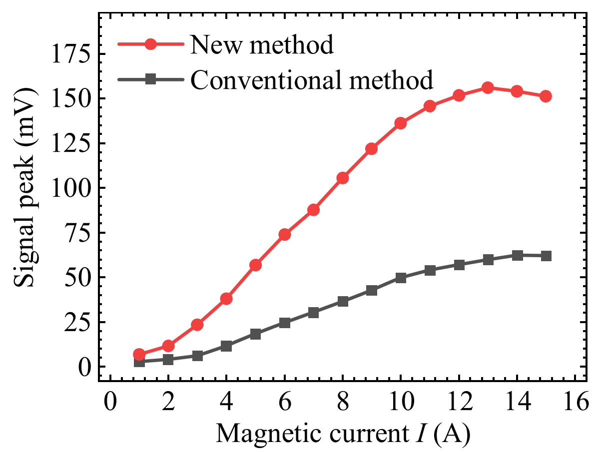

Fig. 13. Change trend of experimental results of LMF strength via two methods under different magnetization currents.

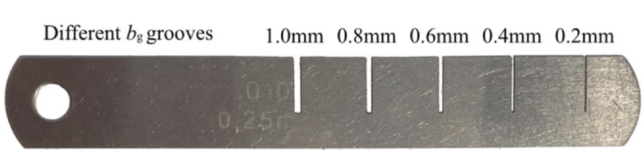

Fig. 14. The picture of the steel sheet with different b_g grooves varied from 0.2 mm to 1.0 mm with an interval of 0.2 mm.

about −0.25, while that of conventional method is about −0.675. The rate of decay of the new method with increasing lift-off value is 0.37 times that of the conventional method, which weakens the lifting effect.

From another perspective, it can be seen from Fig. 16 that the LMF with a 1.0 mm thick steel sheet with a groove is large than that with a 0.2 mm thick copper sheet. Herein, under the conditions of this experiment, when the signal amplitude of the new method is

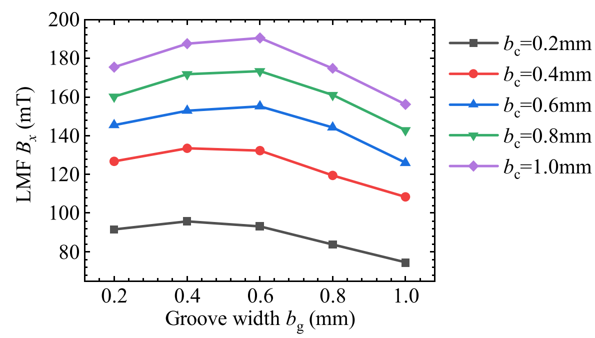

Fig. 15. Change trends of experimental results of B_x with b_g under different b_c.

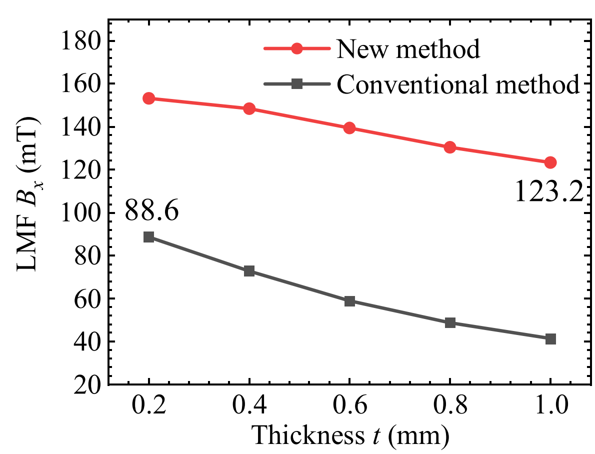

Fig. 16. Change trend of the experimental signal of B_x with t via two methods.

the same as that of conventional method, the thickness of the wear-resistant layer can be at least increased by 5 times, and the wear resistance of the probe will be increased by more than 5 times with

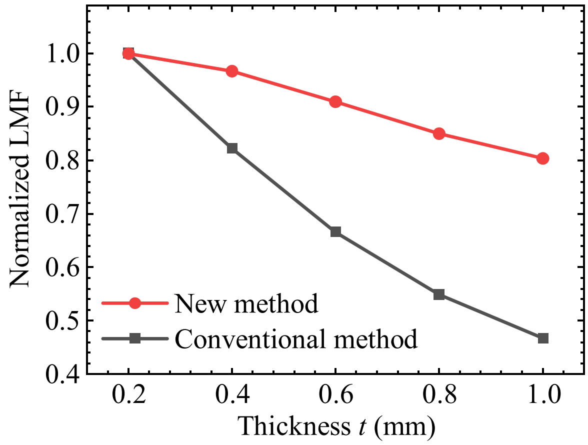

Fig. 17. Change trend of the normalized experimental signal of B_x with t via two methods.

the new method. Therefore, compared with conventional method, the new method can effectively improve the service life of the probe.

4.3. The detection performance of different cracks

In actual detection, the width, depth, and position of cracks are not constant. In this section, to further investigate the detection performance of the proposed new method for different cracks, a series of experiments were performed.

4.3.1. Signal of different crack width and crack depth

The magnetization currents I was 10 A and the thickness of the steel sheet was 0.8 mm. The Hall element was respectively fixed on the 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm wide through groove, and the steel sheet with the fixed Hall element scanned the five experiment samples on the surface with cracks of different sizes, as shown in Fig. 11(a) and 12. The experimental MFL signals of the new method were obtained by the oscilloscope. Then the Hall element was fixed on the 0.8 mm thick copper sheet to obtain the

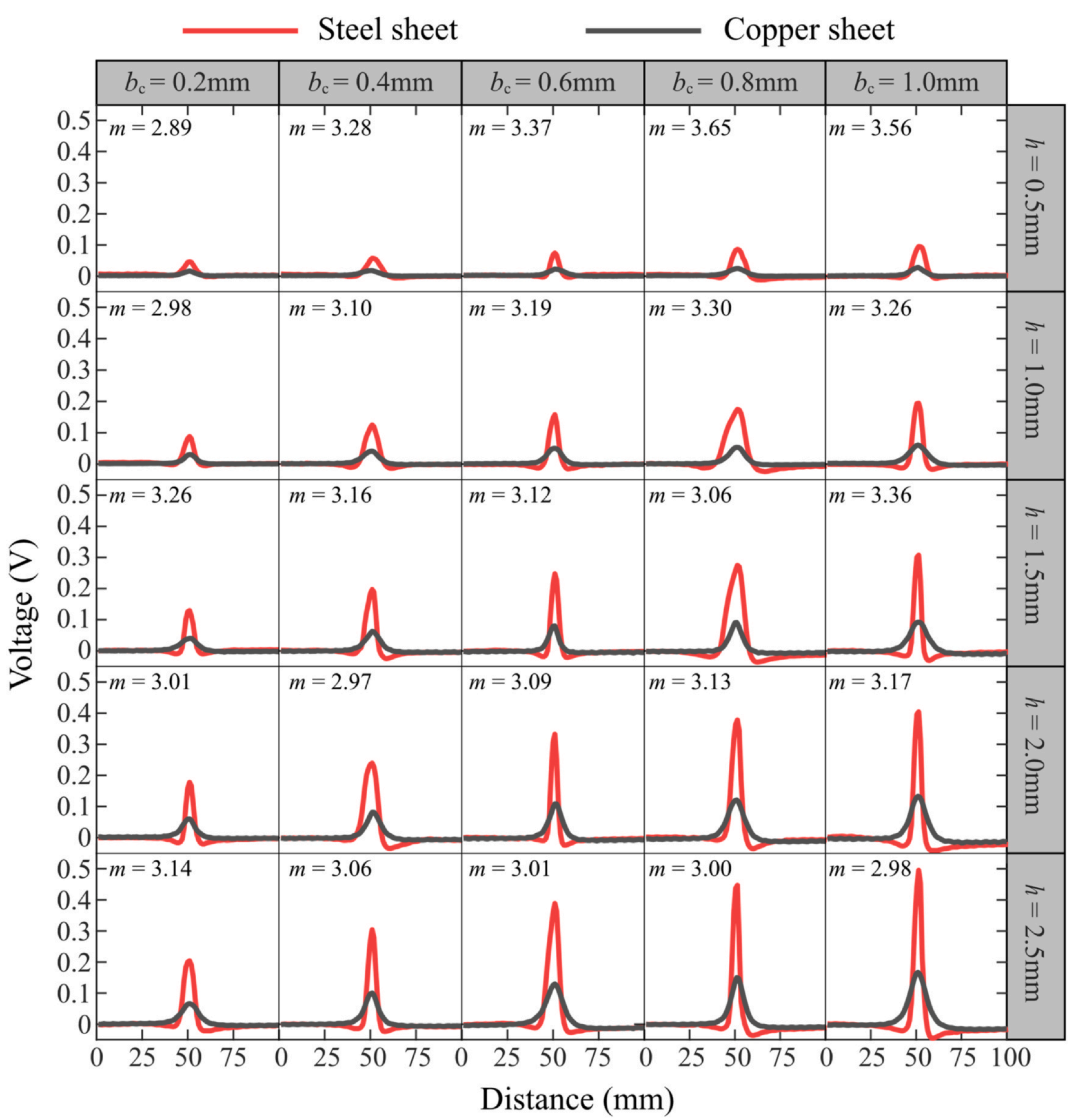

Fig. 18. Experimental signals of different width and depth crack via two methods and signal amplitude magnifications.

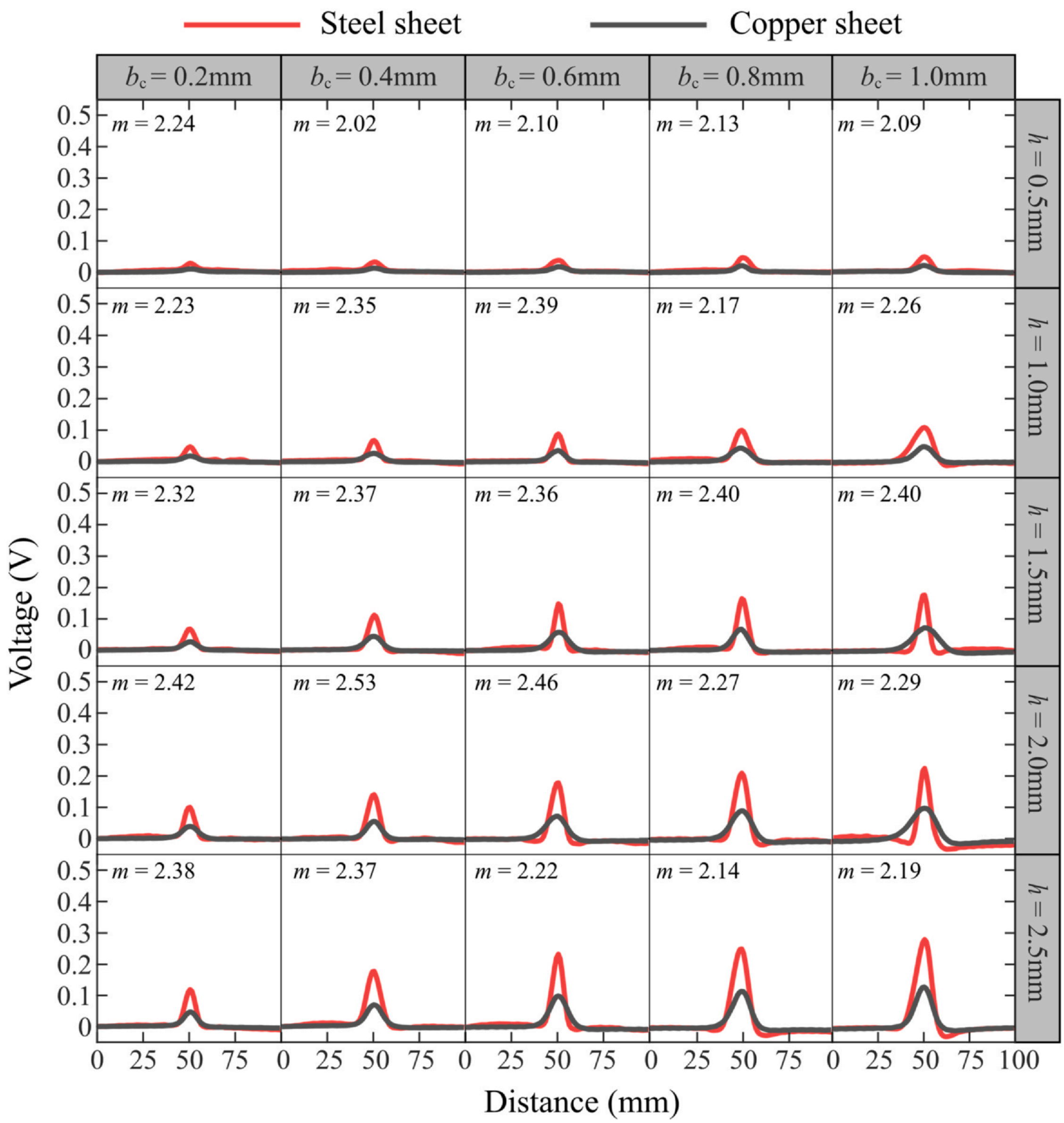

Fig. 19. The farside crack experimental signal of steel and copper sheets.

experimental data in the same way. The magnification *m* is referred as to the ratio of the signal amplitude in the new method to that in conventional method.

The experimental results are plotted in Fig. 18, which depicts that the signal amplitude of both steel sheet and copper sheet increases with the increase of the crack width or depth. The signal amplitudes with a steel sheet are invariably larger than those with a copper sheet and the *m* are in the range of 2.89–3.65 times, which verifies the feasibility of the new method for cracks with different dimensions.

4.3.2. Farside crack detection

Compared with common magnetic powder inspection (MPI) and eddy current testing (ECT), MFL detection method can detect the farside cracks of the sample. As nearside crack, farside crack can also produce similar LMF. For the same size crack, the farside crack has a smaller MFL signal amplitude and a wider MFL signal range than the nearside crack. The detection performance of the new method in farside crack detection is further verified by experiments.

The sample plate was turned over, and the sensor with a lift-off layer scanned the back of the sample plate. Other experimental conditions were consistent with Section 4.3.1. The experimental results of farside cracks are shown in Fig. 19. The signal amplitudes with a steel sheet are invariably larger than those with a copper sheet and the *m* are in the range of 2.02–2.53 times, which verifies that the new method can also strengthen the LMF of farside cracks. The *m* of farside cracks is less than that of nearside cracks because the distance between the crack and the through groove is farther and the mutual magnetization strengthening effect is weakened.

5. Discussion and conclusion

The lift-off layer of conventional MFL detection is air, austenitic stainless steel, and other nonferromagnetic materials, which makes the MFL signal decrease greatly. The existing methods increase the MFL signal by strengthening the source of the LMF, converging the LMF, and developing high sensitivity sensors. Magnetic converging methods proposed by Wu Jianbo, Jia yinliang, and Gwan Soo Park are similar to the new method in this paper. The magnetic converging methods all utilize the magnetic converging effect of the ferromagnetic device to converge the LMF in the air. Sensors are arranged beside the ferromagnetic device where the LMF is large. What the sensor senses is the LMF of the crack. However, the LMF will still attenuate because it is still air or non-ferromagnetic materials between the sensor and the crack. The new MFL method is based on the ferromagnetic lift-off layer with a through groove. On the one hand, the MFL signal originates from the LMF of cracks. On the other hand, it originates from the LMF increment of the through groove and the crack, caused by the magnetization strengthening effect. The MFL signal is amplified in the new method. Compared with the conventional method, the new method effectively improves the detection sensitivity. Besides, the lift-off effect in the new method is weakened and the wear-resistant layer can be thickened to extend the service life of the MFL probe. In addition, the new method has the potential to combine with other methods to increase the MFL signal further.

In this paper, three simulation models are used to analyze the principle of mutual strengthening magnetization between the crack and the groove. The influences of magnetization intensity, groove width, and lift-off layer thickness on the LMF are further studied. The validity of the new method for farside crack detection is also verified. Finally, the experimental results show that the proposed method obtains a higher signal amplitude for nearside and farside crack detection compared with conventional method. The new method is simple and effective. It exhibits broad application prospects in the design of the wear-resistant layer of MFL probes. However, there is still much work that needs to be done in the future for the new method, such as the effect of through groove on cracks detection[33,34] in different directions and the quantitative study on magnetization strengthening effect.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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