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A New Micro Magnetic Bridge Probe in Magnetic Flux Leakage for Detecting Micro-cracks

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Abstract

Magnetic flux leakage (MFL) testing has been widely used as an efficient non-destructive testing method to detect damage in ferromagnetic materials. It's of great importance to improve the testing capability of MFL sensors. In this paper, a micro magnetic bridge method in MFL of high sensitivity is proposed to detect micro-cracks. This method consists of a micro magnetic bridge core and an induction coil. Furthermore, a novel micro magnetic bridge probe (MMBP) of higher spatial resolution is designed and developed with 10 μm width between the two sides of this MMBP in the testing magnetic bridge. The lift-off effect of this new MMBP is studied via finite element method and experimental verification. The results show this MMBP can achieve high sensitivity only when working with a micro-lift-off value. To examine the detecting capability of this MMBP, micro-cracks in magnetic particle inspection sensitivity testing pieces are all inspected, and the lowest depth value is only 7 μm. The MMBP in this paper improves the testing capability of MFL to the micrometre scale and can be widely used to detect grinding micro-cracks in bearing rings.

Keywords Non-destructive testing (NDT) · Magnetic flux leakage (MFL) · Micro-cracks · Micro-magnetic bridge probe (MMBP) · Magnetic particle inspection (MPI)

1 Introduction

As a non-contact nondestructive testing (NDT) technology, magnetic flux leakage testing (MFL) is a powerful and highly efficient method that has been widely used for ferromagnetic objects, such as oil-gas pipelines, rail tracks, steel wire, oil storage tank bottom and bridge cables [1–4]. The basic theory of MFL is that magnetic induction lines will escape from a ferromagnetic material in a saturation magnetization situation when a discontinuous volume, called a defect, is present [5–9]. Different magnetic sensors are utilized to obtain the magnetic leakage field, such as Hall components, coils and magnetoresistors [10–14]. Sensors with a high sensitivity and high stability, such as giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) devices, are applied to detect micro-cracks in MFL [15–18]. However, magnetoresistance (MR) sensors are easily saturated in strong magnetic fields thereby, losing their sensitivity.

The bearing is an important part of modern mechanical equipment. All bearing parts need to be inspected. Most cracks in bearing rings are grinding cracks of 0.03–0.15 mm depth. As a powerful and highly efficient NDT method, MFL can be used to detect cracks in bearing rings. Improving the detection capability of MFL is important for detecting smaller defects because the magnetic leakage field caused by grinding cracks is rather weak. Reducing the lift-off value is another method to improve the detection capability. A series of studies have been performed to improve the sensitivity of MFL sensors by inserting a high-permeability block into the coil centre [19–21]. Research has also been conducted on decreasing the lift-off value. In industrial applications, MFL sensors, like Hall and GMR devices, are enclosed in a protective layer. The thickness of the protective layer is approximately 0.3 mm [19]. To extend the probe life, wear-resistant sheets and wear-resistant blocks are also used between the magnetic sensors and the tested surface. The thickness of the wear-resistant sheets is greater than 0.5 mm. Reducing the lift-off value of an MFL sensor to less than 0.5 mm, which is used for other magnetic sensors, is difficult.

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Other research has been conducted to discover new methods for improving the sensitivity of MFL probes [22,23]. However, most MFL probes can only detect defects on the scale of 0.1 mm, and detecting micrometre micro-cracks is still rather difficult. If the size of the defect is on the micrometre scale, detecting the defect by MFL is still a challenge. Designing a new MFL sensor with a higher sensitivity to detect smaller defects on a micrometre scale is important for MFL testing methods.

Magnetic bridge testing probes have been used in MFL for several years [3,24]. However the testing capability of magnetic bridge and its spatial resolution aren't high and it's difficult to detect grinding micro-cracks in bearing rings. In order to improve the testing capability and spatial resolution of magnetic bridge testing probe, a micro magnetic bridge testing method in MFL is proposed for its lift-off value can be zero in this paper and a novel micro magnetic bridge probe (MMBP) is developed. To improve the testing capability and spatial resolution of this MMBP, the distance between the two sides of the testing magnetic bridge is just 10 µm. The working mechanism of this MMBP is studied by Finite Element Method (FEM). The new lift-off effect curve of the MMBP is different from the conventional lift-off effect operated at the scale of 0.5 mm scale. Experimental verification is also conducted to examine the dependency of this MMBP on different lift-off values. In other words, this MMBP must touch the tested surface tightly. To examine the high testing capability of this MMBP, six magnetic particle inspection (MPI) sensitivity pieces with six micro cracks are all detected by this MMBP. This MMBP improves the testing capability of MFL to a micrometre scale. An NDT system that can detect micro-cracks on micrometre scale instead of MPI is important. Future work in this research will focus on designing different probes for different parts, such as bearing rings and balls, etc.

2 Micro-magnetic Bridge Testing Method in MFL

2.1 Micro-magnetic Bridge Probe in MFL

In the magnetic bridge system, a magnetizing coil is used to generate an AC magnetic field. A U-shaped magnetic yoke is used to generate a magnetic bridge. The magnetic bridge is established through the specimen circuit and the testing magnetic circuit. In the testing magnetic circuit, a magnetic sensor, such as a coil, is applied to measure the change of the magnetic flux in the testing magnetic circuit. If no defects are present in the specimen, the magnetic circuits of the specimen and testing bridge are balanced, and the magnetic flux in the testing magnetic circuit does not change, i.e., the testing coil will not have a positive signal. However, the balanced

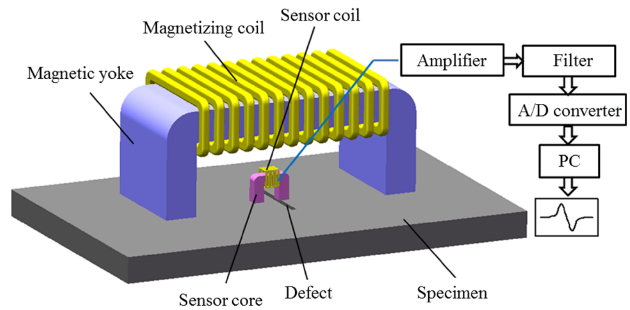

Fig. 1 Micro-magnetic bridge probe in MFL

magnetic circuit is destroyed when a defect is present in the specimen. The magnetic resistance in the specimen increases, but the magnetic resistance in the testing magnetic circuit does not change. This results in an increase in the magnetic flux in the testing magnetic circuit. A sensor coil is applied to monitor the changes of the magnetic flux in the testing magnetic circuit and determine the presence of defects in tested specimens.

The sensitivity of a magnetic bridge probe will become greater as the magnetic bridge decreases. However, the volume of the testing magnetic circuit is large, and the spatial resolution ratio is not high. Detecting defects on the micrometre scale is difficult. To improve the testing capability of magnetic bridge probes, a micro magnetic bridge that has a higher spatial resolution is proposed in this paper, as seen in Fig. 1. The balanced magnetic circuits are composed of the sensor core and a small area of the tested specimen. A detailed diagram of this system is shown in Fig. 1.

There is a U-shaped magnetizer and the magnetic field is generated by the magnetizing coil in it. In the testing process, an AC current in the magnetizing coil causes the specimen to be in the magnetic saturation state. The specimen contains a slot. According to the MFL principle, the defect should be perpendicular to the magnetic line, and the core in the probe is parallel to the magnetization unit. In contrast to other magnetic bridge probes, the probe in this paper consists of a U-shaped core wrapped by a coil. The signals generated by the testing coil are processed through an amplifier, filter, A/D converter and computer. The sensor is moved over the defect, and the sensor core touches the tested surface during the testing process. The lift-off value should not change during the testing process. If the specimen has a defect, the magnetic resistance of the specimen will increase, and the magnetic flux in the sensor coil will change. Different magnetic flux maps of the sensor core are given in Fig. 2. The magnetic flux in the sensor core in the absence of defects is given in Fig. 2a. The magnetic flux in the sensor core in the presence of a defect is shown in Fig. 2e. The magnetic flux is different in these two situations. The coil in the sensor is applied to measure the change in the magnetic flux in the core. If defects

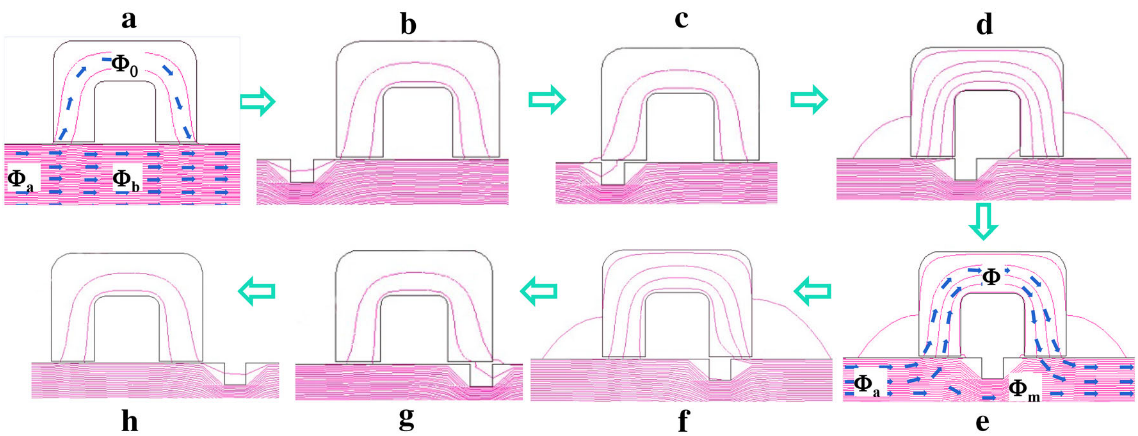

Fig. 2 Magnetic flux in the micro magnetic bridge

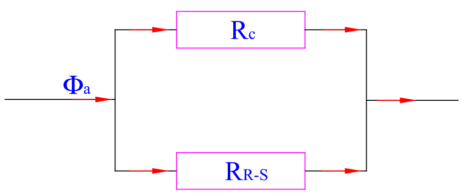

Fig. 3 Magnetic circuit in the micro magnetic bridge

are present, the balanced state of this magnetic bridge will be destroyed, and the voltage in the coil will change.

Initially, the defect is far from the sensor core, as seen in Fig. 2a. As the defect moves closer to the sensor core, as shown in Fig. 2b, the magnetic flux source in the sensor core will decrease because the magnetic flux in the bridge, which is composed of the sensor core and local area of the specimen, is decreasing. The magnetic flux escapes to the sensor core if the defect is under the pole, as seen in Fig. 2c. The magnetic flux in the sensor core will decrease as the defect moves into the region of the testing magnetic bridge. When a defect is in the region between the two ends of the sensor core, the magnetic flux in the specimen will decrease, and all the escaping magnetic flux will be in the sensor core, as seen in Fig. 2d. Fig. 2d shows that the magnetic flux in the sensor will increase when the sensor core moves to this magnetic bridge. When the defect is in the middle position of this sensor core, the magnetic flux in the sensor core will be at a maximum, as shown in Fig. 2e. The magnetic flux in this sensor will continue to change, as shown in Fig. 2(f–h), as the sensor moves away from the defect.

The magnetic flux in the magnetic bridge is shown in Fig. 2a, e. The magnetic flux source in the magnetic bridge is Φ_a, the magnetic flux of the magnetic bridge in the tested specimen region is Φ_b and the magnetic flux in the sensor core is Φ_0, as seen in Fig. 2a. The magnetic reluctance of the core is Rc (Fig. 3), and the magnetic reluctance of the specimen in the testing magnetic bridge is R_{R-S}. R_{R-S} is the magnetic reluctance in the region of the tested specimen of this magnetic bridge. The function of this magnetic bridge is shown in Eq. 1.

$$\Phi_0 = \Phi_a \frac{R_{R-S}}{R_C + R_{R-S}} \tag{1}$$

The number of sensor coil turns is n, and the voltage of the sensor coil is given in Eq. 2

$$e = n\frac{d\Phi_0}{dt} \tag{2}$$

where n is the sensor coil turns and t is time. A new expression, Eq. 3, is obtained.

$$e = n\frac{d}{dt}\left(\Phi_a \frac{R_{R-S}}{R_C + R_{R-S}}\right) \tag{3}$$

If a defect is present in the tested specimen, the magnetic reluctance of the specimen in the magnetic bridge will change. A change will occur in the magnetic flux in the sensor core, and a pulse signal will occur in the sensor coil. This micro magnetic bridge method has many advantages. First, the core in the sensor core can closely touch the tested surface. Thus, the lift-off value of this method can be zero. As a result, this micro magnetic bridge can obtain more magnetic leakage field energy and has a higher efficiency. Second, a higher spatial resolution is obtained when the distance between the two sides of the sensor core is reduced. This method has an excellent sensitivity and spatial resolution for the detection of micro-cracks. However, reducing this distance is difficult due to the size of the U-shaped core. A novel MMBP sensor for MFL with a smaller gap distance is proposed in the next section.

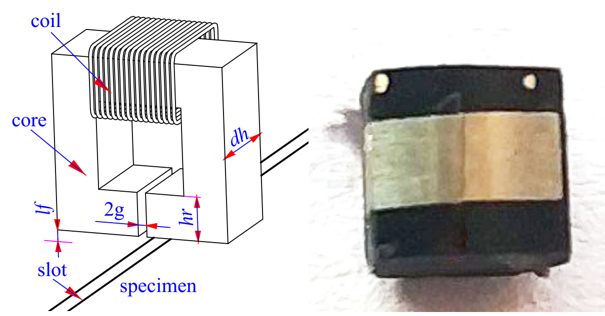

Fig. 4 A new MMBP with a micro-magnetic bridge for MFL

2.2 A New Micro-magnetic Bridge Probe for MFL

To improve the spatial resolution of the MMBP, a new MMBP with a smaller distance between the two sides of the gap in the core is proposed for MFL in this section. Instead of a U-shaped core in the MMBP, a hollow rectangular core with a narrow gap is designed. This sensor is shown in Fig. 4.

This new MMBP has a smaller distance between the two sides of the sensor core. The testing magnetic bridge in this new MMBP is the region between the two sides of the gap. The thickness of the core in this probe is *dh*, the width of this core is *hr*, the number of sensor coil turns is *n*, the gap value is $2g$ and the lift-off value is *lf*. In the testing process, the gap in the MMBP is parallel to the defect, and the scanning direction is perpendicular to the defect. The magnetization in this testing system is same as that in Fig. 1. The material of this new MMBP core is a high-permeability amorphous alloy. Because determining the magnetic flux and voltage of the sensor coil in this new MMBP is difficult, an FEM model is established to study the characteristics of this sensor in COMSOL Multiphysics 4.4. In this FEM model, a new MMBP is designed, and the size of this new MMBP is given in Table 1.

The material of the tested specimen is Q235-A. The gap value of the new MMBP core is 10 μm. The thickness of this sensor, *dh*, is 1.5 mm, which is far larger than the gap value. Thus, a 2D FEM model is given in Fig. 5 instead of a 3D FEM model. The U-shaped MMBP made of Q235-A is shown in Fig. 5. The thickness of the magnetizing yoke is 15 mm and that of the tested specimen is 10 mm. The DC current in two regions of this model is shown in Fig. 5. The current density J_1 is 2e5 A/mm^2. The defect on the surface of the specimen has a size of 0.1 mm*0.1 mm (depth*width), and the lift-off value, *lf*, is 10 μm. A different magnetic flux, Φ, is obtained when the new MMBP moves across the defect. The curve of the magnetic flux, Φ, in the sensor core is shown in Fig. 6 at different positions (*lf*=0.01 mm). When the sensor is far from the defect, the magnetic flux in the sensor core will not change, as seen in the magnetic flux curve when $x < -2$ mm. The magnetic flux in the sensor core will decrease as the sensor moves closer to the defect, as seen in Fig. 6 (*lf*=0.01 mm), for -2 mm $< x <$ -0.8 mm. In the testing magnetic bridge, the magnetic source will decrease if a defect is present before the testing magnetic bridge. However, for -0.8 mm $< x < 0$ mm, the magnetic flux in the sensor core will sharply increase. During this process, the magnetic reluctance, R_{R-S}, in the tested specimen will increase, and the magnetic flux in the new MMBP will also sharply increase. When the sensor moves away from the defect, a symmetrical curve is obtained. Therefore, the curve in Fig. 6 (*lf*=0.01 mm) is an axis symmetrical waveform.

The absolute value of the magnetic flux in this new MMBP core is not relevant. The magnetic flux values in the sensor core for other lift-off values are shown in Fig. 8 below. The maximum magnetic flux in this new sensor core will sharply decline as the lift-off value increases. The signal in the new MMBP will sharply decline when the lift-off value is larger than 0.01 mm. Traditional MFL sensors, such as Hall and coil sensors, usually operate at a lift-off value of 0.5 mm. However, this new MMBP for MFL can work on a micrometre scale. To improve the performance of this new MMBP, the theoretical results show that the lift-off value must be less than 0.01 mm. If the lift-off value of this new MMBP sensor is larger than 0.01 mm, the efficiency will sharply decline. To reduce the lift-off value, a series of tests are conducted.

3 Experimental Verification

3.1 Reducing the Lift-Off Value of the New MMBP by a Flexible Probe Mechanism

This new MMBP should operate at an extremely small lift-off value according to the FEM results. However, the lift-off value will change during the testing process. A challenge of this new MMBP is to avoid changing the lift-off values. A flexible probe mechanism is designed, as shown in Fig. 7, to decrease the lift-off value of the new MMBP in MFL testing. The new MMBP contains an elastomer linked with a flexible printed circuit (FPC) cable. The elastomer material is polyurethane rubber. Super glue is used to connect the new MMBP and the elastomer. The range of motion error of the new MMBP is approximately 0.5 mm, which is enough to account for the run-out tolerance of the sensor mechanism. The front surface of the shoe can closely fit on the surface of the specimen. The dimensions of the new MMBP are 3 mm*3 mm*3 mm (length*width*height), and its core width value, *dh*, is 1.5 mm. The new MMBP is not fixed on the shoe, and it can freely slide in the shoe. In the testing process, the elastomer will extend until the front surface of the new MMBP is in close contact with the tested specimen.

Table 1 Size of the new MMBP

hr (mm)	2*g* (μm)	*n*	*h* (mm)	*w* (mm)	*dh* (mm)	μ_r	material
0.5	10	200	2	2	1.5	6e5	1J50

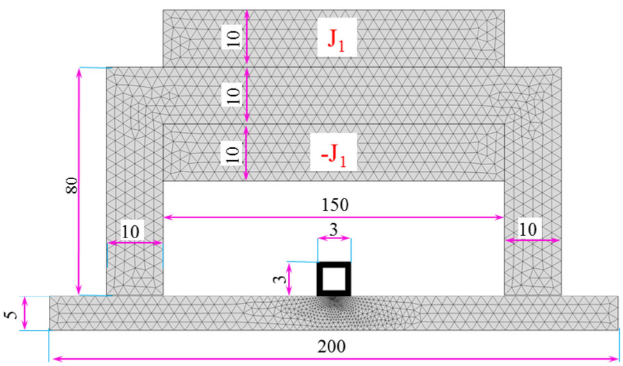

Fig. 5 2D FEM model of the new MMBP in MFL

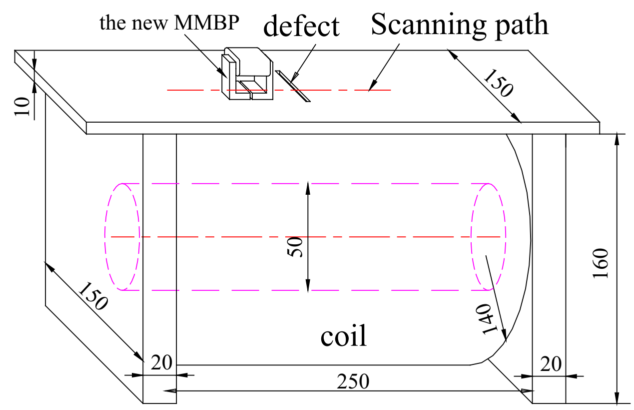

Fig. 8 The MFL experiment platform for the new MMBP

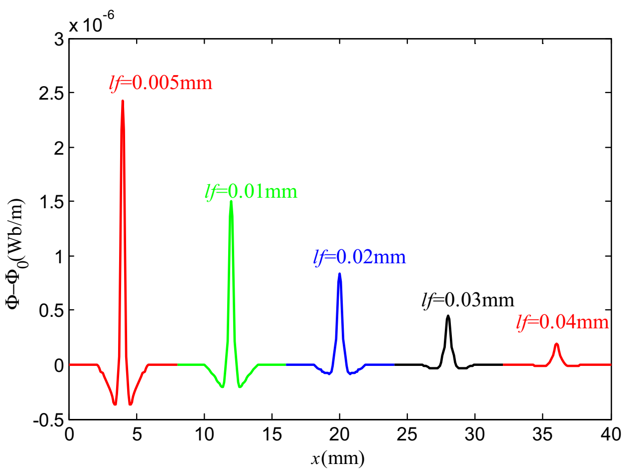

Fig. 6 Different curves for the new MMBP core at different lift-off values

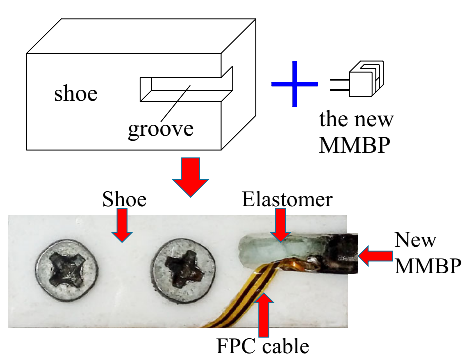

Fig. 7 A flexible probe mechanism

3.2 Detecting Micro-cracks at Different Lift-Off Values

Experiments are implemented to verify the theoretical results above. The testing system consists of a specimen, an amplifier circuit board, an AD card, and a power source to magnetize the coil. The sampling speed of the AD card is 10 K. The number of coil turns is 1600. In the experimental process, the current in the coil is 4A. A PC is used to obtain and store the testing data. The specimen material is Q235-A and its thickness is 10 mm. The detailed sizes of the magnetization, including the coil, are all shown in Fig. 8. A U-shaped magnetizer is used. Two yokes are connected by a rob with a diameter of 50 mm and the thickness of the yokes is 20 mm. The rob and yoke are both Q235-A. The defect is in the centre of the specimen, and its size is 0.1 mm*0.1 mm*20 mm (depth* width* length). The scanning direction of this new MMBP is parallel to the magnetic induction lines in the specimen. Three new MMBPs are utilized in this section with the same shape and size. The length of the new MMBPs is 1.5 mm, and the gap value is 10 μm. The first MMBP does not have any transparent adhesive tape. Two of the new MMBPs are covered with transparent adhesive tape with thicknesses of 20 and 40 μm. The MFL testing signals are shown in Fig. 9.

Figure 9a shows the MFL testing data obtained by this MMBP at a lift-off value of zero. Figure 9b shows the MFL testing data obtained by this MMBP when the lift-off value is 20 μm. Figure 9c shows the MFL testing data obtained by this MMBP when the lift-off value is 40 μm. If the lift-off value is zero, as shown in Fig. 9a, there are three signals as the MMBP scans the head over the defect three times.

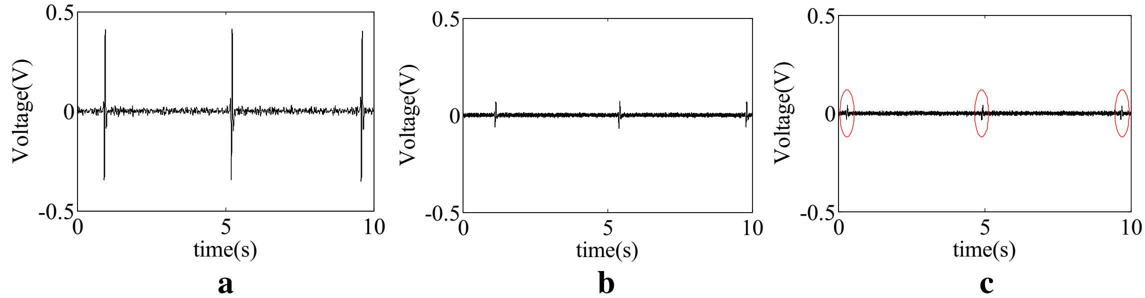

Fig. 9 MFL testing signals at three lift-off values: **a** lift-off value of zero, **b** lift-off value of 20 μm, and **c** lift-off value of 40 μm

The signal voltages in Fig. 9b are much weaker than those in Fig. 9a. There are three weak signals in Fig. 9c, i.e., the signal voltages in Fig. 9c are smaller than that in Fig. 9b.

4 Results and Discussion

4.1 Verification of the Lift-Off Effect on the New MMBP

The lift-off effect in the MFL shows that the magnetic leakage field will decline as the lift-off value increases. The same defect is more difficult to detect at a larger lift-off value. The lift-off effect in MFL is described as the change in the maximum value of the magnetic leakage field at the centre position of the defect as the lift-off value changes. If the sensor in the MFL testing system is a Hall sensor, the MFL signal voltage will decline in the lift-off curve of the magnetic leakage field. In contrast to the lift-off effect on the magnetic leakage field, the signal voltage of this new MMBP will sharply decline for a micro lift-off value. The lift-off effect curves of this new MMBP obtained from FEM and experiments are shown in Fig. 10. The lift-off curve of the new MMBP obtained by FEM is shown as a dotted line with stars, and the lift-off curve obtained by experiments is shown as a solid line with square markers. Experiments are conducted at lift-off values of 0, 20 μm and 40 μm. Therefore, the experimental curve has three points.

The magnetic leakage field is measured by Hall sensors and other magnetoresistive sensors when the lift-off values are larger than 0.5mm. Conventional lift-off effect are obtained by hall sensors are operated when the lift-off value is larger than 0.5mm. However, the MMBP must operate at a very small lift-off value both from experimental results and theoretical results. The Φ value in this new MMBP core will decline to 10% as the lift-off value changes from 0.01 mm to 0.04 mm, according to the FEM results. This change indicates that the lift-off effect is more prominent in this new MMBP in MFL, and a micro lift-off value is necessary to improve the testing capability of this new MMBP. The experimental results in Fig. 11 also show that the test signal voltage will sharply decline when the lift-off value is larger than 0.02 mm. To detect micro-cracks with a high efficiency, the flexible probe mechanism in Fig. 7 is a crucial component in the testing system for the new MMBP.

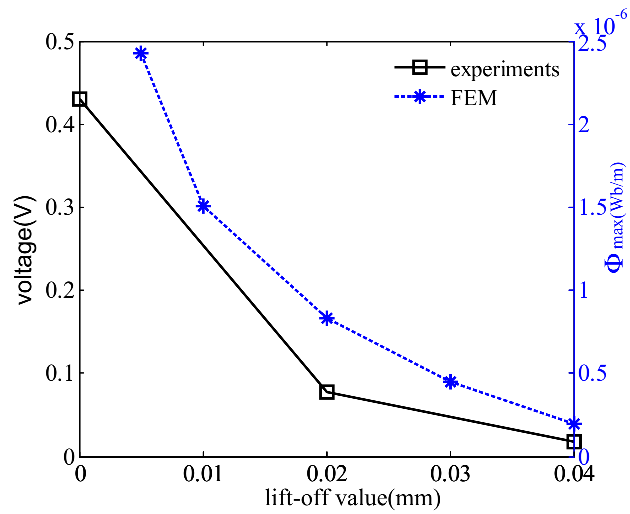

Fig. 10 Lift-off curves of this new MMBP from FEM and experiments

4.2 Application for Testing Grinding Micro-cracks in Bearing Rings

Micro-cracks cannot be detected when the roughness of the tested surface is large because the magnetic leakage field caused by the defect is weaker than that caused by the rough surface. In contrast to other MFL sensors used in pipe lines and wire ropes, this new MMBP should perform well for a grinding surface and can be used to detect micro-cracks in bearing rings. Bearing rings have small run-out errors and surface roughnesses, and most bearing ring cracks are grinding cracks.

Firstly, the run-out error of bearing rings will cause the lift-off value to change. However, the change due to the run-out error is less than the sliding displacement of this new

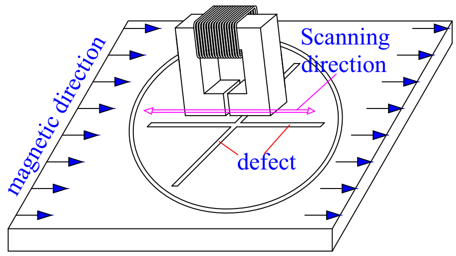

Fig. 11 Magnetic line and scanning direction of the new MMBP

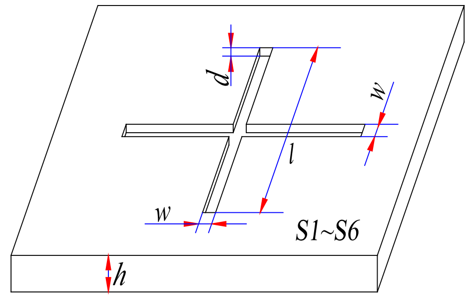

Fig. 12 Defects in the MPI sensitivity testing piece

MMBP, as shown in Fig. 7. This new MMBP can always closely touch the test surface of the bearing rings, and the lift-off values of this new MMBP are always zero.

Secondly, the tested surface should be smooth so the magnetic leakage field caused by micro-cracks is stronger than that caused by the rough surface. In other words, the tested surface requires grinding. All bearing ring surfaces are grinding surfaces. The surface roughness (Ra) of bearing rings is usually less than 0.8 μm.

Thirdly, the directions of the grinding cracks are basically consistent and they are normal and near the normal grinding direction lines. The angles between the grinding cracks and bearing rings are usually less than 5°. Most grinding cracks in bearing rings are 0.03−0.15 mm deep. Thus, the angle between the gap of this new MMBP and the grinding micro-cracks is small. The testing signals caused by the inconsistent distance between the gap and defects have little influence on testing grinding micro-cracks in bearing rings.

Some clear disadvantages of this MMBP presented here are its testing direction and low testing lift-off value. In other words, it is very difficult for MMBP to detect unspecified defects with variable orientations. This MMBP is also difficult to detect cracks in rough surface like hot rolled steel pipe. It's hard to detect cracks in wire rope for the lift-off value is so large.

5 Detection of Micro-cracks in MPI Specimens by the New MMBP

According to the MFL lift-off effect, the sensor will get more energy from the magnetic leakage field in the presence of a defect than other magnetic sensors. As a result, the new MMBP can detect smaller defects in MFL testing. In this section, experiments are conducted to verify the high sensitivity of the new MMBP in an MFL testing system.MPI is a widely used NDT method with a high sensitivity. Micro-cracks in MPI standard sensitivity gauges according to ASME SE-709 can be used to examine the MPI sensitivity. These sensitivity gauges can also be utilized to examine the sensitivity level of the new MMBP in this paper by MFL testing. The scanning path of the new MMBP is shown in Fig. 11.

Six MPI sensitivity pieces and the micro-cracks in these pieces are shown in Fig. 12. The largest crack in these gauges has a depth of 60 μm, and the smallest crack has a depth of 7 μm. The sizes of the MPI standard sensitivity pieces and defects are shown in Table 2. The experimental platform is the same as that presented in Sect. 3.2. The specimen with a thickness of 10 mm does not have any defects in the above section, but an MPI sensitivity piece with defects was attached to its surface with the defects facing outward. The magnetic flux lines are perpendicular to the defect and the gap is normal to the defect, as seen in Fig. 11. In the testing process, the scanning path is parallel to the defect. The detection data is obtained by a computer as the probe is moved across the defect. The testing signals are shown in Fig. 13 below.

All the defects in the MPI sensitivity gauges are detected by the new MMBP during MFL testing. The signal voltage declines as the defects decrease. The maximum signal voltage appears when the defect has 60 μm depth in the piece of 100 μm thickness. However, the signal voltage named S6 is only 0.05 V, and the SNR is only 2.3 dB. In this section, experiments are conducted to examine the testing capability of the new MMBP. All micro-defects in the MPI sensitivity pieces are detected, even the smallest defect with a depth of 7 μm. These defects are designed to examine the sensitivity of MPI techniques. However, this paper designed a new MMBP sensor to detect these defects. This new MMBP can automatically detect these defects.

6 Conclusions

In this paper, a new high-sensitivity MMBP for MFL is proposed. This new MMBP consists of a micro-testing magnetic bridge and sensor coil. The testing magnetic bridge is composed of a narrow gap in a hollow, rectangular testing core. The working mechanism of this sensor is studied by FEM. In contrast to the magnetic leakage field lift-off effect, a new lift-off effect curve is observed, which indicates the new MMBP must closely touch the testing surface during the testing process. This new MMBP has an excellent performance and high sensitivity for the detection of micro-cracks. The results of this paper are shown below.

Table 2 MPI standard gauges and defects

		S1	S2	S3	S4	S5	S6
Defect length (mm)	l	6					
Defect width (μm)	w	60–80					
Specimen thickness (μm)	h	100 ± 10			50 ± 5		
Defect depth (μm)	d	60 ± 8	30 ± 4	15 ± 2	30 ± 4	15 ± 2	7 ± 1

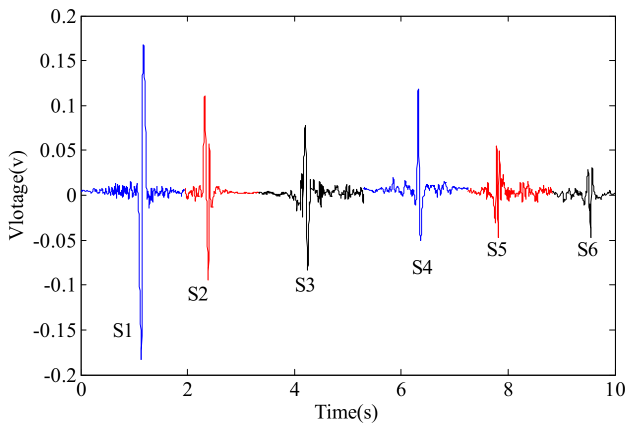

Fig. 13 MFL testing signals for micro-cracks in the MPI sensitivity pieces

(1) An MMBP is proposed for MFL. A new MMBP with a higher spatial resolution and high sensitivity is also proposed.
(2) The lift-off effect of this novel MMBP is revealed, and it shows this probe should operate at micro-lift-off values different from Hall and other magnetoresistive sensor which can work at larger lift-off values than 0.5mm.
(3) The MMBP has an excellent performance in detecting grinding micro-cracks in bearing rings.
(4) This new MMBP substantially improves the testing capability of MFL. A micro-crack in an MPI sensitivity piece with a depth of 7 μm is detected. This new MMBP provides the highest testing capability for MFL so far.

This MMBP is a novel magnetic probe that can be used to test micro-cracks. It improves the testing capability of MFL to the micrometre scale. This is of great importance, and the MMBP can be widely used to detect cracks on the micrometre scale.

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