Electromagnetic Non-Destructive Evaluation (XXI)
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A New MFL Testing Sensor Based on Localized Magnetization for Micro Crack Detection

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Abstract: Magnetic flux leakage (MFL) testing method has been used in defect detecting for decades. However, the capability of micro defect inspection mainly depends on the characterization of the sensor. This paper proposes a new MFL testing sensor based on localized magnetization for micro defect detection, which can detect micro crack with high sensitivity and accuracy. Preliminary introduction for the structures and working principles are presented. By the subsequent comparison of simulations and experiments between common MFL method and the new MFL sensor, we can conclude that this sensor possesses the capability of micro defect inspection. Finally, both the simulation results and the detection signals in the experiments demonstrated its feasibility and practicality.

Keywords: MFL, Sensor, Localized magnetization, Micro crack

1. Introduction

Magnetic flux leakage (MFL) testing method has been widely used in the field of nondestructive testing (NDT). As one of the most prevalent defect detection techniques, large amount of studies have been reported since the MFL method was proposed the first time. Likewise, surface quality of a part is also the vital factor for its effective operation and lifetime especially in the precision engineering of machining and manufacturing where the surface characterizations are usually influenced by the mechanical actions and thermal features. Therefore, precise inspection is of great significance to ensure safety and manufacturing efficiency. In other words, the detection precision or accuracy mainly depends on the characterizations of the inspection sensors. Although the traditional MFL testing sensors may be used for conventional defect detection [1, 2], most of them fail to inspect micro defect with a relative high sensitivity and accuracy. Such as the tri-axial sensor technology which was able to detect corrosion, mechanical defects proposed in [3], but incapable of local micro defect inspection. Despite the improvement of sensor system presented in [4] may increase the sensitivity of defect detection, the signals were very weak and the processing difficulty was enhanced as well. Additionally, researches of [5-8] have been occupied in the weak signal processing techniques when detecting

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micro defects, thus making the online micro defect inspection become more difficult and the inspection efficiency is thereafter decreased. Other methods such as barkhausen noise (BN) measurement in [9], which is mainly used in the measurement of corrective and residual magnetic field. However, the signal processing difficulty is also increased. Besides, the micro defect in the so called collinear wave mixing technique in the study of [10] resembles the common defect with bigger size, thus the detection feasibility for smaller micro defect cannot be well demonstrated. Ultrasound infrared thermography (UIRT) methods [11] may also be used in micro defect detection which has a merit to inspect a wider range in a short time with no contact with the target object, but the testing results often depend on the variable frequency, as well as the proposed enhanced acoustic emission detection method in [12]. The magnetic memory method [13, 14] is a NDT method that can detect the microscopic damage on the basis of the magneto striction and magneto elasticity effect. However, it couldn't avoid the influence of the residual stress and interference of other physical characterizations in the tested object. By the way, the E-shaped magnetic sensor or magnetic flaw detection apparatus in patent [15] maybe capable of improving the detection sensitivity while may still failed in micro defect inspection.

Therefore, a new MFL testing sensor based on local micro magnetization is proposed here. The sensor structures with tiny magnetic sensing bottom make the new sensor become more sensitive to micro defects. Consequently, the localized magnetization nondestructive evaluation method could provide significant information about the surface features of the tested object. The proposed micro defect detection method based on localized magnetization is introduced through a description of the sensor structures and principles. Then the experiments and comparisons results between the new MFL testing sensors and common MFL methods manifest that the new MFL testing sensor is predominant in micro crack detection. Finally, the detection accuracy and precision as well as the sensitivity are enhanced with a remarkable signal to noise ratio.

2. New sensor structures and principles

A new local micro magnetization sensor is introduced in this section. Specifically, the structures and principles are separately explained.

2.1. New sensor structures

The new sensor mainly consists of three modules, namely, MFL signal capture unit, magnetic sensing part and local micro magnetization module. As illustrated in Fig.1. The main components of the new proposed sensor are magneto-sensitive element, insulating sleeve, search coil, annular magnetic yoke, permanent magnets, magnetic guide core with high permeability and tiny sensing bottom, magnetic conducted object.

Concretely, the conical magnetic guide core of 3 or 10 with high magnetic permeability of 200 mH/m such as permalloy is connected with the magneto-sensitivity element of 2 such as hall element electrically. The height and diameter of the overall sensor are about 20mm and 10 mm, respectively. The remanence of each permanent magnet is approximate to 1.12 T, and the coercivity and (BH)max are 780 kA/m and 223kJ/m.

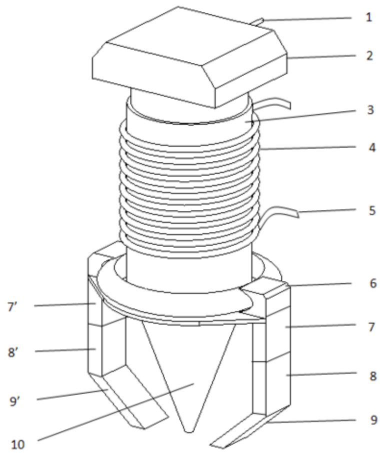

Figure 1. Structures and components of the new sensor;1. signal output end; 2. magneto-sensitive element, 3. insulating sleeve; 4. search coil; 5. output end of the coil; 6. annular magnetic yoke; 7. one pole of permanent magnet; 8. another pole of permanent magnet; 9. magnetic guide part with high permeability; 10. tiny sensing bottom of the magnetic guide core.

The insulating sleeve is used to isolate the guide core and the search coil which is made of copper enamelled wire. The diameter and electrical resistivity of the coil wire are about 0.1mm and 0.0172 Ω·m, and the number of turns could be 100 or more. Furthermore, the excitation sources of magnetic yoke of 6 and the permanent magnet of 7 (or 7’) and 8 (or 8’) are symmetrically assembled, as well as the magnetic guide parts of 9 and 9’.

2.2. Working principles

When detecting defect with the new proposed sensor, the schematic diagram is illustrated in Fig. 2 and as follows.

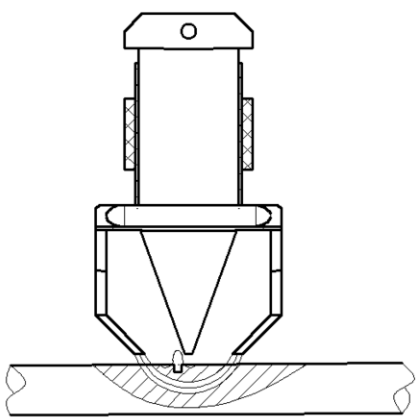

Figure 2. Working principles of the new sensor

As expressed in Fig. 2, the process of micro defect detection is briefly explained as follows. When the magnetic guide core is approaching or scanning the tested specimen in a certain speed, corresponding small region of the tested object under the bottom of the tiny end of the guide core will be locally magnetized. Therefore, if any discontinuity or defect is encountered, the MFL produced by the micro defect would be caught by the tiny bottom of guide core and picked up by the search coil or the magnetic-sensitive element. Then the MFL signals are generated by the search coil and the upper magneto-sensitive unit. After the signal data acquisition and the analog to digital converting as well as signal conditioning, the final output signals are obtained. Owing to that the magnetization region in the bottom of guide core is super small and could reach 0.01mm in radius, the magnetization area in the tested object is thereafter reduced and the magnetization field is focused as well. Thus, micro defect with a width or length of 0.1mm or smaller could be well detected. Finally, the local micro magnetization and defect detection are achieved. Additionally, the scanning speed of the sensor could be various and has an effect on the testing signals especially when the magnetic-sensitive element is the coil. According to the law of the electromagnetic induction, the signal amplitude is influenced by the gradient of the magnetic flux which is related to the scanning speed of the sensor. Generally, as the scanning speed of the sensor increases, the magnitudes of the three components of MFL signals are nonlinear monotone increasing and the increasing gradient of Bx and Bz is greater than By according to related researches [16, 17]. However, the scanning speed of the sensor is uninfluential to the detection signals when the magnetic-sensitive element is hall or other elements.

3. Comparison of simulations and experiments

To reveal the characterizations and advantages of the new proposed sensor further, comparisons by simulations and experiments were separately conducted as follows.

As one of the most frequently used NDT techniques, the MFL produced by the excitation of permanent magnet and magnetic yoke is expressed in Fig. 3, where the defect is 0.1×0.1mm in width and depth in the two dimensional (2-D) simulations. Observed by the color map of magnetic density of H, what could be noticed is that the maximum density is approximate to 691.89 (A/m).

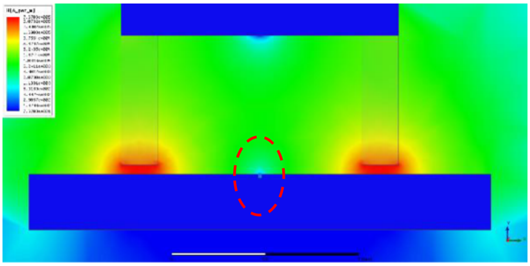

Figure 3. Simulation of the common MFL detecting method

Similarly, the MFL generated by the localized magnetization micro crack on the specimen model and corresponding magnetic density cloud chart are exhibited in Fig. 4. Obviously, the magnetic strength is relatively stronger compared with conventional magnetizing sources. According to the numerical simulations, the MFL strength of the defect could reach 1.51×10^4 (A/m) under the same circumstance conditions. Finally, the distinct MFL characterization indicates that the detection accuracy and sensitivity of micro defects are vastly improved by the proposed localized magnetization sensor, which has great potential in the future application in defect inspection of ferromagnetic materials and surface topography compared with the common MFL testing method.

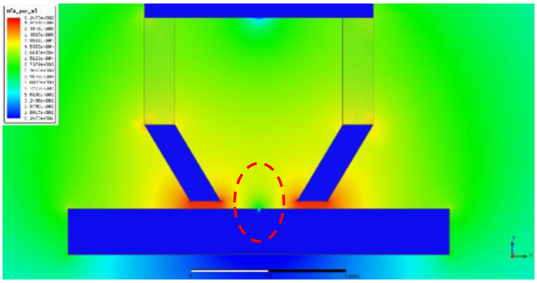

Figure 4. Simulation of the new MFL sensor

Besides, corresponding experiments by different micro cracks are also conducted. Specifically, the length, width and height of the specimen are 40mm, 10mm and 6mm, respectively. As for the dimensions of these defects, all the length × depth are 2mm × 0.1mm, while the widths are various from 0.05mm to 0.8 mm, namely, 0.05mm, 0.1mm, 0.3mm, 0.5mm and 0.8mm. the displacement of the sensor from the surface of the tested specimen is 0.1 to 2 mm.

The experiments results are obtained separately by the new proposed sensor and common MFL method which uses the typical and classical permanent magnetic yoke method and the hall element. When the specimen with defects are scanned by the two sensors, corresponding signals are acquired and, as shown in Fig.5 to Fig.9. Explanatorily, the signals are all acquired by the repeating scanning of the sensors in two opposite directions above the defect. Hence, there should be several signal peaks with different shapes when the defect is scanned or encountered iteratively. Additionally, owing to the differences in scanning speeds of the detection sensors, the signal peak values are also various.

When the defect is 0.8 mm in width and repeatedly scanned, the signals are expressed in Fig. 5 which are respectively acquired by the new sensor based on localized magnetization and the common MFL method for comparison purposes.

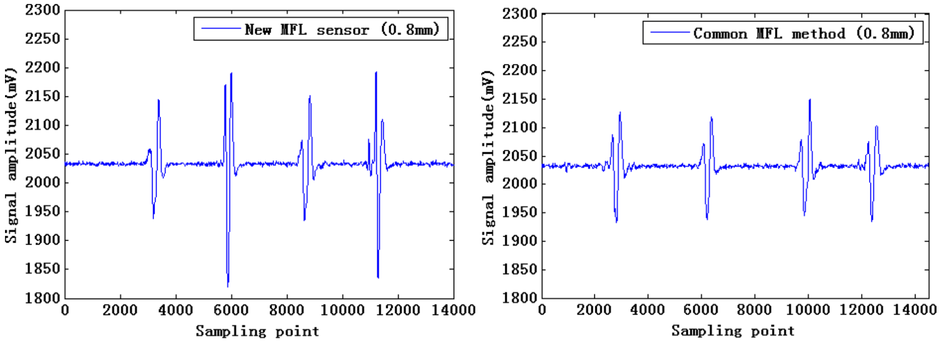

Figure 5. Experiment results of detection signals when the defect is 0.8mm in width

It's clear that the signals from the new sensor are stronger than that of the classical MFL method in amplitudes. What's more, owing to the electromagnetic induction effect, the signals from the search coil of the new sensor maybe further enhanced when the scanning speed is increased in a certain range. Similarly, when the defect with width of

0.5mm is encountered and detected by the scanning sensors, corresponding experiment results are presented in Fig. 6, as expressed below.

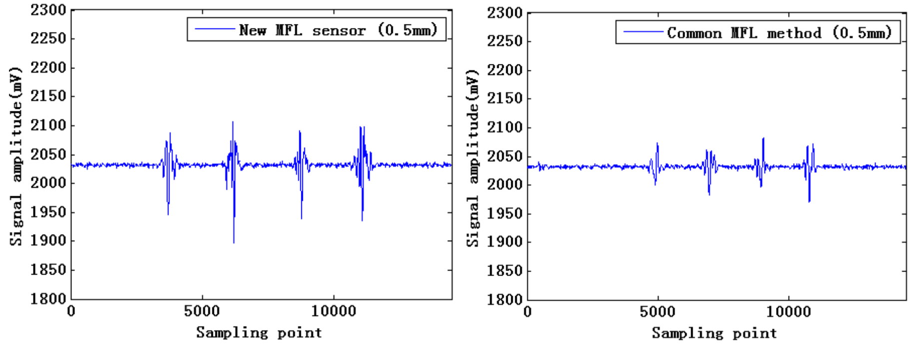

Figure 6. Experiment results of detection signals when the defect is 0.5mm in width

Observed by the signals from Fig. 6, we can draw the conclusion that even the signals are all decreased in amplitude compared with signals from Fig.5, signals of the new sensor are still stronger than that from the common MFL method. That further demonstrates the effectiveness and feasibility of the new method. By the same token, when the defect widths are 0.3mm, 0.1mm and 0.05mm, the experiment results of the comparison between the new sensor and the classical MFL method are separately shown in Fig. 7 to Fig. 9.

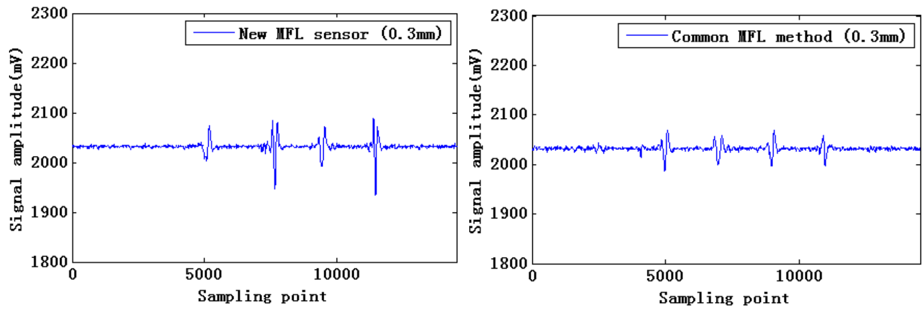

Figure 7. Experiment results of detection signals when the defect is 0.3mm in width

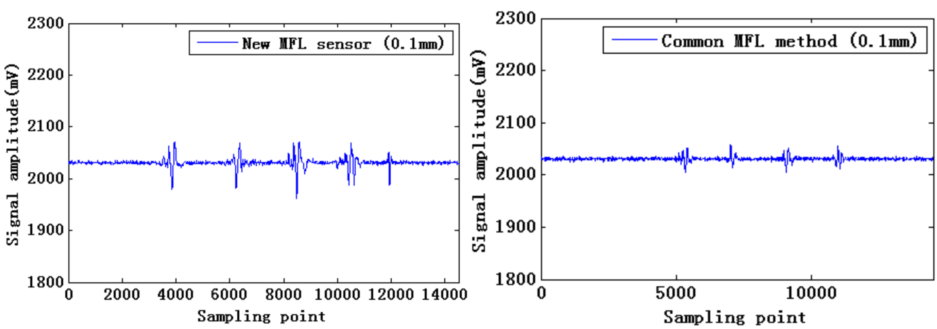

Figure 8. Experiment results of detection signals when the defect is 0.1mm in width

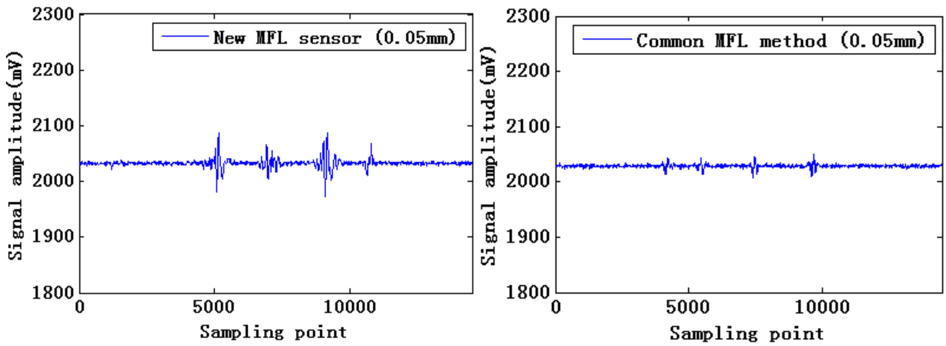

Figure 9. Experiment results of detection signals when the defect is 0.05mm in width

From the experiment results of signal waveforms presented above, we can find that although the signals are decreased slowly in amplitude as the defect width becomes smaller, the signals from the new sensor are always bigger than that from the common MFL method, especially when the defect is as small as 0.05mm in width. Particularly, the sensitivity of the new sensor for the crack width detection could reach 300 mV/mm while the old common MFL sensor is approximate to 100 mV/mm. Consequently, the experiment results not only manifest that the capability of defect detection for the new sensor is more advantageous than the latter, but also demonstrate that the new testing sensor based on local micro magnetization possesses better characterization in micro defect inspection. As the processing and manufacturing technology progresses, the detection precision could be further improved in the future.

4. Conclusion and discussion

As the MFL testing methods further developed, the requirement for micro defect detection is needed and it is necessary especially in the precision engineering of machining and manufacturing. Therefore, this paper proposed a new MFL testing sensor based on localized magnetization. Furthermore, the subsequent simulations and experiments both demonstrated the advantageous of the localized magnetization method based on the new sensor compared with the classical MFL method. Finally, we can draw a preliminary conclusion that the new sensor is more effective in defect detection and possesses a better micro crack inspection capability, which is of great significance and promise to the future practical application.

However, some factors such as the motion effect of the new sensor, the difference with the field obtained in the absence of a defect, the sensitivity of the receiver device as a function of the amplitude, as well as the orientation of the field may influence the inspection results. Therefore, the new MFL sensor is more suitable in detecting the surface of a part in precision engineering. Naturally, a relative better inspection circumstance could be guaranteed.

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