Academic Journal of Engineering and Technology Science
ISSN 2616-5667 Vol.2, Issue 5: 57-66, DOI: 10.25236/AJETS.2019.020507

Finite Element Simulation and Experimental Research of Magnetic Flux Leakage Testing Based on Single Permanent Magnet Magnetization

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ABSTRACT. *About the magnetic flux leakage testing technology for the defect in steel storage tanks, in this research, a new method of constructing magnetization system by using cubic single permanent magnet was proposed. Using ANSOFT MAXSWELL finite element software, the influence law of permanent magnet size on magnetization effect and the magnetic induction intensity at different positions in space were investigated. A magnetic flux leakage (MFL) testing system was specially built up, based on which testing performance of the MFL system for the artificial circular-hole and rectangle deflects was evaluated. The testing results show that the method, with respect to constructing the magnetization system relying on the single permanent magnet, is feasible and effective, laying a foundation for the future research on geometrical morphology evaluation for the defect. Compared with the traditional magnetization system constituted by double permanent magnets, the newly proposed method possesses a better design flexibility and a lower cost, showing a good application prospect.*

KEYWORDS: *steel material, magnetic flux leakage testing, single permanent magnet magnetization system*

1. Introduction

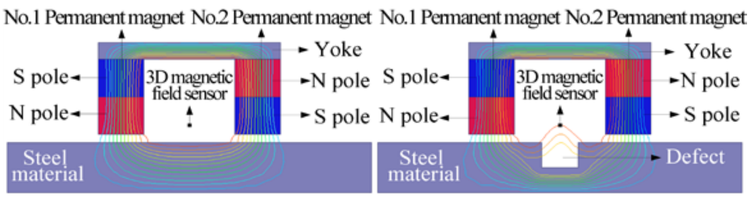
Steel materials are widely used in petroleum, chemical and metallurgical industries. During the use of steel materials, pits or cracks will occur due to corrosion or external force, which is easy to cause safety accidents. Therefore, it is very necessary to carry out nondestructive testing on steel materials regularly [1]. At present, non-destructive testing for steel materials mainly includes ultrasonic testing [2], magnetic particle testing [3], penetration testing [4] and magnetic flux leakage testing [5], among which magnetic flux leakage testing has the advantages of fast testing speed, high sensitivity and the like, and is most widely used in non-destructive testing of steel materials [6].

The advantages and disadvantages of magnetization system will directly affect the size and accuracy of magnetic flux leakage signals, which has always been a hot topic in the application of magnetic flux leakage detection technology. For example, Shi Han used analytical method and numerical method to establish a mathematical model to analyze the influence of permanent magnet height, area and medium on excitation effect [7]. Song used finite element method to analyze the influence of the distance and size of permanent magnets on the magnetization effect of steel plate, and established an optimal design method of magnetization system [8]. Katoh investigated the influence of air gap between permanent magnet and steel specimen and specimen thickness on leakage magnetic field by finite element method [9]. Park used Maxwell's equations to solve the optimal size of the magnet [10]. Wang combined theoretical analysis and finite element method to analyze the influence of magnetization system moving speed on magnetic flux leakage detection effect [11].

This paper proposed a method of constructing magnetization system by using single permanent magnet, and built a magnetic flux leakage signal detection system. Simulation analysis and experimental tests proved the feasibility and effectiveness of the single permanent magnet magnetization system.

2. Single Permanent Magnet Magnetization System

Figure.1 shows a typical structure of a permanent magnet magnetization system widely used in magnetic flux leakage detection of steel plate defects. It is constructed into an "n" shape by two permanent magnets and yoke. When there are no defects on the surface of the steel material, due to the different permeability of air and the steel material, the magnetic lines of force are bound inside the steel material and the direction is parallel to the surface of the steel material, and there is no magnetic induction line distribution near the measuring point at this time; When a defect occurs on the surface of the steel plate, a leakage magnetic field occurs in the three-dimensional space above the defect due to the reduction of the flow area of the internal magnetic induction line of the steel plate with high permeability.



(a) Magnetic field lines without defects (b) Magnetic field lines with defects

Figure. 1 Typical structure of permanent magnet magnetization system

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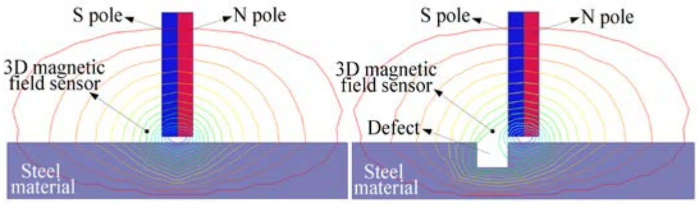
In the new simplified magnetization system, the magnetic pole of the single permanent magnet is perpendicular to the surface of the steel material to be tested, and the yoke is omitted at the same time. As shown in Figure.2, when there is no defect on the surface of the steel material to be tested, the permanent magnet excites a magnetic field in the air, and a nearly constant magnetic field can be detected near the measuring point (this is different from the traditional magnetization system); When there is a defect near the magnetic induction intensity test point, the distribution of magnetic induction lines above the defect is significantly affected, thus changing the magnetic induction intensity near the test point. Using this phenomenon, it is expected to realize defect detection.



(a) Magnetic Field Lines without Defects (b) Magnetic Field Lines with Defects

Figure. 2 Simulation of single magnet magnetization system

Magnetic flux leakage testing does not pay attention to all the magnetic fields in space. The main measurement and concern is the leakage magnetic field on the surface of the steel material to be measured. Therefore, the surface of steel to be measured is taken as the research object. The magnetic induction intensity distribution diagram of the plane is drawn, as shown in Figure.3, which shows the magnetic induction intensity distribution of the plane when there is no defect, and Figure.3 (b) shows the magnetic induction intensity distribution of the plane when there is a defect. It can be seen in the diagram that when there is a defect on the surface of the steel material, the magnetic induction intensity near the defect obviously changes.

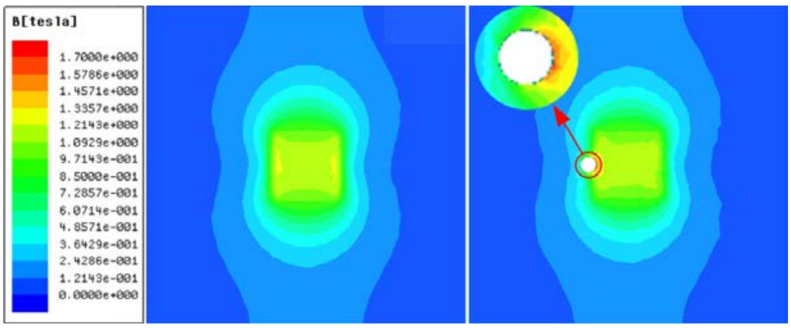


Figure. 3 Distribution diagram of magnetic field intensity on the surface of steel material to be measured

In order to investigate the feasibility and effectiveness of the method, further research was carried out around the size of permanent magnet, the selection of measuring point position, magnetization and the construction of detection system.

3. Size of Permanent Magnet and Selection of Sensor Measurement Position

3.1 Determination of permanent magnet dimensions

Using magnetic flux leakage detection technology to realize corrosion defect detection of steel materials requires magnetization of steel materials near defect pits. The closer the magnetization degree of the steel material in the area near the pit defect is to saturation, the better the magnetic flux leakage detection effect will be. The carbon structural steel plate (Q235) with a thickness of 10mm was selected as the research object. According to the "Manual for Quick Check of Magnetic Characteristic Curves of Common Steel", the magnetic induction intensity required for carbon structural steel to reach the near saturation magnetization state is about 1.7T. Generally, the magnetic induction intensity of near saturation magnetization should be 80% of the magnetic induction intensity of saturation magnetization, i.e. the magnetic induction intensity value is 1.36 T.

In the traditional double magnet magnetization system, the magnetic field generated inside the magnetized steel plate is close to the uniform magnetic field [12], so when determining the permanent magnet size of such a system, it is only necessary to ensure that the magnetic induction intensity at any point in the magnetization scope is close to the near saturation magnetization intensity. The simulation results shown in Figure.2 show that the magnetic field generated by the single magnet magnetization system proposed in this paper is non-uniform in the magnetization scope, and the further away from the magnet, the worse the magnetization effect. In order to investigate the influence of the geometric size of a single permanent magnet on the magnetization effect, this paper defined a 20 mm 20 mm 10mm magnetization effect detection area under the permanent magnet. Moreover, the initial length, width and height of the permanent magnet are all set to 40 mm. As shown in Figure.4, it can be clearly seen that the position of the minimum magnetic induction intensity in the detection domain is the vertex of the four corners below the cube detection region, and the magnetic induction intensity values are basically the same. The vertex D located in the first quadrant (its coordinates are (10, 10,-10)) is taken as the research object. If the magnetic induction intensity at this point is greater than 1.36 T, the magnetic field detection domain can be ensured to be near saturation magnetization, and then the relevant size parameters of a single permanent magnet can be determined.

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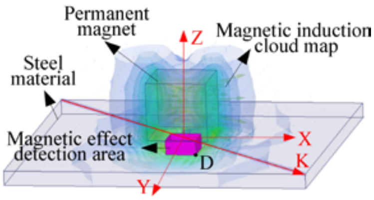

Figure. 4 3D Simulation of single magnet magnetization system

A new coordinate axis K is established at the bisector of the angle of ∠XOY. Its positive direction is the first quadrant of XY plane. By simulating the K coordinate axis and its magnetic induction intensity at different depths, it can be verified whether point D above is the lowest point of magnetic induction intensity in the magnetization effect detection domain. The result is shown in Figure.5 which can be seen that point D is the lowest point of magnetic induction intensity at different depths.

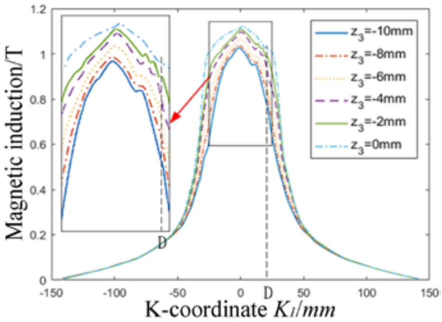

Figure. 5 Magnetic flux density at different positions of steel plate

Therefore, the influence of the length, width and higher parameters of the cubic permanent magnet on the point D magnetization effect is further investigated. The specific method is as follows: Keep the lift-off value of permanent magnet and any two size parameters unchanged, adjust the other geometric parameter, and investigate the magnetization effect of point D at the same time. The analysis results are shown in Figure.6. When the length a of the permanent magnet gradually increases from 40 mm to 100 mm in Figure.6 (a), the magnetic induction intensity at point D increases approximately linearly from 0.88 T to 1.32 T, indicating that the length a of the permanent magnet has a significant influence on the magnetization effect. Figure.6 (b) shows that when the width w of the permanent magnet gradually increases from 40 mm to 100 mm, the magnetic induction intensity at point D reaches the maximum when the width w of the permanent magnet is about 65 mm, but the influence of the width of the magnet on the magnetization effect is limited. Figure.6 (c) shows that when the height h of the permanent magnet gradually

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increases from 40 mm to 100 mm, the magnetic induction intensity at point D increases approximately linearly from 0.88 T to 1.09 T, indicating that the influence of the height of the permanent magnet on the magnetization effect of point D is also not very significant. Figure.6 (d) shows that when the lift-off value Z1 of the permanent magnet increases from 0 mm to 12 mm, the magnetic induction intensity decreases from 0.98 T to 0.5 T, indicating that the lift-off value has a very significant influence on the magnetization effect.

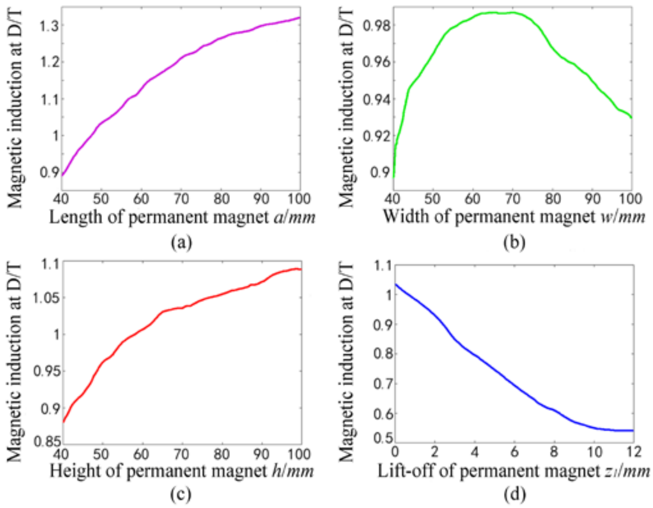

Figure. 6 Influence of size and position of permanent magnet on magnetic flux density

In conclusion, the length and lift-off value of the permanent magnet have a very significant influence on the magnetization effect, but the height and width of the permanent magnet have a limited influence on the magnetization effect. Therefore, when selecting the size of the permanent magnet, its length and lift-off value are the main factors to be considered, while the width and height consider the processing and installation factors of the permanent magnet more. Based on the above analysis, the length of the permanent magnet is 80 mm, the width is 40 mm, the thickness is 60 mm, and the lift-off value is 2 mm. ANSYS Maxwell simulation analysis results show that the magnetic induction intensity corresponding to point D is 1.51 T, which indicates that the permanent magnet of this size can make the magnetic field detection domain of the set steel plate reach near saturation magnetization.

3.2 Selection of measuring position

Due to the uneven distribution of magnetic induction intensity in the space of the detection area in the single permanent magnet magnetization system, in order to make the sensor have good magnetic flux leakage detection effect, it is necessary to

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analyze the magnetic induction intensity in the space above the magnetization area of the steel plate to be detected to determine the best sensor installation point.

In the magnetization effect detection domain shown in Figure.3, the magnetic induction intensity at different positions is analyzed by simulation, and the analysis results are shown in Figure.7. Looking at Figure.7(a), it is found that the maximum magnetic induction intensity appears at the edge of the permanent magnet along the X-axis direction, indicating that the magnetic flux leakage detection sensor should be as close to the permanent magnet as possible in the X-axis direction; Figure.7(b) shows the distribution of magnetic induction intensity at different positions along the Y-axis direction. Observation shows that the magnetic induction intensity is basically the same within the width range of the permanent magnet, and the magnetic induction intensity is significantly reduced beyond the width range of the permanent magnet, indicating that the sensor should be set within the scope of the width direction of the permanent magnet. Figure.7(c) shows the change curve of magnetic induction intensity along the Z-axis direction. Observation shows that the magnetic induction intensity reaches the maximum value at the Z-axis coordinate of 2 mm, indicating that this height is the best height for setting the sensor, that is, setting the sensor lift-off value to 2 mm. Therefore, the position coordinates of the sensor are finally determined to be (22mm, 0mm, 2mm).

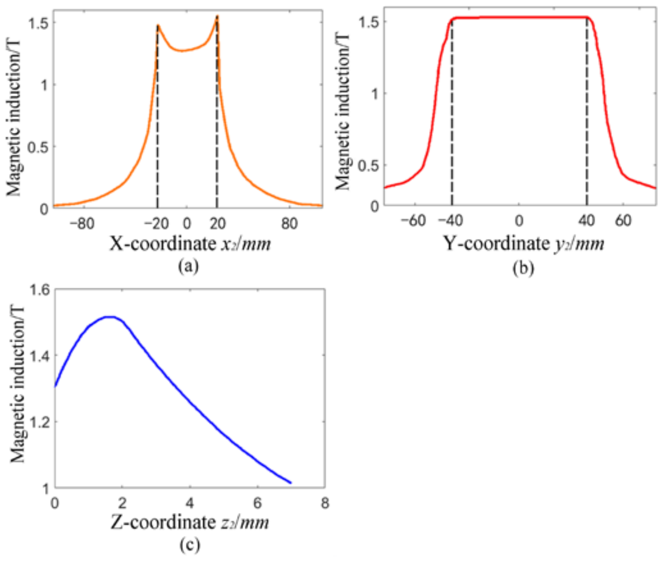

Figure. 7 Magnetic flux density at different locations

4. Actual measurement

In order to verify the feasibility and measurement effect of the proposed magnetization system, an experimental platform for magnetization system is built

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based on single permanent magnet magnetization mode as shown in Figure.8. This experimental system includes master computer for displaying and processing magnetic leakage signals, magnetic & sensing system for detecting magnetic leakage signals and traction system for pulling magnetic & sensing system.

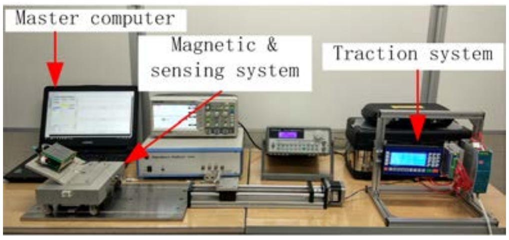

Figure. 8 Experimental system

A series of artificial defects are processed on carbon structural steel plates with a thickness of 10mm by numerical control machine tools. Two groups of representative defects are selected and analyzed as follows:

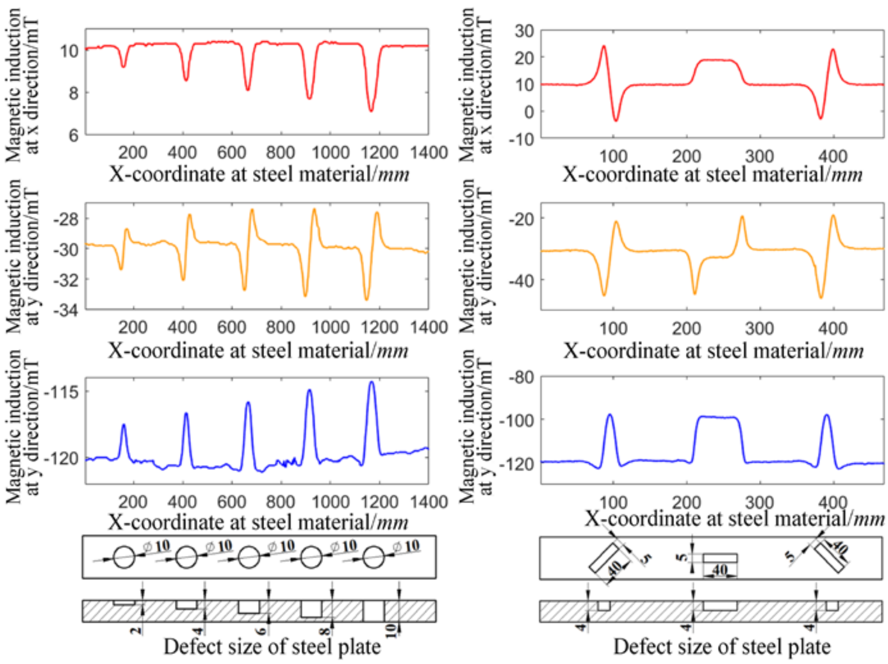

Figure. 9 3D magnetic induction intensity signal of defects

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Figure.9(a) is the actual signal of the detected circular hole defect, which corresponds to the dimensions of the defect from left to right (length * width * depth in mm) of 10*10*2, 10*10*4, 10*10*6, 10*10*8, 10*10*10. Analysis of the detection signals shows that with the increasing depth of the defect, the detection signals increase continuously, and there is a strong correlation between the defect and the detection signals. The detection signal proves that the single magnet magnetization method is feasible in practical application, and the circular hole magnetic flux leakage signal can be detected and its depth can be distinguished in actual operation.

Figure.9(b) is the actual signal of the detected rectangular defect, which corresponds to the left-to-right dimension of the defect (length * width * depth in mm) of 20*5*4 with angles of -45°, 90° and 45° respectively. Analyzing the detection signals, it can be seen that the X-direction magnetic induction intensity of rectangular hole defect is obviously different from that of circular hole defect, and the angle of rectangular hole defect will also significantly affect the magnetic flux leakage signal.

Through the preliminary analysis of the above two defects, the feasibility and effectiveness of the single magnet magnetization method proposed in this paper in practical application can be verified.

5. Conclusion

A method of magnetic flux leakage (MFL) detection of steel material defects using a single permanent magnet system is presented. Using ANSOFT MAXSWELL finite element software, the influence law of permanent magnet size on magnetization effect and the magnetic induction intensity at different positions in space were investigated. The results show that the final permanent magnet is 80 mm in length, 40 mm in width, 60 mm in thickness, 2 mm in lift-off value, and the position coordinates of the sensor are (22mm, 0mm, 2mm). The experimental system of magnetic flux leakage (MFL) is built, and the circular hole and rectangular artificial defects are tested systematically. The analysis results of MFL signal characteristics show that the magnetization system constructed by single permanent magnet is feasible and effective, which lays a research foundation for the geometric morphology evaluation of defects. Compared with the traditional scheme of constructing magnetization system with double permanent magnets, single permanent magnet has better design flexibility, better cost advantage and good application prospect.

Acknowledgments

Fund Project: Tianjin Enterprise Science and Technology Special Commissioner Project (19JCTPJC50500)

ISSN 2616-5667 Vol.2, Issue 5: 57-66, DOI: 10.25236/AJETS.2019.020507

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