



Remanent magnetization of steel plates after being magnetized by moving magnets

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ABSTRACT

Inconsistent initial magnetization of ferromagnetic specimens may result in low signal-to-noise ratio and poor consistency in detecting defects and stress anomalies of magnetic methods. One of the solutions to the problem is to magnetize specimen in advance and make it magnetized uniformly. Via theoretical analysis, finite element simulation and experiment verification, the distribution of remanent magnetization and remanent flux density of steel plates after being magnetized by moving single and dual magnets is studied. The results show that the remanent magnetization of the steel plate becomes uniform and in the same tangential direction of the magnet moving. The remanent magnetization inside the steel plate is layered, and the magnetization between different layers may be opposite. However, the magnetization of each layer is uniform, and the tangential remanent magnetization is large, while the normal remanent magnetization is small. The longer the length of the steel plate specimen, the longer the flat area of the magnetic flux density near the surface after magnetization, and the value of the flat area is closer to zero. The research results provide important guidance for the magnetization method and the defect detection scheme design.

1. Introduction

Magnetic detection is widely used in ferromagnetic specimens, which can detect the stress, defect, deformation and crack of ferromagnetic specimens [1,2]. However, ferromagnetic specimens have inconsistent initial magnetization, and it is difficult for different specimens to obtain consistent magnetic characteristics change laws [3,4], resulting in low signal-to-noise ratio and poor consistency of detection signal. Therefore, it is necessary to enhance the sensitivity and consistency of the magnetic anomaly signal by applying uniform magnetization to the specimen [5,6].

Strong magnetization can form a relatively stable distribution of residual magnetization inside the tested specimens by enhancing the external excitation magnetic field, effectively overcoming the randomness of the initial magnetization state in magnetic detection [5,6], which is one of the key technologies of magnetic nondestructive testing. The magnetization methods mainly include coil magnetization and permanent magnet magnetization. Coil magnetization method needs to be equipped with power supply and magnetic induction intensity control

device, which has high power consumption and cost [7,8]. With simple structure, zero power consumption and low cost, permanent magnet can be used to build a strong adaptive magnetization system [9]. Therefore, permanent magnet magnetization is more widely used.

At present, the structures of permanent magnet magnetization devices employ single and dual magnets for flat-shaped specimens and ring magnets for rod-shaped or tubular specimens [9,10,11]. The structure design of the magnetizing device mainly considers the shape of the specimen and the magnetization effect.

The magnetization state inside the specimen, namely the magnetization effect, determines the characteristics and intensity of the magnetic anomaly signal. Therefore, the distribution of magnetization intensity is an important concern of magnetization methods. The magnetization state can be divided into static magnetization and dynamic remanent magnetization according to whether the magnetization action is complete. Static magnetization refers to the distribution of magnetization intensity when the specimen is being magnetized, the magnetizing device and the specimen is relative static. Dynamic magnetization refers to the distribution of the residual magnetization of

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the specimen after the magnetization device has moved over on the surface of the specimen.

In the aspect of static magnetization, many scholars have studied deeply with the aim to establish the relationship between magnetization and defect signal, and put forward the method to improve the amplitude and uniformity of magnetization. In literature [9], a single magnet was used to magnetize steel specimens, and the point farthest from the origin of coordinates in the detection area was selected as the magnetic induction intensity measurement point. By adjusting the length, width, height and lifting parameters of the magnet, the magnetic induction intensity of the measuring point reaches the maximum, then the magnetization effect is the strongest. Using the strongest magnetization state to detect the defects of the specimen, the prediction model of the geometrical parameters of defects is more accurate. In literature [11], in order to improve the amplitude and uniformity of magnetization field, the magnetization structure of permanent magnet was designed, and the relationship among the angle between the poles, the magnetization uniformity and the surface magnetic field was discussed. In literature [12], parameters such as the number of magnets in each pole of the magnetizer, the distance between the poles and the lift value were changed to affect the magnetization of the specimen, and the state of the magnetization was divided into saturated magnetization and unsaturated magnetization, so as to obtain the corresponding defect signal function. Because the position of the magnetizing device and the sensing part is fixed in static magnetization, the two parts move synchronously, so the magnetic signal is the result when the specimen is magnetized. Therefore, the influence of magnetization velocity and direction on defect signal detection was pointed out in literature [13,14]. First of all, the larger the moving speed of the magnetization detection device, the shorter the effective magnetization time, the greater the magnetic aftereffect, and the worse the defect detection effect [13]. Second, under different propulsion modes, magnetization direction is different for the characteristics and normalization judgment of transverse and longitudinal damage detection signals [14]. It can be seen that different magnetization states caused by different moving speeds and directions of the magnetizing device in static magnetization have a great influence on the effective detection and quantification of defects.

Compared with static magnetization, dynamic magnetization has a more stable remanent magnetization state and does not need to consider the effects of magnetization velocity and direction, which is a more potential magnetization method. However, there are few relevant researches. Literature [15] proposed a non-destructive detection method of incremental permeability based on moving magnetization of permanent magnets. The bias magnetic field is formed by permanent magnet, and the sample is magnetized aperiodic by moving the permanent magnet in one direction. The relationship between the characteristic value and yield strength was established by using the change of incremental permeability, and a good detection effect was obtained in the yield strength detection of steel plate samples.

In this paper, based on the theory of hysteresis magnetization, the magnetic magnetization effects of single and dual magnets on steel plates is analyzed. Finite element simulation (FEM) model of static magnetization of steel plates is established, the magnetization distribution of steel plates below magnets is analyzed, and the remanent magnetization state of steel plate after being magnetized with moving magnets is predicted. FEM model of moving magnetization of steel plates by single and dual magnets is established, and the residual magnetization of steel plates with different lengths and the magnetic flux densities near the surface are obtained. Finally, a series of magnetization and magnetic measurement experiments are conducted to verify the correctness of the simulation results of the remanent magnetization distributions of steel plates with different lengths when single and dual magnets are used as magnetization devices.

2. Theoretical analysis

2.1. Magnetization process

When the external magnetic field H acts on the ferromagnetic specimen, the magnetization M of the specimen changes as the external field changes. The magnetization of the specimen can be obtained iteratively from the initial magnetization state and the changes of the external field as Eq(1).

$$M_{n+1} = M_n + \Delta h \cdot f(H_n, M_n) \tag{1}$$

Wherein, the magnetization function.

$f(H_n, M_n) = \frac{dM}{dH} \Delta h = H_{n+1} - H_n, n = 1, 2, 3...$ is the change of the external magnetic field from time n to time $n + 1$. When the external field gradually decreases, $\Delta h < 0$; when the external field gradually increases, $\Delta h > 0$. Therefore, if the external field change and magnetization function are known, the magnetization intensity at time $n + 1$ can be obtained iteratively by Eq (1).

2.2. Hysteresis magnetization function

Magnetic domain recombination occurs in ferromagnetic materials under the action of externally applied magnetic field, and the magnetization intensity is divided into reversible component M_{rev} and irreversible component M_{irr} in the J-A magnetization model [16 17]:

$$M = M_{irr} + M_{rev} \tag{2}$$

According to the physical mechanism of the magnetization process, the relationship between the irreversible component M_{irr} and the reversible component M_{rev} can be written as follows:

$$M_{rev} = c(M_{an} - M_{irr}) \tag{3}$$

In the formula, M_{an} is the magnetization without hysteresis; c is the reversible magnetization coefficient, $0 < c < 1$.

The relationship between the non-hysteretic magnetization M_{an} and the effective magnetic field intensity H_e can be expressed by Langevin function as:

$$M_{an} = M_s \left(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e} \right) \tag{4}$$

In the formula, M_s is saturation magnetization, a is the shape parameter of hysteresis magnetization curve, and H_e can be expressed as: $H_e = H + \alpha M$. In the formula $M_{an} = M$, α is the mean field parameter of the coupling inside magnetic domain. Energy conservation formula in magnetization process [17]:

$$\mu_0 \int M_{an}(H) dH_e k = \mu_0 \int M(H) dH + \mu_0 k \delta (1 - c) \int \frac{dM_{irr}}{dH_e} \tag{5}$$

In the formula, k stands for hysteresis property, and is the coefficient between domains. Its unit is A/m. δ is the direction coefficient; when $dH/dt > 0$, $\delta = 1$; when $dH/dt < 0$, $\delta = -1$.

According to the above equation, static hysteresis model can be obtained:

$$\frac{dM}{dH} = \frac{(1 - c^2)M_{an} - M}{k\delta - \alpha(1 + c)M_{an} + \frac{\alpha}{1-c}M} + c \frac{dM_{an}}{dH} \tag{6}$$

According to the magnetization process formula (1) and magnetization function (6), the magnetization change curve under the external field can be described, as shown in Fig. 1. Let the magnetic field intensity peak H_m be $H_{m1} = 150$ A/m, $H_{m2} = 300$ A/m, $H_{m3} = 500$ A/m, $H_{m4} = 800$ A/m. When the magnetic field decreases to zero, the hysteretic magnetization M_r decreases with the decrease of H_m , that is, $M_{r1} < M_{r2} < M_{r3} < M_{r4}$. The material hysteresis parameters a, c, k and α mentioned in formula (6) may be different for different steel plates, but the strong magnetization will reduce the difference of these parameters in different

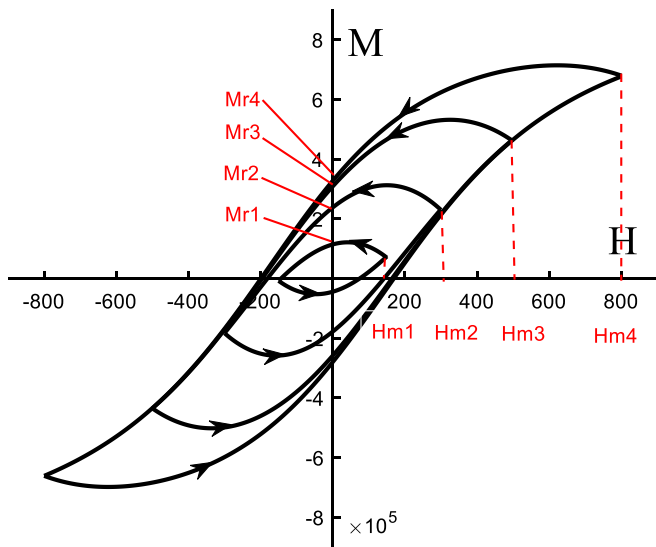


Fig. 1. Influence of maximum field intensity on remanence.

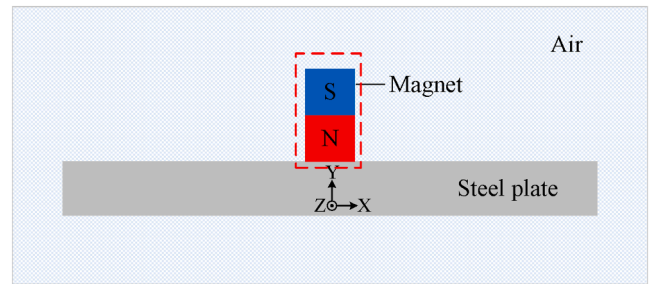
part of a specimen to a very small value. The process of reducing the maximum field to zero determines the magnitude of the remanent magnetization.

The magnetization process of moving steel plate by magnet can be decomposed into an infinite number of sequential iterations of static magnetization. When the magnet is placed above the steel plate, the magnet generates a stable spatial magnetic field in which the steel plate is magnetized. The spatial magnetic field will change the internal magnetization intensity of the steel plate, so that the magnetic distribution inside the steel plate is consistent with the magnitude and direction of the external magnetic field. When the magnet moves above the specimen, it is equivalent to the stable magnetic field moving parallel, and for a fixed point of steel plate surface, the external field decreases from the maximum field to zero. This process is consistent with the process of generating remanent magnetization by fixing the measuring point and changing the strength of the magnetic source. Therefore, the process of moving magnetization of steel plate by magnet can be decomposed statically, and the residual magnetization generated after the action of steel plate specimen at the last moment can be used as the initial condition to iteratively calculate the residual magnetization of steel plate at the next moment until the end of moving magnetization. Eventually, the residual magnetization distribution after dynamic magnetization can be obtained.

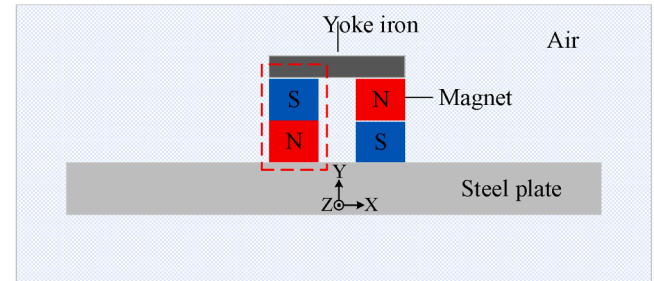
3. Simulation of magnetization state of magnetized steel plate

3.1. Magnetization of steel plate by static magnet

FEM of magnetization of steel plate by static magnet was carried out. As shown in Fig. 2, a three-dimensional model is used, including permanent magnet, steel plate, and air domain. There are two magnetization modes: single magnet and dual magnets. For example, when the magnet is about to move in the +x direction, the magnetic poles of the end magnet of the dual magnets and the single magnet are the same, so the magnetic poles framed by red dashed lines are consistent in Fig. 2. For dual magnet mode, magnets, yoke iron and steel plate constitute magnetization circuit. Physical field uses magnetic field, no current, and steady state. Magnet material is N50, by using the residual magnetic flux density model, $\mathbf{B} = \mu_0 * \mu_{rec} * \mathbf{H} + \mathbf{B}_r$, $\mathbf{B}_r = |\mathbf{B}_r| * \mathbf{e} / |\mathbf{e}|$, recoil permeability $\mu_{rec} = 1.05$, remanent flux density norm $|\mathbf{B}_r| = 0.035$ T. The direction of magnetization of each magnet is shown in Fig. 3. The magnetization model used for steel plate is $\mathbf{B} = \mu_0 * \mu_r * \mathbf{H}$, μ_0 is vacuum permeability, μ_r is relative permeability, $\mu_r = \chi + 1$, and magnetization $\mathbf{M} = \chi * \mathbf{H} = (\mu_r - 1) * \mathbf{H}$,



(a) Single magnet magnetizing steel plate



(b) Dual magnets magnetizing steel plate

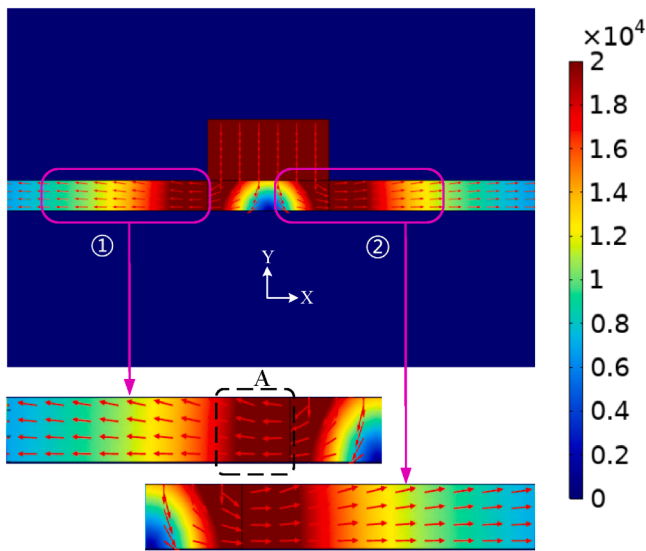
Fig. 2. Model of magnets magnetizing steel plate.

where χ is magnetic susceptibility. Free tetrahedral custom fine mesh is used for steel plate and magnet, and normal mesh is used for air domain. The magnetization distribution on xy cross-section is shown in Fig. 3.

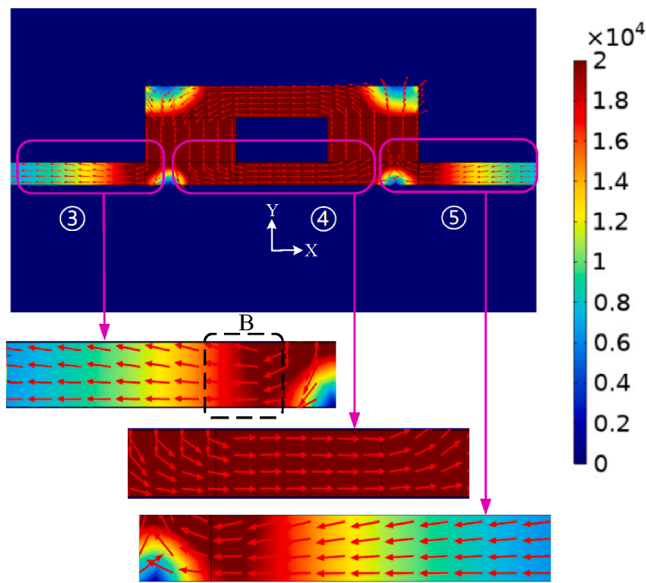
As can be seen from Fig. 3 (a), after the steel plate is magnetized by a single magnet, two parts of different magnetization distributions are formed inside the steel plate, namely, areas ① and ②. The mainly direction of magnetization in area ① is -x direction, that in area ② is +x direction, and the y component in both areas is small. In areas ① and ② magnetization norm values are symmetrically distributed. When the magnet is magnetized from left to right on the steel plate, the area ① is equivalent to being magnetized by the end of the magnet's magnetic field. The remanent magnetization can be roughly judged by the magnetization of the sub-area A in the area ①. The residual magnetization will be mainly in -x direction, the magnitude will be about 10^4 A/m, and M_y component will be very small.

As can be seen from Fig. 3 (b), after the steel plate is magnetized by dual magnets, three different magnetized areas are formed inside the steel plate: ③, ④ and ⑤. The magnetization of area ③ is in -x direction, that of area ④ is in +x direction, and that of area ⑤ is in -x direction. The M_y components of the three regions are all small. In the area ③ and ⑤, the magnetization norm are symmetrically distributed, and in the area ④, the magnetization norm are strong and evenly distributed. When the permanent magnet moves from left to right on the steel plate, the area ③ is equivalent to being magnetized by the end field of the magnet. The residual magnetization can be roughly judged by the magnetization of the sub-area B in the area ③. The residual magnetization will be mainly in -x direction, the magnitude will be about 10^4 A/m, and M_y component will be very small.

According to the magnetization results in Fig. 3, for example, when the magnet is about to move in the +x direction, the remanent magnetization state of the steel plate after magnetization by a single magnet is determined by the region ①, and the remanent magnetization state of the steel plate after magnetization by dual magnets is determined by the region ③. The direction of magnetization state in region ① ③ is the same, mainly in the direction of -x; at the same time, the values in +x direction are similar and the value in y direction is small. It can be inferred that the direction of the remanent magnetization of the steel plate after single and dual magnets magnetization is the same, mainly in the direction of -x, and the order of magnitude is similar.



(a) Static magnetization by single magnet



(b) Static magnetization by dual magnets

Fig. 3. Magnetization of steel plate below the magnets.

3.2. Magnetization of steel plate by moving magnet

The simulation adopts a two-dimensional dynamic mesh model, as shown in Fig. 4. The material domains includes magnet, steel plate and air. The dynamic mesh area includes 1,2,3, and the static mesh area is 4. Moving mesh area 2 is the area where the magnet is located, and area 2 moves uniformly from left to right, while areas 1 and 3 increase and decrease in width to simulate the moving magnetization of the magnet to the steel plate. Physical field selects magnetic field. Steel plate is hysteresis material, so the constitutive relation of steel plate adopts the hysteresis magnetization model of formula (6), and the parameters of the hysteresis model come from the material, $\mathbf{B} = \mu_0^* (\mathbf{H} + \mathbf{M})$. Magnet material is N50, by using the residual magnetic flux density model, $\mathbf{B} = \mu_0^* \mu_{rec}^* \mathbf{H} + \mathbf{B}_r$, $\mathbf{B}_r = |\mathbf{B}_r| \cdot \mathbf{e} / |\mathbf{e}|$, recoil permeability $\mu_{rec} = 1.05$, remanent flux density $\text{norm} \|\mathbf{B}_r\| = 0.035 \text{ T}$, and the residual flux density is in $-y$ direction.

Areas 1 and 3 are meshed using mapped distribution, and the opposite sides of areas 1 and 3 are set to be the same number of fixed

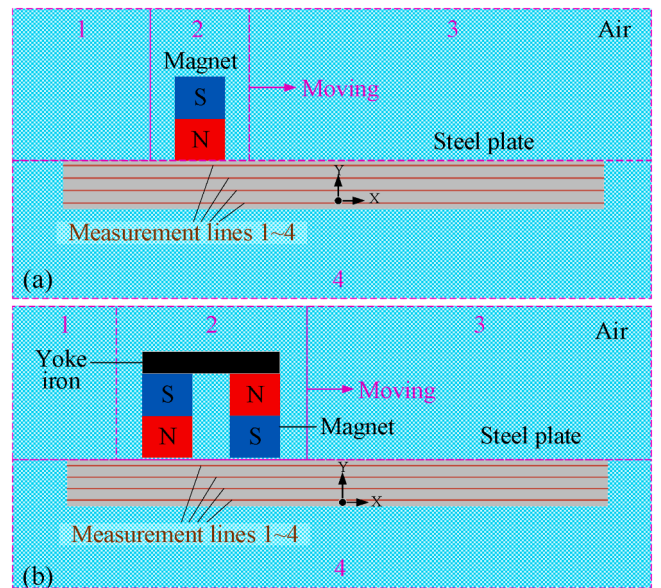


Fig. 4. Moving magnetization model of single (a) and dual (b) magnets.

grids. The steel plate area is also meshed using mapped distributions. The remaining areas are meshed into free triangular grids. Steady state solution is adopted. The moving position of the area 2 is controlled by $x = v^*t$, where v is the velocity. The scanning parameter is time t . In the process of dynamic magnetization, formula (1) is used; the magnetization state at time $t + 1$ is obtained by iterating the magnetization state at time t . In order to improve the computational efficiency, a two-dimensional model is adopted.

The magnetization distribution inside the steel plate after being magnetized by the single and dual magnets is shown in Fig. 5, and the arrow shows the remanent magnetization direction. For both dual and single magnets magnet magnetization, the direction of the remanent magnetization in the middle region is reversed, showing the characteristics of stratification. The direction and magnitude of the remanent magnetization for different layers are different. A layer with large remanent magnetization appears near the surface, and the magnetization direction of this layer is in $-x$ direction, which is the same direction of the magnetic field on the lower left side of the single and the dual magnets. The remanent magnetization of the left and right ends of the steel plate is weak. Four measurement lines inside the steel plate are selected, as shown in Fig. 4. The remanent magnetization on these lines

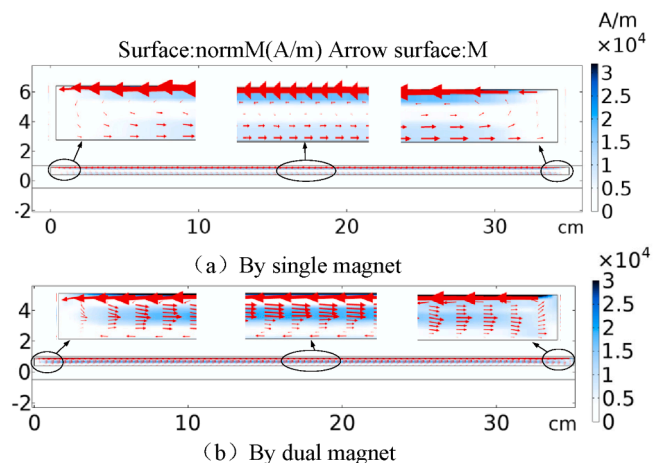


Fig. 5. Internal magnetization distribution of steel plate after being magnetized by moving single and dual magnets.

is shown in Fig. 6, the remanent magnetization M_x and M_y on the measuring lines inside the steel plate is uniform, and M_x amplitude is large and is different in different lines. M_x can be positive or negative. M_y is small and close to zero. The magnetization at both ends of the steel plate is uneven.

In order to observe the external remanent magnetic flux density after the steel plate is fully magnetized, measuring lines are taken near the surface of the steel plate, and magnetic flux density curves under two magnetization modes are obtained, as shown in Fig. 7.

As can be seen from Fig. 7, tangential and normal magnetic flux density distributions near the surface of the steel plate become smooth, uniform and almost identical after single and dual magnet magnetization. The horizontal magnetic flux density curve is relatively flat in the middle, with positive amplitude and approximately even symmetry about the middle vertical line of the steel plate. The normal magnetic flux density curve changed gradually from positive to negative, and approximately odd symmetry about the middle vertical line of the steel plate. It shows that the overall remanent magnetization of steel plate can be uniform after moving magnetization with both single and dual magnet modes, and the overall magnetization effect is nearly the same for the two modes.

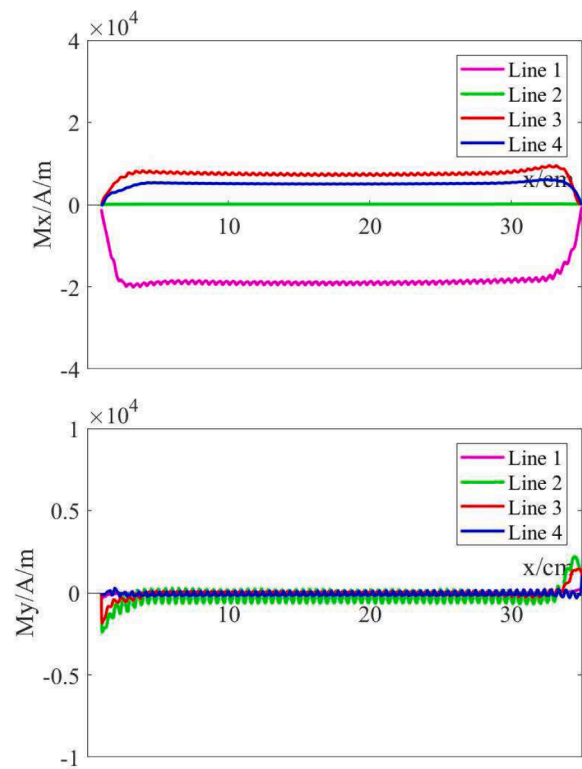
3.3. Moving magnetization of steel plates of different lengths

When the length of the specimen increases, the magnetic flux density curve of the measured line will be changed due to the change of the geometric size. The distribution of magnetic flux density is further explored when the length of steel plate is 0.35 m, 1 m, 2 m, 3 m and 4 m. According to the above research, the magnetization effect of single and dual magnets is equivalent, so single magnet magnetization is adopted. Two-dimensional dynamic mesh FEM model is established. The magnetic flux density curve of measured lines near the surface of the steel plate is obtained, as shown in Fig. 8. It can be seen that for steel plates of different lengths, the B_x curve is concave in the middle and convex at both ends. The longer the length of steel plate, the longer the flat area in the middle and the smaller the amplitude. The curve B_y changes gradually from positive to negative, and the middle is a flat transition area with a small amplitude near to zero. The longer the steel plate length, the longer the flat area in the middle.

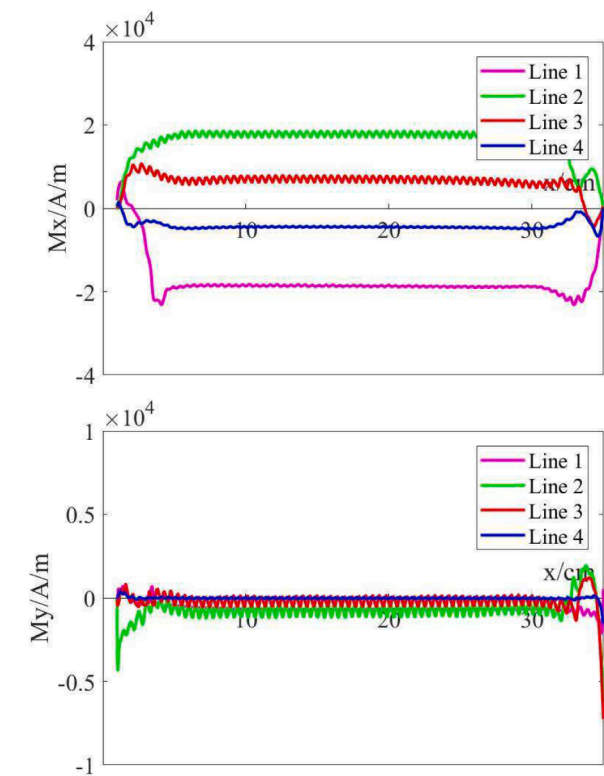
According to the above results, it is preliminarily speculated that the length of the specimen will affect the amplitude of the flux density in the flat area in the middle of the steel plate. In order to determine the middle flat value of the magnetic flux density curve of the longer steel plate specimen, a ring shaped steel plate specimen with inner diameter $r = 4.97$ m and thickness $t = 0.03$ m is adopted to simulate the magnetization of the infinite length specimen. FEM is a two-dimensional dynamic grid model, as shown in Fig. 9. Material areas include permanent magnets, circular steel plates, and air areas. The dynamic grid area is 1 and the static grid area is 2. Region 1 is set as the rotation domain in the moving grid, with a constant angular velocity of 0.2 rad/s, and scanning time parameter t during the model calculation. The material parameters and constitutive relation of steel plate and magnet are set in the same way as in Section 3.2.

The simulation results are shown in Fig. 10. The tangential and normal components of measured magnetic flux density near the surface of the circular steel plate after magnetization are zero. It can be seen that the longer the specimen is, the flatter value of the magnetic flux density curve of measured line near the surface after magnetization is closer to zero. When the specimen is infinitely long, such as an oil and gas pipeline or railway track, the magnetic flux density near the surface is zero after undergoing strong magnetization.

In conclusion, the remanent magnetization inside the steel plate is mainly in the horizontal direction when the magnets are moved over. The direction and magnitude of the remanent magnetization in different layers are different. The remanent magnetization in the surface layer is larger. The increase of the specimen length does not affect the



(a) Magnetization by moving single magnet



(b) Magnetization by moving dual magnets

Fig. 6. Remanent magnetization on measuring lines inside steel plate.

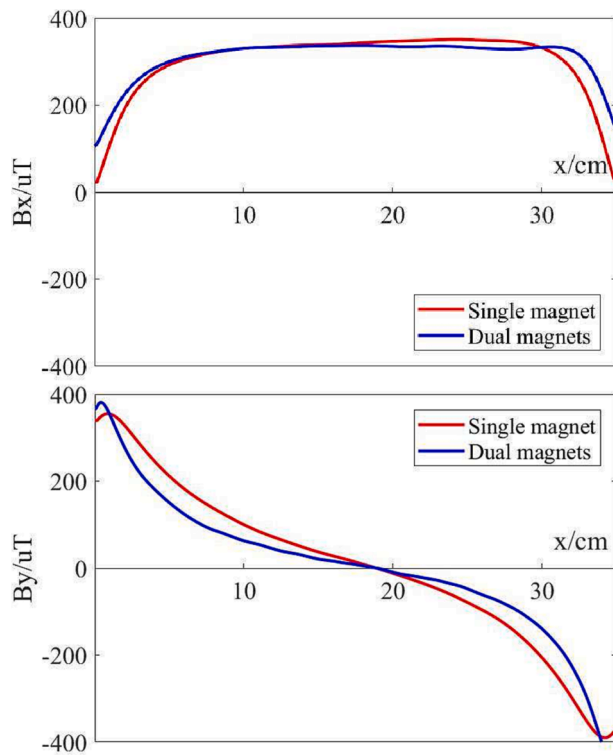


Fig. 7. Residual magnetic flux density near the surface of the steel plate after magnetization.

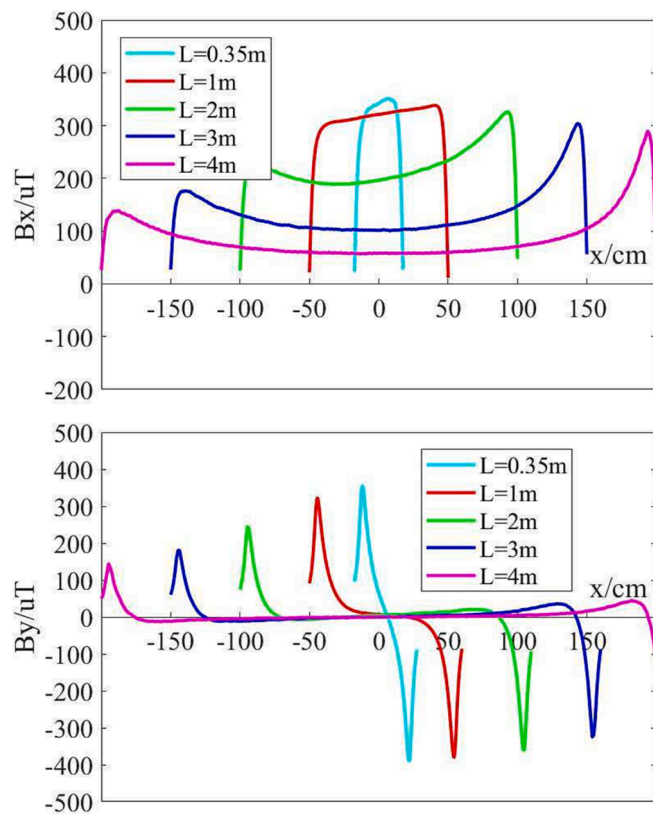


Fig. 8. Remanent magnetic flux density near the surface of steel plates of different lengths.

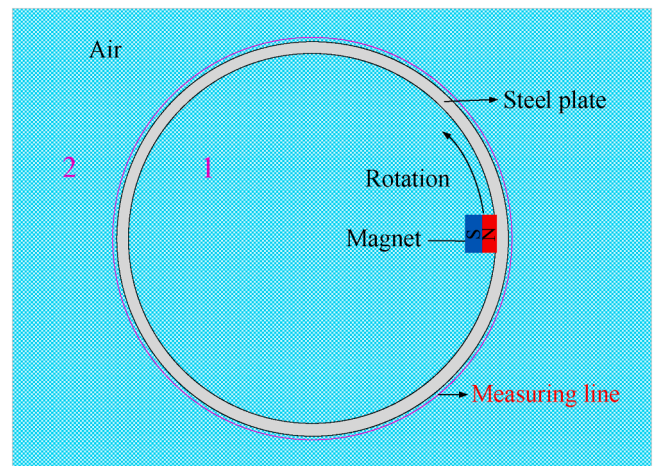


Fig. 9. Simulation model of single magnet moving on and magnetizing circular steel plate.

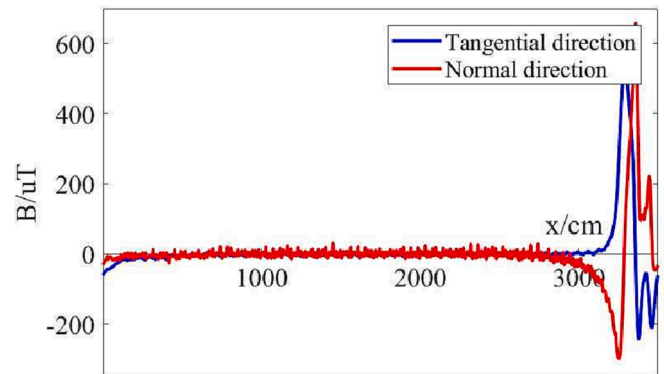


Fig. 10. Remanent magnetic flux density near the surface of circular steel plate.

distribution shape of the residual magnetization inside the steel plate, but increases the length of the middle flat area of the magnetic flux density near the surface of the steel plate, and reduces the amplitude of the magnetic flux density in this flat area. The next step is to verify the correctness of the above law of remanent magnetization by magnetizing steel plate and measuring the magnetic flux density on the surface of different steel plates.

4. Experiment

Experiments of moving magnetization and surface magnetic field measurement were carried out for single-layer steel plates of different lengths and a stacked steel plate made of multilayer thin steel plates. The experimental equipment is shown in Figs. 11 and 12. An electric pushrod is used to push the magnet, making it move slowly and evenly over the steel plate to magnetize it. When magnetization is complete, the electric pushrod returns to its original position and pushes the magnetic sensor to move, measuring the magnetic flux density above the plate. Four groups of experiments were carried out: (1) homogenization verification of magnetization state of four steel plates with the same dimension size; (2) comparison of magnetization effects of single and dual magnets; (3) magnetic flux density distribution of different lengths of steel plates after magnetization; (4) verification of the stratification of the remanent magnetization of a stacked steel plate made of multilayer thin steel plates.

The process of the long steel plate experiment is to manually push the magnetization device to move above the steel plate, use a fixed device to clamp the sensor above the steel plate, push it to move, and take

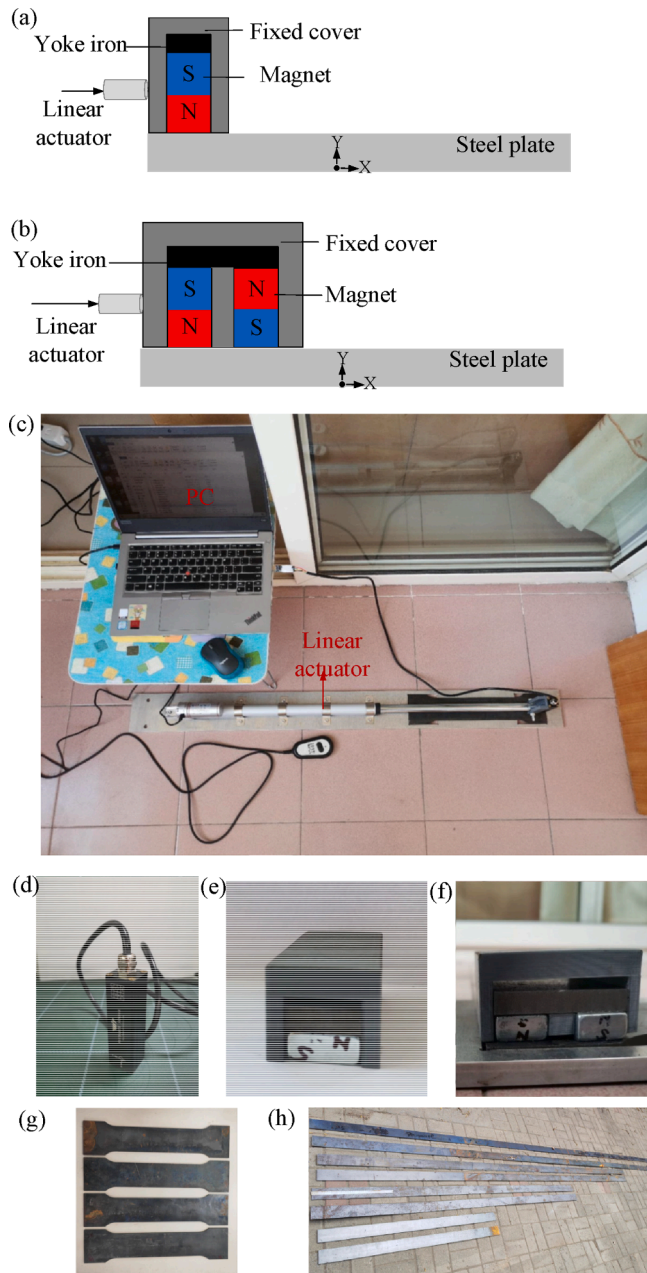


Fig. 11. Experimental scheme: (a) magnetization by single moving magnet; (b) magnetization by dual moving magnets; (c) photograph of the experiment; (d) magnetic sensor HWT3100; (e) single magnet; (f) dual magnets; (g) four short steel plates; (h) steel plates with different lengths.

measurement points every 10 mm.

The layered steel plate experiment is shown in Fig. 12. 4 pieces of 1.5 mm thickness steel plates, whose surface are ground with high precision. The four steel plates are placed close together from top to bottom and numbered 1,2,3,4. An electric pushrod is used to push the single and double magnets across the upper surface. When magnetization is complete, the four steel plates are separated. The magnetic sensor is driven by an electric push rod to measure the magnetic flux density near the surface of each steel plate and observe whether the magnetic flux density reverses. If so, the simulation results in Section 3.2 is correct.

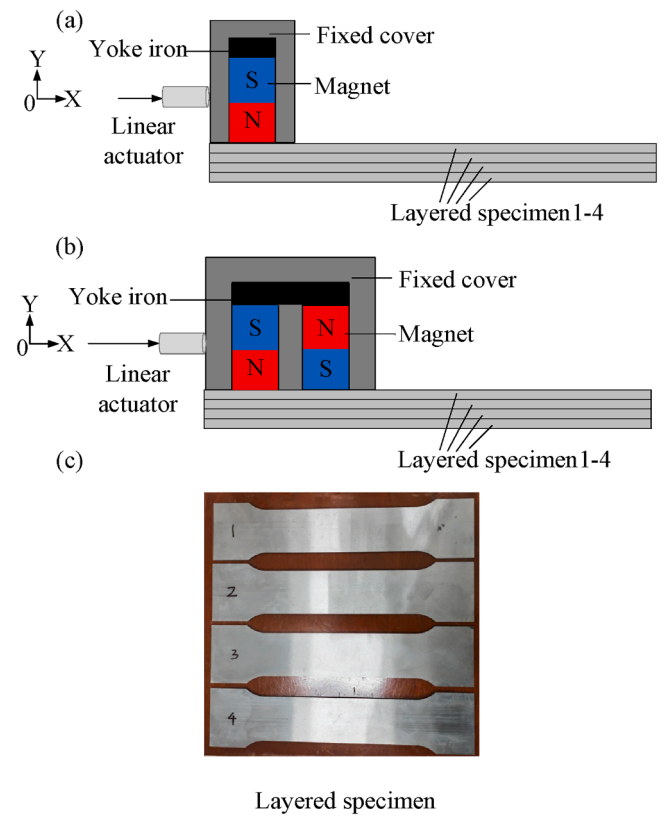


Fig. 12. Layered steel plate experiment: (a) magnetization by single moving magnet; (b) magnetization by dual moving magnets; (c) photograph of four layered steel plates.

5. Results and discussion

5.1. Verification of remanent magnetization uniformity of steel plates

The magnetic flux density measurement results of 4 steel plates with the same size before and after magnetization are shown in Figs. 13 and 14. It can be seen that before magnetization, the magnetic flux density on the surface of different steel plates is different, and the shape is also very different, indicating that the initial magnetization state of different steel plates is different and irregular.

After magnetization, the tangential and normal flux density distributions near the surface of the specimen become smooth, uniform and basically the same. The middle region of tangential flux density curve is relatively flat, and the curve is approximately even and symmetric about the middle vertical line of the steel plate. The normal flux density curve changes gradually from high to low, and the sign changes. The curve shows odd symmetry about the middle vertical line of the steel plate. These test results are consistent with the simulation results, which verifies the correctness of the simulation results. After magnetization by moving magnet, the steel plate obtains uniform remanent magnetization.

5.2. Comparison of magnetization effects of single and dual magnets

Single and dual magnets were used to move on and magnetize the same steel plate specimen respectively, and then the magnetic flux density on its surface was measured. The results are shown in Fig. 15. The magnetic flux density curves near the surface of the steel plate under the two magnetization modes almost coincide, indicating that the magnetization effect of the two magnetization modes is the same, and the steel plate can obtain the same uniform residual magnetization distribution. This also verifies the correctness of the simulation results.

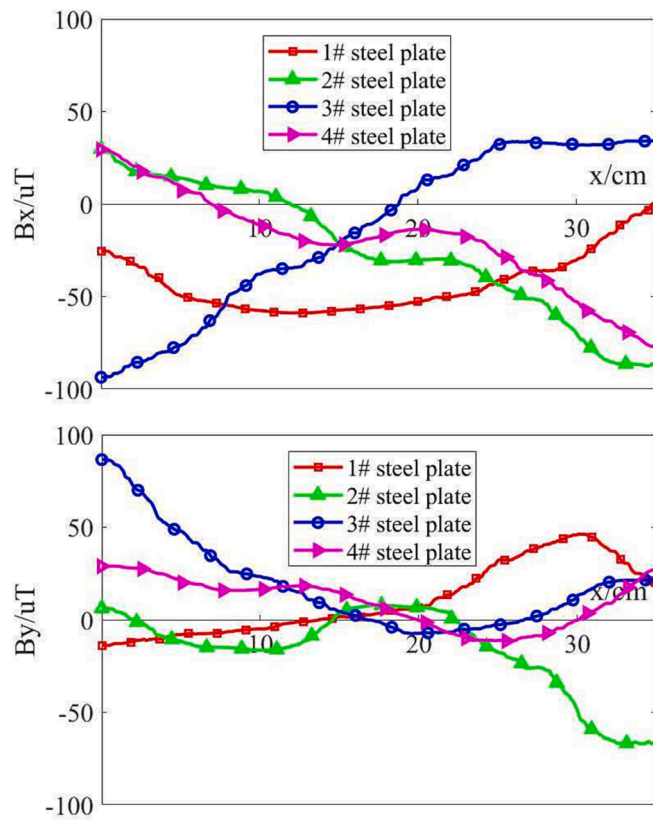


Fig. 13. Magnetic flux density near the surface of the steel plates before magnetization.

5.3. Magnetization effects of steel plates with different lengths

A single magnet was used to move on and magnetize steel plates with lengths of 1 m, 2 m, 3 m and 4 m, and the distribution of magnetic flux density near the surface of the steel plate was measured. The results are shown in Fig. 16. The tangential magnetic flux density curve is relatively flat in the middle, and the amplitude is positive; the curve is roughly even symmetric about the middle vertical line of steel plate. The normal flux density curve gradually decreases from high to low, and the amplitude changes from positive to negative; the curve shows odd symmetry about the middle vertical line of the steel plate. As the length of the steel plate becomes longer, a fixed phenomenon is that the middle area of tangential magnetic flux density curve is concave and the two ends are convex. For both the tangential and normal flux density curves, the longer the length, the longer the flat area in the middle, and the lower the amplitude of the flat area. When the length of the steel plate is 4 m, the amplitude of the flat middle part is close to zero. These phenomena are the same as the simulation results in Section 3.2.

5.4. Layered magnetization of steel plate

Single magnet and dual magnets were used in the layered magnetization experiments of steel plate respectively. In the magnetization process four pieces were placed close together to form a thick steel plate. After the magnetization was completed, the four steel plates were separated and the magnetic flux density distribution near the surface of each steel plate was measured, and the results were shown in Figs. 17 and 18.

It can be seen that the magnetic flux density near the surface of the bottom fourth layer of steel reverses, regardless of whether it is magnetized by a single magnet or a double magnet, compared with that of the previous three layers of steel. This indicates that the remanent

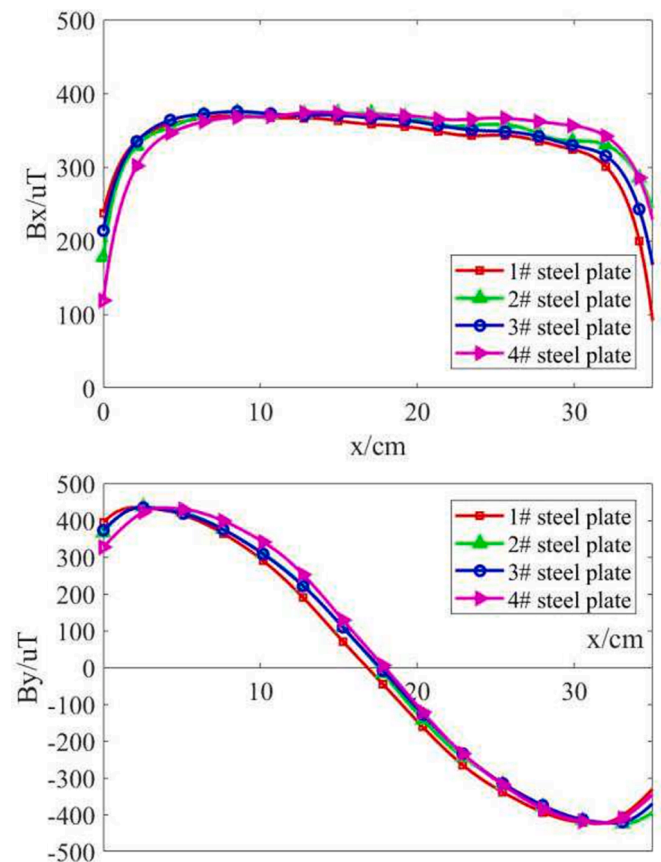


Fig. 14. Magnetic flux density near the surface of the steel plates after magnetization.

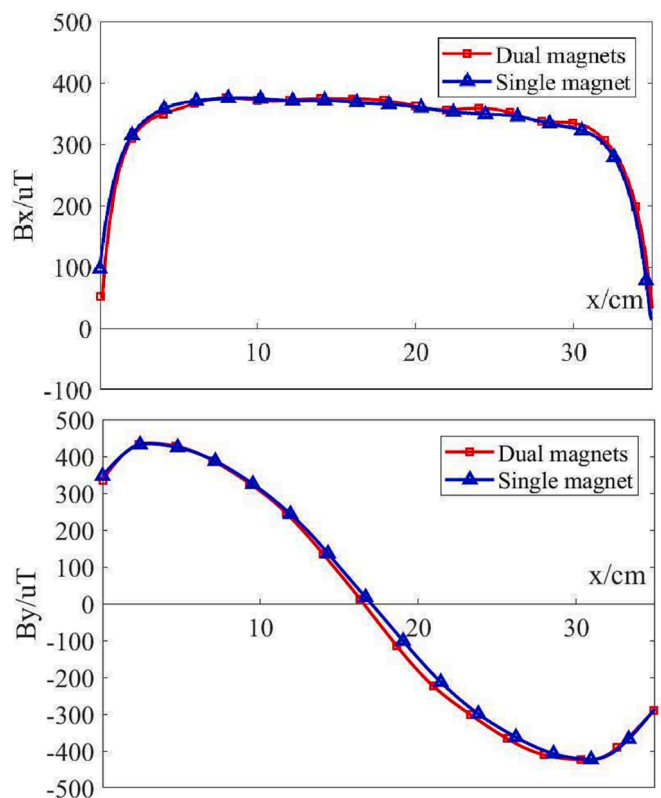


Fig. 15. Magnetization results of single and dual magnets.

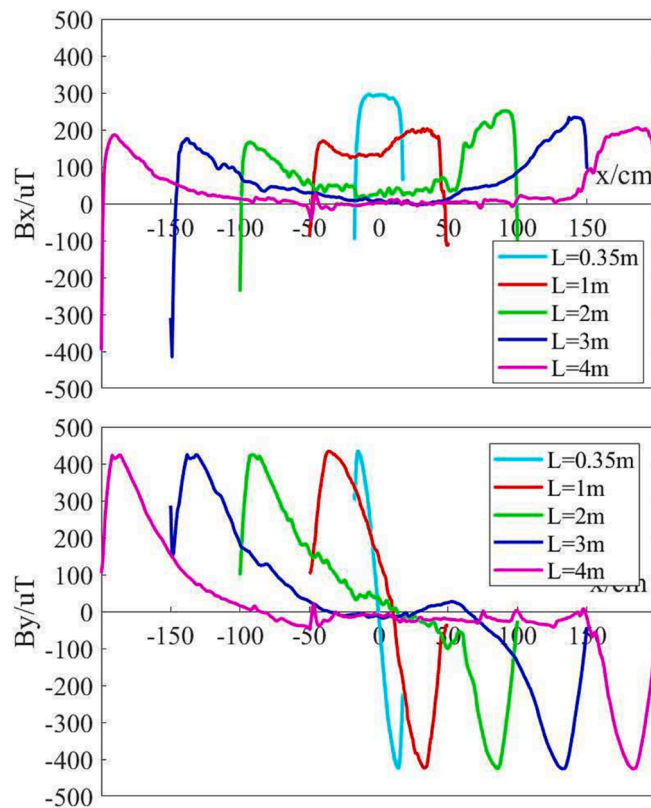


Fig. 16. Magnetization effects of steel plates with different lengths.

magnetization of the bottom steel plate is opposite to that of the other layers. The flux density curve near the surface of each layer of steel plate is smooth, but the flux density amplitude of different layers of steel plate is different. Among them, the layer with the best uniformity has the largest flux density amplitude. This indicates that the layer with the strongest remanent magnetization of the steel plate determines the magnitude and direction of the overall remanent magnetic flux density.

The magnetic field distribution of steel plate and multilayer stacked steel plate after magnetization was compared. After the steel plate is magnetized, the magnetic induction intensity curve near its surface is very uniform and smooth. After the multilayer stacked steel plate is magnetized, the magnetic induction curve of the surface of each layer becomes smooth. The layer with the largest amplitude has the best uniformity, and the curve amplitude of the layer with the largest amplitude is consistent with that of the whole steel plate.

6. Summary

Through theoretical analysis, FEM and experiments, the magnetization state of steel plates after magnetization by moving magnet is studied. The results have important guiding significance for the magnetization in magnetic non-destructive testing and the design of defect detection scheme. The main conclusions are as follows:

- (1) After the steel plate is magnetized by a single and dual moving magnets, the remanent magnetization inside the steel plate is layered, and the magnetization of each layer is uniform along the direction of the magnetic field of the magnet. The direction of the magnetization of the upper layer of the steel plate is the same to the direction of the magnetic field at the end of the single and dual magnets.
- (2) The steel plate can obtain the same remanent magnetization distribution after the single and dual magnets are moved over the

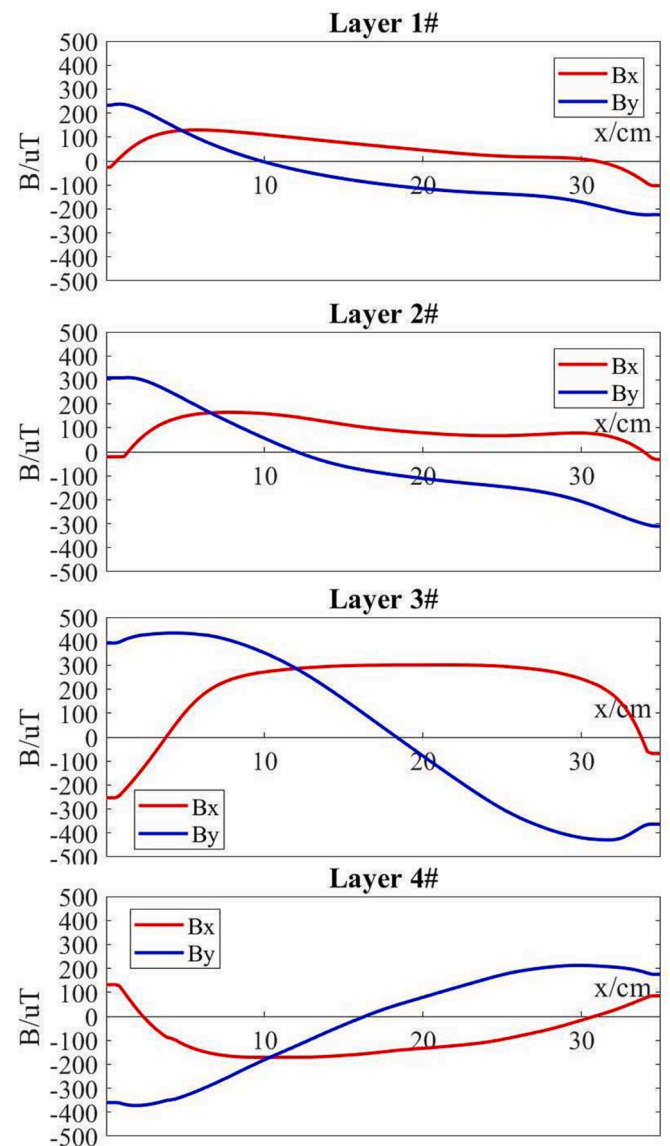


Fig. 17. Magnetization results of layered steel plates by single magnet.

plate. The tangential component of the residual magnetization is much larger than the normal component.

- (3) The longer the steel plate is, the longer the intermediate flat magnetized region is, and the closer the amplitude of the remanent magnetic flux density in the middle is to zero.

CRediT authorship contribution statement

Liu Shan: Conceptualization, Methodology, Data curation, Formal analysis, Software, Validation, Visualization, Writing - original draft. **Ma Jinyu:** Data curation, Investigation, Writing - review & editing. **Zeng Zhumo:** Validation, Supervision. **Rui Xiaobo:** Visualization, Validation. **Zhang Hui:** Resources, Software, Supervision. **Huang Xinjing:** Conceptualization, Methodology, Investigation, Funding acquisition, Supervision, Resources, Project administration, Writing - review & editing.

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.

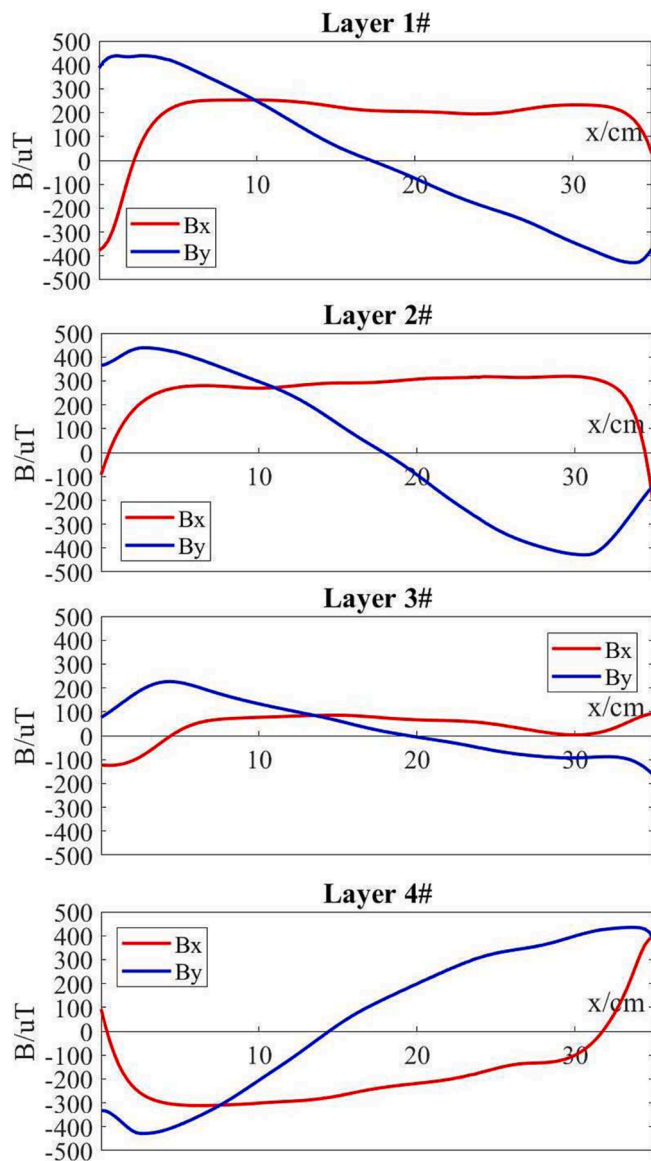


Fig. 18. Magnetization results of layered steel plates by dual magnets.

Data availability

Data will be made available on request.

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