Studies on test technique of stress concentration for ferromagnetic component based on permeability

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Abstract. The stress concentration detection technology based on the permeability is an evaluating method on the stress concentration which is according to the induction voltage signal of the closed magnetic circuit composed of the probe and the specimen. The permeability is related to the detection signal, but also to the degree of stress concentration. Through the permeability parameter, the relation between the detection signal and the degree of stress concentration can be established. The permeability measurement technique can be used to detect various micro-structural changes of component related to permeability, such as stress concentration, fatigue damage, aging and transformation. The basic principle of permeability measurement technology is analyzed, and the optimum setting method of detection parameters is discussed. Taking steel 20 as an example, the relationships between the detected signal and the tensile stress, tensile residual stresses have been studied experimentally which is based on the measured signals data. It is found that the change of detection signal caused by tensile stress can reach 33.3%, and the change of detection signal caused by residual stress after unloading can reach 35.8%. It is also found that the detection signal is particularly sensitive to the yield strength, and the signal will decrease sharply when the stress exceeds the yield strength. According to the characteristics of the detected signal, it can effectively detect the stress state in a certain area of the specimen, and has a broad application prospect.

1. Introduction
In modern industry, iron and steel components are the main materials in aerospace, railway, electric power, pressure vessel and other industries. In the course of the use of components, due to stress, fatigue load, high temperature, high pressure and other adverse working environment, stress corrosion, aging, fatigue and fracture are easy to occur. It is easy to cause serious accidents in the areas of stress concentration and fatigue damage, and will eventually bring disaster to the country and the people [1-2]. Therefore, when performing nondestructive testing of components, rapid, accurate and convenient detection of stress concentration and fatigue damage in the severe region, it is important to prevent the breakdown of components and prevent the occurrence of disasters [3-4].

Permeability test technique has a very high testing sensitivity[5-6], which is a new method to evaluate stress concentration and fatigue damage, which can find the stress concentration and fatigue damage degree of ferromagnetic specimens in advance[7]. The method can also detect the translation of martensite austenite in ferromagnetic material, detect the change of mechanical toughness and mechanical brittleness, and detect the change of dislocation density and so on[8-9].
2. Basic principle of permeability testing technology

The structure of the sensor probe is shown in figure 1. The sensor probe includes detection coil, exciting coil and U type yoke. The test coil and the exciting coil are wound on the magnetic yoke; when detecting, the magnetic yoke is placed on the detecting piece; an alternating signal is passed in the exciting coil; the detecting probe is close to the ferromagnetic specimen to checked; the magnetic yoke and the test piece form a closed magnetic circuit. The stress concentration of the component can cause the change of permeability and will cause the change of magnetic resistance and magnetic flux of the closed magnetic circuit. The ratio of the induced voltage signal to the exciting current can sensitively reflect the change of permeability of the tested component in the closed magnetic circuit.

Figure 1 Schematic of probe structure

According to the principle of electromagnetic induction, the output signal of the inducting coil varies with the change of the magnetic flux density inside the closed magnetic circuit. By extracting the value of the voltage in the induction coil, the change of magnetic permeability in ferromagnetic specimens can be reflected, so that the stress concentration of ferromagnetic specimens can be detected accurately.

The number of turns of the test coil is \( N_1 \), and the number of turns of the exciting coil is \( N_2 \). The magnetic permeability of the magnetic yoke and the sample to be tested is \( \mu_1 \) and \( \mu_2 \) respectively. The effective magnetic circuit lengths of the yoke and the sample are \( l_1 \) and \( l_2 \) respectively. The average equivalent cross sectional area of the magnetic yoke and the sample are \( S_1 \) and \( S_2 \) respectively. In the closed magnetic circuit, The induced signal \( \varepsilon \) in the induction coil can be expressed as:

\[
\varepsilon = N_1 \frac{d\Phi}{dt} \tag{1}
\]

The magnetic flux \( \Phi \) is related to the excitation current \( I \), proportional to the \( N_2 I \), and inversely proportional to the magnetic circuit magneto-resistance (\( R_M \)). The magnetic circuit magneto-resistance (\( R_M \)) includes the yoke magnetic circuit reluctance (\( R_Y \)) and the specimen magnetic reluctance (\( R_S \)), mathematical expression is:

\[
\Phi = \frac{N_2 I}{R_S + R_Y} \tag{2}
\]

From the formula (2) and the formula (1), it can be seen that if the permeability of the specimen is changed, the magnetic resistance of the specimen (\( R_S \)) will also change, which leads to the change of the magnetic flux, which is manifested as the change of the inductive signal in the detecting coil.

It can be seen that the permeability of the specimen is closely related to the detection signal, the permeability of the component can be detected by detecting the signal, then the stress concentration degree of the specimen can be measured.

3. Optimal design of sensor parameters

The core of the probe is U type yoke which material is Mn Zn ferrite, and the specific dimensions are shown in Table 1 and Figure 2. The exciting coil is wound on the beam of yoke, and the detecting coil is wound on the leg of yoke, winding 500 turns respectively.
Table 1 probe core structure size

| size (mm) |
|-----------|
| A   | B   | C   | D   | E   | F   |
| 57.13 | 33.35 | 13.05 | 12.95 | 31.23 | 18.87 |

Figure 2 Schematic diagram of probe magnetic core

The AC voltage source is used as the exciting signal source, which voltage value is 10Vpp. Two magnetic circuits are selected in the test: the ferromagnetic circuit and the air circuit. The ferromagnetic circuit is a closed magnetic circuit consisting of a magnetic core and ferromagnetic specimens when the probe is placed on a ferromagnetic specimen; the air circuit is a closed magnetic circuit consisting of the probe core and the air environment. The difference of detection signal between the ferromagnetic circuit and the air circuit can reflect the sensitivity of the test technique, and the greater the difference, the higher the sensitivity. The testing sensitivity can be set in the proper range by adjusting frequency.

It found that with increasing of the excitation frequency, the detection signals of ferromagnetic circuit and the air circuit both increase, which difference is proportion to detection frequency approximately, which increases with the increasing of the excitation frequency, as shown in figure 3.

Figure 3 Under the unit excitation current, the difference between the test signal of the ferromagnetic circuit and the air circuit versus the excitation frequency

Figure 3 shows the relationship of between the difference of detection signals and frequency under the condition of per current excitation. The difference between the detection signals of the ferromagnetic circuit and the detection signal of air circuit increases approximately linearly with the increase of frequency.

Figure 3 shows that the detection sensitivity increases with increasing of excitation frequency, but
the excessive exciting frequency can lead to eddy current loss and reducing resolution. The excitation frequency of the test is selected 400Hz, the detection sensitivity is enough to meet the requirements of the test.

The effect of the amplitude of the excitation signal on the testing signal will be discussed below. AC voltage source with frequency of 400Hz is selected. The variation law of the differential signal of the ferromagnetic circuit and the air circuit with the amplitude of the exciting source is measured. Under unit excitation current condition, as shown in figure 4. It is found that the difference between the detection signal of the ferromagnetic circuit and the detection signal of the air circuit decreases with the increase of the amplitude of the exciting current per unit current. To select the amplitude of exciting voltage, we should consider three factors, that is, the difference signal of detection, the difference signal of the unit current and the signal to noise ratio.

![Figure 4](image_url)  
Figure 4 The difference between the detection signal of the ferromagnetic circuit and the detection signal of the air circuit versus the amplitude of the excitation voltage of per unit current

Figure 4 shows that under unit current condition, the difference between the detection signal of the ferromagnetic circuit and the detection signal of the air magnetic circuit varies with the amplitude of the excitation voltage. It shows from figure 4 that the difference decrease with the increase of excitation voltage amplitude. The smaller excitation current amplitude can improve the signal to noise ratio and improve the detection resolution. The test signal increases with the increase of the exciting current, but the test signal of the unit current is not so. On the premise of meeting the sensitivity requirement of detection, in order to ensure the stability and reliability of the test data, the voltage amplitude of this test is 10Vpp.

4. Experimental studies
Specimens materials are no.20 steel, which is widely used in industry, and has certain representative. The static load tension test for the specimen is carried out, the excitation frequency taking of 400Hz and the excitation voltage taking of 10Vpp. The structural dimensions of the specimens are shown in figure 5 with a thickness of 3mm. The INSTRON 8801 of Mechanical test machine was used to carry out the static tensile test, and probe was placed in the center of the specimen to measure. The induction voltage signals are recorded in accordance with the step mode of the 1kN.

![Figure 5](image_url)  
Figure 5 Sketch map of specimen structure
In the experiment, the methods of measurement of loaded specimens and unloaded specimens after loading are recording the induced voltage and the exciting current. Calculate the ratio of the detected voltage to the exciting current, which is the detection signal per unit current, then, the relationships between the signal per unit exciting current and the residual stress of tension, tension are studied.

For tensile and tensile residual stresses, the detection signals of unit exciting current have a similar change rule. The curve of the detection signal per unit current with the residual stress is shown in figure 6. Here, we define the residual stress after tensile unloading, which numerical value is expressed by the tensile force.

![Figure 6 The detection voltage signal per unit exciting current versus the tensile residual stress](image)

Figure 6 The detection voltage signal per unit exciting current versus the tensile residual stress;

As can be seen from Figure 6, when the residual stress is less than the yield strength of 310MPa, the detection signal of unit excitation current decreases with the increasing of residual stress, but the change is not large, about 10%. When the residual stress is greater than the yield strength of 310MPa, the detection signal per excitation current will reduce dramatically. When the residual stress reaches the vicinity of the fracture strength of the specimen (430MPa), The induction signal of unit current drops and the variation can reach 33.33%. It shows that the permeability detecting technique to detect the stress concentration will have very high sensitivity.

5. Conclusions
Permeability is related to the detection signal, but also to the degree of stress concentration. The relationship between the detection signal and the stress concentration is established through the permeability. Permeability testing is a method of detecting the stress concentration of component in a certain region with high accuracy, which is according to the induction voltage signal of the closed magnetic circuit composed of the probe and the specimen. Through the experimental study of steel 20 specimens, we can draw the following conclusions:

1) It is found that the detection signal is closely related to tensile stress and tensile residual stress, which decreases with the increasing of tensile stress and residual stress. It shows that according to the characteristics of the detecting signal, the stress state in a certain region of the specimen can be effectively detected, which provides a new method for accurate measurement of stress distribution.

2) The detection signal is particularly sensitive to yield strength, and when the stress exceeds the yield strength, the detection signal will decrease dramatically. It shows the yield strength of the specimen can be effectively and accurately detected.

3) If specimen is subjected to tensile force near tensile strength, loading and unloading, it is found that the change of test signal caused by tensile stress can reach 33.3%, and the change of the test signal caused by residual stress after unloading can reach 35.8%.
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