State-of-the-art of magnetic memory testing technique

Shujun Liu*, Qiwei Yong, Dean He, Yonggang Zuo, Zhen Zhang and Guodong Zeng
Army logistics academy, Chongqing, China

*Corresponding author. Email: 119042856@qq.com

Abstract. Magnetic memory testing is a new nondestructive testing technique. It has the incomparable advantages of traditional nondestructive testing technique, and can find the stress concentration of ferromagnetic materials. In this paper, the development of magnetic memory testing is analysed, and the problems encountered in the development of magnetic memory is studied. The research on magnetic memory mainly focuses on the following three aspects, study on the mechanism of mechanical magnetic coupling, analysis of external influence factors of signal and extraction of damage evaluation parameters. Finally, in the paper, the development direction of magnetic memory testing in the future is summarized. That is, to strengthen the research on the micro mechanism of magnetic memory and to establish the correct mechanical magnetic coupling model.

1. Introduction
Ferromagnetic materials are widely used in modern equipment manufacturing because of their good strength, hardness, plasticity and toughness. Because of its particularity, military equipment often bears high temperature, high pressure and high load. Some key parts of military equipment are prone to stress concentration and fatigue damage after long-term service, which is called early injury. Early damage is often recessive and has not yet developed into a macro defect. Traditional nondestructive testing technique cannot detect early damage. Therefore, a new nondestructive testing technique is needed to detect the early damage of ferromagnetic materials.

In the 1990s, Russian scholar Dubov first proposed magnetic memory testing technique, which is referred to as Magnetic Memory testing technique [1]. Magnetic memory testing is a new nondestructive testing technique. It uses the magnetic memory effect of ferromagnetic materials under the action of external working load and geomagnetic field to realize the rapid detection of early damage. This technique can effectively detect the stress concentration region of ferromagnetic materials without additional external excitation magnetic field.

2. The basic principle of magnetic memory
As shown in Fig. 1, the basic principle of the magnetic memory testing technique can be expressed as: For the effect of the load, the domain organization orientation will cause magnetostriction properties and irreversible reorientation in the Ferromagnetic components working in a geomagnetic field. The maximum leakage magnetic field is formed in the stress and deformation zone. The tangential component of the magnetic field in the stress concentration area \( H_r(x) \) has the maximum value, while the sign of the normal component \( H_r(y) \) changes and has zero-crossing position. The irreversible change of the magnetic state remains after the elimination of the working load. By the testing of the
magnetic flux leakage field’s normal component \( H_x(y) \) and the calculation of gradient \( K \) given by equation (1), the stress concentration position of the component can be exactly deduced [2].

\[
K = \frac{dH_x(y)}{dx}
\]  

\( (1) \)

Figure 1. Schematic of magnetic memory method.

3. Development of magnetic memory
Since Dubov proposed magnetic memory testing technology, magnetic memory testing technology has developed rapidly and has been widely used in many engineering fields [3]. The research on magnetic memory testing mainly focuses on the following aspects.

3.1. Study on magnetic coupling mechanism of Magnetic Memory
For the coupling effect between stress and magnetism, some scholars have proposed linear and nonlinear force magnetic coupling relations. According to the literature, these linear or nonlinear magneto mechanical coupling models still have big defects, and they have not accurately constructed the complex magneto mechanical coupling relationship of ferromagnetic materials, which leads to the inconsistency between some experimental results and the theory.

British scholar Wilson [4] studied the variation of residual magnetic field on the surface of welded steel under tensile stress through tensile test. His research results show that stress concentration can be identified in advance by using magnetic curve distribution. Roskosz studied the variation of maximum magnetic field gradient and maximum equivalent residual stress with plastic strain. The results show that there is a good qualitative and quantitative relationship between residual stress and gradient distribution of residual magnetic field. But Roskosz did not quantify the relationship between them.

On the basis of analyzing the characteristics of scattered magnetic field of austenite pipe under external force, Dubov firstly used magnetic memory testing method to evaluate the strength and distribution direction of welding residual stress, which verifies the feasibility of using magnetic memory signal to predict fatigue life.

Liu Shujun[5] of Logistics Engineering College conducted the magnetic memory test of X60 pipeline steel specimens under different tensile stress and different cycle fatigue load. This experiment simulates the simplest loading environment of the work piece in actual service. It analyzes the relationship between stress concentration and magnetic memory signal, and further discusses the mechanism of magnetic memory detection from the micro point of view, which provides a theoretical basis for the quantitative evaluation of early damage of ferromagnetic materials by magnetic memory testing.

From the current research situation at home and abroad, it can be seen that magnetic memory method can be used in the detection and evaluation of early damage or defect of ferromagnetic materials, and the researchers have explored the method of magnetic memory for the detection and evaluation of early damage or defect of ferromagnetic materials[6]. Because the micro mechanism of magnetic memory testing is complex, the existing force magnetic coupling model has its own defects, which can not accurately describe the force magnetic coupling effect. In quantifying the early damage or defect of ferromagnetic materials and analyzing the complex relationship between stress-strain and magnetic memory signal, uniaxial and biaxial tensile tests or fatigue tests under various typical loads are mainly used, which is used to analyze the qualitative relationship between the mean stress and the magnetic memory signal. A large number of experimental statistical data can fit the quantitative
3.2. Analysis of external influence factors of magnetic memory testing signal

Researchers found the following phenomena in a large number of magnetic memory testing practice [7]. When the same workpiece is in different detection positions or the magnetic memory detector uses different detection parameters, such as different detection speed, detection probe lift off value, etc., the acquired magnetic memory signals are not exactly the same. Therefore, due to the influence of various external factors, the magnetic memory detection signal will show certain randomness. Different factors have different influence on the detection signal. That is to say, magnetic memory detection is a kind of micro magnetic detection method under the action of geomagnetic field. Because the magnetic memory signal is the weak magnetic signal produced by ferromagnetic materials under the action of stress and geomagnetic field, it is easily affected by many factors such as external environmental factors and human factors. Therefore, the accurate extraction of magnetic memory signal is the key to the quantification of magnetic memory detection technology. In recent years, many scholars have carried out in-depth research and Analysis on the factors affecting the magnetic memory signal.

After studying the relationship between the magnetic memory phenomenon and the geomagnetic field, Li Luming of Tsinghua University thinks that the magnetic memory testing method can effectively judge the stress concentration area of steel pipe, and the geomagnetic field has no decisive influence in the process of magnetic memory testing. Li Lianxiu used magnetostrictive equations to study the conditions and laws of magnetic memory phenomenon in detail. He found that stress can change the magnetic properties of the material, while the geomagnetism can change the piezomagnetic field of the material, and the two work together to produce a net magnetic field. The phenomenon of magnetic memory is not only related to the stress and magnetic properties of materials, but also related to the position and direction of the workpiece in space.

Yu Fengyun studied the influence of component placement direction on magnetic memory signal through experiments. It is found that the distribution of magnetic field intensity on the surface of the sample would not change regardless of the placement of the sample. The orientation of the component affects the intensity of the magnetic field, but it has no influence on the judgment of the stress concentration area.

Liu Shujun analyzed the influence of external factors such as probe lift off, pipe placement direction, crack orientation and detection speed on the magnetic memory detection signal through the comprehensive test bench. The influence of external factors on the magnetic memory detection signal is obtained. It is found that the intensity and gradient of magnetic field decrease with the increase of lift off value. The relationship between signal attenuation $S$ and lift off fluctuation $\Delta h$ is given by equation (2).

$$ S = K \Delta h / h^\omega $$

In the equation (2), $K$ is impact factor, and $h$ is value of lift off. Lift off does not affect the determination of the stress concentration position according to the existing criteria. However, in the actual detection, the sensitive area should be avoided as far as possible.

3.3. Extraction of damage evaluation parameters

The unique advantage of magnetic memory testing technology is that it can detect the early damage of ferromagnetic components. It can predict the dangerous area with serious stress concentration, so as to avoid accidents. However, a large number of engineering practices show that the above criteria for determining the stress concentration area sometimes lead to misjudgment [8].

Li Luming of Tsinghua University studied the quantitative relationship between magnetic memory signal and welding residual stress of 16MnR steel pipe. His research shows that there is a correlation between welding residual stress and magnetic memory signal.
Zhang Jun of Harbin Institute of Technology put forward a method of combining wavelet transform with gradient of normal component of magnetic field intensity to judge abnormal stress concentration area.

Ren Jilin of Nanchang Institute of Aeronautical Technology extracts normal and tangential magnetic memory signals at the same time and makes Lissajous diagram. The size of the closed defect ring in the diagram reflects the degree of stress concentration. In fact, the error of this method is large.

Huang Bingyan of Tianjin University used the Gauss equation in the magnetic field and the intensity of the magnetic memory signal at the prefabricated welding crack. The relationship model between stress and MFL signal is established, and the quantitative analysis of stress concentration at crack tip of pipeline steel is preliminarily discussed.

Di Xinjie of Tianjin University extracted two characteristic quantities, namely, the distance DL between the peaks and troughs of the first-order differential magnetic memory signal and the difference DH between the peaks and troughs of the first-order differential magnetic memory signal, to quantitatively evaluate the welding cracks. The characteristic quantity DL mainly reflects the length of welding crack and DH mainly reflects the buried depth of welding crack.

Ding Hui of Wuhan University established a mathematical model between the stress field of crack like defects and the change of magnetic flux, and clarified the change law of magnetic flux at different time of crack buried depth, width, strike, stress condition and external magnetic field, which provides a theoretical basis for the magnetic memory testing of crack like defects.

The above criteria of stress concentration area are analyzed by extracting the feature pairs of one or several aspects of the signal. Therefore, the accuracy and reliability of the decision rules need to be improved. In the future, the signal characteristics can be comprehensively analyzed to improve the reliability of the decision rules.

4. Future research direction of magnetic memory
At present, the most important problem in the development of magnetic memory is quantitative detection, which directly limits the application and development of magnetic memory. Because the mechanism of magnetic memory testing is not clear, magnetic memory testing technology can only detect the stress concentration position of ferromagnetic materials, and can not quantify the early damage [9]. For ferromagnetic equipment, quantifying early damage is not only the premise of taking correct maintenance measures, but also the important basis of predicting the remaining life of equipment [10]. In other words, it is easy to waste to replace the equipment or components too early, and it may lead to accidents to take maintenance measures too late. Therefore, the quantitative study of early damage is very necessary, and it has become a key scientific and technological problem restricting the development and application of magnetic memory testing technology. Because the research work of magnetic memory technology mainly comes from engineering practice and lacks systematic mechanism research and experimental verification, the micro mechanism of magnetic memory detection has not yet formed a systematic theoretical system. The complex coupling relationship between stress concentration and magnetic flux leakage (MFL) is not fully clear, and the complex nonlinear relationship between stress concentration, MFL and magnetic memory (MMM) signal is even more difficult to establish, which leads to fact that the magnetic memory technology can not quantify the early damage identification. Therefore, it is very important to establish a correct mechanical magnetic coupling model, which is the basis of magnetic memory testing research.

5. Conclusions
The development of magnetic memory testing is analyzed, and the problems encountered in the development of magnetic memory are studied. The research on magnetic memory mainly focuses on the following three aspects, study on the mechanism of mechanical magnetic coupling, analysis of external influence factors of signal and extraction of damage evaluation parameters. The development direction of magnetic memory testing in the future is summarized. That is, to strengthen the research
on the micro mechanism of magnetic memory and to establish the correct mechanical magnetic coupling model.

References
[1] A.A. Dubov, Metal Science and Heat Treatment, 39, 401(1997)
[2] H. Fan, W. Wang, Mater Sci Eng, 32, 705 (2014)
[3] S. Bao, P. F. Jin, Z. Y. Zhao, Nondestruc Eval, 39, 11(2020)
[4] J. W. Wilson, G. Y. Tian, S. Barrans, Sensors and Actuators A: Physical, 135,381(2007)
[5] S.J. Liu, Z.X. Li, Y. Su, Applied Mechanics and Materials, 148, 1404(2012)
[6] P.P. Shi, S. Hao., Acta Physica Sinica, 70, 3 (2021)
[7] W. Wang, G. C. Ren, S. Q. Su, Mater Sci Eng, 36, 66(2018)
[8] C.C. Li, L.H. Dong, H.D. Wang, Nondestructive Testing, 37, 3(2015)
[9] J.L. Ren, J.L. Sun, P. Zhou, Chinese Journal of Mechanical Engineering, 49, 8(2013)
[10] A.A. Dubov, A. Dubov, S.Kolokolnikov, Welding in the World, 58 , 225(2014)