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EFFECT OF EXTERNAL FIELD ON THE VARIATION OF MAGNETIC MEMORY SIGNALS

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ABSTRACT

Tensile-tensile fatigue tests of 16MnR steel sheet specimens with prefabricated flaws were carried out to measure spontaneous stray field signals of stress concentration zones by GMR sensor, and excitation device was used to make external field excitation for sheet specimens. The results showed that the tangential component of stray field signals can still be considered as generalized magnetic memory signals when tests were conducted in external field without load. Magnetic memory signals were strengthened due to external magnetic excitation, improving sensitivity of detection system. The tangential component of stray field signals presented the maximum value at the stress concentration zones, which increased as cycle number increase, and the growth rate isn't identical in different stages of fatigue damage..

Keywords: metal magnetic memory; external field; stress concentration zone; 16MnR steel

1. INTRODUCTION

Pressure vessels under alternating loads are prone to induce micro-defects and implicit discontinuous damage. If micro-defects could not be found in time, a catastrophic accident may happen [1-3]. Conventional non-destructive testing techniques, such as ultrasonic testing and magnetic particle inspection, only can detect already developed defects, but show powerless to early damage caused by stress concentration.

The MMM technique was put forward by Russia scholar Dubov A. A in the late 1990s, and has been widely studied by Chinese scholars and Eastern Europe scholars. The physics of the technique is the coupling of stress, magnetic and material structures, and the magneto-mechanical effect is dominant in the elastic stage. The MMM technique is a novel non-destructive testing method which inspects damage to ferromagnetic parts by analyzing the magnetic memory signals of the surface of testing specimens [4].

However, owing to weak field detection, the detection information which is very weak could be affected easily by some interfering factors, such as the difference of demagnetizing field, microstructure distribution and heat treatment and so on, leading to a serious distortion of test results and cannot obtain valid conclusions [5,6].

In this paper, tensile-tensile tests were carried out to verify the feasibility that enhanced external field excitation through excitation device can suppress the effect of interference noise and improve the sensitivity of detection system.

2. THE SENSITIVITY ANALYSIS OF DETECTION SYSTEM

Metal magnetic memory effect is a magneto-mechanical effect under geomagnetic field. From the broad perspective, the magneto-mechanical effect indicate that a series of changes of the magnetic properties of ferromagnetic materials due to the coupling between stress and the magnetization [7].

According to the magnetic effective field, the magnetic memory signal is equivalent to the change of the magnetic induction intensity derived by the magnetic effective field. So we can propose the detection system sensitivity

$$K = \frac{\mu\left(H_{e\sigma} - H_{e0}\right)}{\left(\sigma - \sigma_0\right)} \tag{1}$$

Where μ is magnetic permeability, $H_{e\sigma}$ is effective field under loading, H_{e0} is effective field before loading, σ is stress, σ_0 is the initial residual stress prior loading. H_{e0} and σ_0 can be considered as constant to specific specimen.

Effective magnetic field $H_{e\sigma}$ can be expressed as [8]

$$H_{e\sigma} = H_{eo} + \alpha M + \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{\partial \lambda}{\partial M}\right)_T \tag{2}$$

Where α is the strength of the coupling of the individual magnetic moments to the magnetization M , λ is the magnetostriction, and μ_0 is the vacuum magnetic permeability.

Owing to λ symmetrical about $M = 0$, so when M is in the case of smaller values, we can conclude

$$\lambda = bM^2 \tag{3}$$

$$(\frac{\partial\lambda}{\partial M})_T = 2bM \tag{4}$$

Where the coefficient b can be determined by experiment.

According to Weiss molecular field theory, the magnetization of the specimens can be modified in terms of Langevin function representation in the ideal case, and the magnetization in small magnetic field can be expressed as [9]

$$M = M_s\left[\coth\left(\frac{H_{e\sigma}}{a}\right) - \frac{a}{H_{e\sigma}}\right] = M_S\frac{H_{e\sigma}}{3a} \tag{5}$$

So we can obtain

$$M = \frac{\mu_0 H M_S}{3a\mu_0 - M_S(a\mu_0 + 3b\sigma)} \tag{6}$$

$$H_{e\sigma} = H\left[1 + \left(\alpha + \frac{3b\sigma}{2}\right)\frac{\mu_0 M_S}{3a\mu_0 - M_S(a\mu_0 + 3b\sigma)}\right] \tag{7}$$

By the above formula, the magnetic effective field $H_{e\sigma}$ increase while the external field increases. The permeability isn't constant, but increases as the external field increases dramatically under external field.

Fig.1 shows the permeability of 16MnR steel, the permeability increase sharply when the external field is in the range of 0 to 560 A/m [10]. According to the relevant literature [11], the geomagnetic field H =40 A/m; M_S =1.71×10^6 A/m; a =995 A/m; α =0.8×10^{-3}; b =2.4×10^{-18} (A/m)$^{-2}$; μ_0 =4π×10^{-7} H/m. It can obtained by calculating, the sensitivity increase about 30 times when external field change from 40 A/m to 560 A/m.

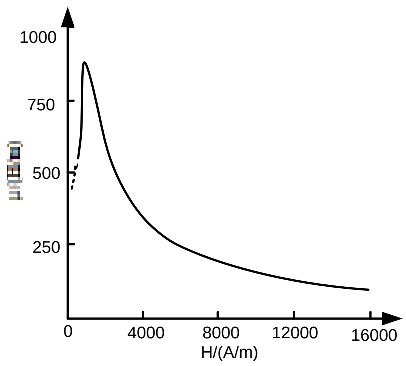

Figure1. The permeability curve of 16MnR steel

3. EXPERIMENT

3.1 Specimen

The specimens are made of 16MnR steel which is an important pressure vessel steel and has a high strength and toughness. Its tensile strength is 549MPa, and yield strength is 398MPa, respectively. Its main chemical composition is shown in Table 1.

Table.1 Chemical composition of experimental material (mass fraction, %)

Steel	C	Mn	Si	P	S
16MnR	≤2.20	1.20~1.60	0.20~0.55	≤0.035	≤0.030

In the experiment, the measured area is 60 mm×20 mm×4 mm. A 2.5mm gap was symmetrically prefabricated on both sides of the middle of the specimen. Fig. 1 illustrates its shape and size. Prior to the testing, the specimens were heated to 650℃ and kept for 30 min in a vacuum heat treatment furnace, and then cooled naturally in the furnace. Then, the specimens were demagnetized by TC-50 demagnetization machine to eliminate the magnetism during processing. The parallel lines drawn on the surface of the specimen is a fixed detection area.

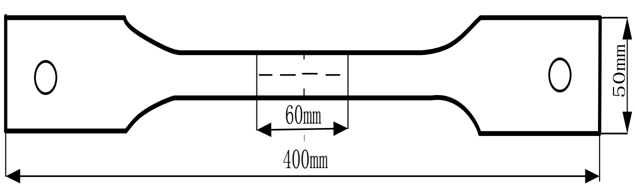

Figure.2 Specimen shape and scanning line

3.2 Experiment instruments

The detection system is comprised of GMR sensor, processing circuit, data acquisition system and post-processing, as shown in Fig.2.

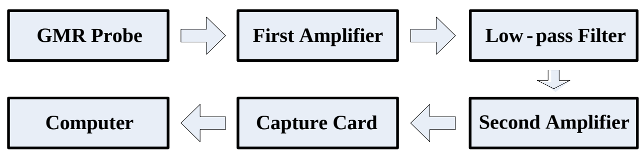

Figure.3 Detection system based on GMR sensor

The type of GMR sensor is AA002, which has a high sensitivity for measuring magnetic field, choosing Wheatstone bridge to analogue output. It can endure the highest continuous working temperature of 125 ℃ with a wide range of linear output. It is suitable for low power, low voltage situations and usually works on the condition of low magnetic field.

The DC excitation device which can float along the surface of the specimens could still be effective in the case of tensile deformation. The excitation device contains mainly the coil, the core and the hinge plates. A closed field circuit is formed once the current is connected.

3.3 Experiment method

Tensile-tensile testing was carried out, which used the sinusoidal waveform cycle, and the maximum tension is 330MPa and the minima is zero, loading frequency is 1 Hz.

Using off-line detection, probe scanned in the middle of specimen of the speed of 10 mm/s, tracking the whole process of specimen's change from unloading till failure. Owing to far distance from the crack tip, the results should be magnetic signals generated by stress concentration zones in the central region of the specimen.

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1 The effect of external field on magnetic memory signals

By analyzing the test results, we found that magnetic memory signals exhibited the same variation regularity under different specimens. The total fatigue process is divided into the initial stage, the intermediate stage and the final stage, choosing a representative specimen for analysis.

Fig.4 shows that the signal curve at different excitation field and the abscissa is detection distance while the vertical axis is the tangential component of magnetic signals measured by the GMR sensor. Under geomagnetic field excitation condition, micro-cracks appear at the notch root of the specimen after 1000 cycles. The crack growth to about 1 mm after 5000 cycles, then to about 2 mm after 9000 cycles, at that moment the width of specimen is only 11 mm. The specimen failed after 11015 cycles. The crack propagation under external magnetic excitation which fractured at 12867 cycles is similar to that under geomagnetic field. While the magnetic memory signal is influenced by interference noise under geomagnetic field, a numerous number of abnormal peaks appeared in detection zone, as shown in Fig.4. The position of the maximum value is not uniform, so it cannot evaluate fatigue damage only through the tangential component of the magnetic field under geomagnetic field.

However, after the specimens were excited by the excitation device, the magnetic memory signal was strengthened and the external interference factors were suppressed effectively. There is only a peak in detection zone whose position maintained in the range of 30 to 33 mm, which is good agreement with the specimens of prefabricated defects, as shown in Fig.4. So, external field appropriately can suppress effectively stray interference fields and increase the sensitivity of the detection system, improving significantly the detection effect.

4.2 The effect of cycle number on magnetic memory signals

Fig.5 shows magnetic signal amplitude curve under different cycles under geomagnetic field and external field, respectively. When the specimen was excited under geomagnetic field, the amplitude is in the range of 100 to 900 mV, and the relationship between the amplitude and cycle number is irregular due to the presence of interference. However, the amplitude of magnetic signals is in the range of 300 to 5700 mV under external field, and the external field can strengthen the magnetic memory signals and weaken the impact of interference fields.

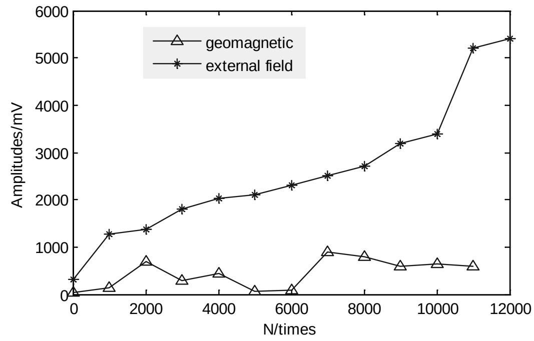

Figure.5 Magnetic signal amplitude curve under different cycles

The magnetic memory signals increase gradually with the number of cycles, and the change rate is different in different stages of fatigue process, as shown in Fig.6. At first, the magnetic field intensity varied due to the irreversible movement of domain wall derived by alternating stress. The magnetic field intensity produced cumulative effect with the number of cycle, resulting leakage magnetic field increase gradually. After the micro-cracks formed, the stress concentration zones emerged quickly around the cracks, accelerating the local magnetization and two poles formed immediately in two end faces of micro-cracks. When the micro-cracks developed into the macro-cracks, the crack and the end reach up to magnetic saturation, forming the N-S pole and resulting in a strong magnetic field leakage.

5. CONCLUSIONS

1) Owing to interference by external field, it is difficult to evaluate exactly stress concentration zones through the tangential component of magnetic memory signal exhibits peak. The detection effect can be improved significantly by means of strengthening external field excitation.

2) The permeability of ferromagnetic materials and the stress-induced effective field increase due to the effect of external field excitation, enhancing the sensitivity of the magnetic memory system.

3) The specimens tested exhibit peak which increases with cycle number in the stress concentration zones under external field excitation. The change rate of amplitude varies in different stages of fatigue damage, and the regularity is more obvious than that in geomagnetic field.

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REFERENCES

[1] Gilanyi A, Morishita K, Sukegawa T, et al. Magnetic nondestructive evaluation of fatigue damage of ferromagnetic steels for nuclear fusion energy systems[J]. Fusion Engineering and Design, 1998, 42: 485-491.
[2] Nian Li, Baiping Du. The effect of low-stress high-cycle fatigue on the microstructure and fatigue threshold of 40Cr steel. Int J Fatigue 1995; 17(1):43-48.
[3] Xiulin Zheng. On some basic problems of fatigue research in engineering. Int J Fatigue 2001;(23): 751-766.
[4] Dubov A A. Diagnostics of boiler tubes with usage of metal magnetic memory [M]. Moscow: Energoatomizdat, 1995: 6-8.
[5] Jing Zhang, Keyin Zhou, Entao Yao, et al. Improved metal magnetic memory testing method [J]. Physical Testing and Chemical Analysis Part A: Physical Testing, 2004,40(4):183-186.(in Chinese)
[6] Lihong Dong, Binshi Xu, Shiyun Dong, et al. The effect of tensile stress and residual stress on the spontaneous stray field signals from the surface of 0.45%C steel [J]. Chinese Journal of Mechanical Engineering, 2007, 20(6): 29-32.
[7] Jilin Ren. Electromagnetic non-destructive testing [M]. Beijing: Science Press, 2008:370-377.(in Chinese)
[8] Naus H W L. Ferromagnetic hysteresis and the effective field [J]. IEEE transactions on Magnetics, 2002, 38(5):3417-3419.
[9] Garikepati G, Chang T, Jiles D C. Theory of ferromagnetic hysteresis: Evaluation of stress from hysteresis curves [J]. IEEE Transactions on Magnetics,1998, 24(6):2922-2924.
[10] The qualification examination committee of weapon industrial nondestructive testing personnel. The quick manual of magnetic properties curve of commonly used steel [M]. Beijing: Mechanical Industry Press,2003:41.(in Chinese)
[11] Jiles D C. Theory of the magnetomechanical effect [J]. Journal of physics D-applied physics, 1995, 28(8):1537-1546.