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Residual magnetic field variation induced by applied magnetic field and cyclic tensile stress

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ABSTRACT

Magnetic memory testing (MMT) method is a novel non-destructive testing technique due to its unique advantages of stress concentration identification and early damage detection for ferromagnetic materials. However, a thorough understanding of the impact of exciting magnetic source and cyclic stress on the residual magnetic field variation has not been clearly addressed. The surface magnetic memory signal $H_p(y)$ induced by applied magnetic field and cyclic tensile stress was measured throughout the fatigue process. The correlation of $H_p(y)$ and its gradient K changes with loading cycles and applied magnetic field intensity H reported. The results show that applied magnetic field can only change the magnitude of MMT signal instead of changing the $H_p(y)$ curve's profile. The $H_p(y)$ value increases with the increase of the H, and the K value is approximately linear to the H. The maximum gradient K_{max} indicating the degree of stress concentration increases with the increase of either stress cycles or H. The phenomenon was also discussed from the view of the magnetic dipole in a ferromagnet.

1. Introduction

Stress concentration and fatigue crack, as a result of fatigue, are critical indicators to predict the fatigue life of ferromagnetic components which are subjected to alternating load in service [1]. Traditional nondestructive testing (NDT) technique, such as ultrasonic testing, eddy current testing, magnetic particle testing, magnetic flux leakage testing and X-ray testing developed for the crack detection, are supposed to be insensitive to material property degradation, though recent researches also revealed some NDT techniques, e.g. ultrasonic testing, to be sensitive for fatigue before micro cracking [2]. Magnetic memory testing (MMT) method, a novel and passive magnetic method, was developed for inspecting early damage, including stress concentration, micro-detects or mechanical degradation of ferromagnetic materials [3–5]. It has great potential to be used in various areas such as welding, pressure vessels, boiler, power, and pressure pipeline.

MMT method utilizes the stress-induced surface magnetic fields of ferromagnetic materials under the excitation of geomagnetic field to investigate its stress distribution. The normal component of the residual magnetic field, $H_p(y)$, which is known as magnetic memory signal, was investigated in both tensile [6–9] and bending tests [10–11]. The results reveal that the normal component $H_p(y)$ shows apparently different variation characteristics in the elastic and plastic ranges for low carbon steels; and the inverse magnetostrictive effect (Villari effect) and its early detection have also been well documented for the MMT method.

While the magnetic memory signals are influenced by the initial magnetic field, stress concentration of the ferromagnet and the environmental magnetic field during detection. The stress concentration extremely affects the magnetic memory signals of a ferromagnet [12–15]. And the gradient of the residual magnetic field components was further used to identify the degree of stress concentration. The values and the distributions of the gradients show a good, both qualitative and quantitative, correlation with the values and distributions of residual stress; and the quantitative relationships between the gradients and equivalent residual (von Mises) stress were developed and verified [16–17]. Moreover, the initial magnetic states also have great impact on the variation of surface magnetic memory signals [18–19]. And the environmental magnetic field during detection can only change the magnitude of MMT signal instead of changing the curve's profile or variation trend [20]. As it is well known, the geomagnetic field plays the role of an exciting source in generating residual magnetic field for the MMT method. It is still unknown that how residual magnetic field varies with the applied exciting magnetic field, and how applied magnetic field combined with stress contributes to the magnetic memory signals. This paper carried out tension–tension fatigue tests of Q345 steel specimens when a magnetic field is applied with different magnetic field intensities. The quantitative relationships between the surface residual magnetic memory signals and applied magnetic field and cyclic stress were investigated.

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Table 1
Chemical composition of the Q345 steel (wt%).

Steel	C	Mn	Si	P	S	Cr	Ni	Cu
Q345	0.17	1.36–1.56	0.32–0.36	0.017–0.022	0.011–0.033	0.02–0.13	0.035–0.12	0.12–0.15

Table 2
Mechanical properties of the specimens.

Steel	Yield strength σ_s/MPa	Ultimate strength σ_b/MPa	Elongation rate/%
Q345	358	484	25.71

2. Experimental section

2.1. Specimen preparation

The specimen is made of Q345 low-carbon steel, which is a kind of structure steel widely used in pressure vessel and bridge. Its chemical constitution and mechanical properties are listed in Tables 1 and 2. The shapes of sheet specimens are given in Fig. 1. Test lines were marked on each specimen, and these specimens were polished and demagnetized before loading.

2.2. Experimental instruments

An experimental system in which both applied magnetic field and stress are controllable was established as shown in Fig. 2. Dynamic tension loads were applied to the specimens on MTS810 servo hydraulic testing machine, whose dynamic load error is within $\pm 1.0\%$. Tension–tension fatigue tests of constant amplitude (sinusoidal waveform) were performed, with the maximum stress at 333 MPa and the minimum stress at 33.3 MPa. The one-dimensional Helmholtz coil was placed vertical to the ground, so that the direction of applied magnetic field was parallel to the tensile stress. Thus the applied magnetic field worked on the specimen along with the geomagnetic field and cyclic tensile stress.

The experiments were carried out at room temperature. The one-dimensional Helmholtz coil can generate a constant magnetic field range from -1600 A/m to 1600 A/m in the center of the coil. The applied magnetic field intensity can be precisely controlled by adjusting the current passing through the coil. EMS2003 magnetic memory/eddy current detection diagnostic instrument was used for the measurements of magnetic memory signals. Two-channel probe was installed on a non-ferromagnetic scanning platform, with the lift-off value of 0.5 mm and movement speed of 8 mm/s along the scanning lines during testing. The instrument was calibrated in the magnetic field of the Earth, with a value assumed at 40 A/m.

2.3. Experimental procedure

In the fatigue tests, the specimens were unloaded when the number of loading cycles reached to 2000, 3000, 4000 and 5000, and examined away from the testing machine by laying them on the scanning platform in south to north direction. For specimen 1, the current passing through the Helmholtz coil was set as the fundamental current $I_B = 0.24$ A. It produced a magnetic field whose intensity was $H_B = 200$ A/m. Adjusting the current passing through the Helmholtz coil to $1.5I_B$, $2I_B$ and $2.5I_B$ for specimens 2, 3 and 4, and they produced a series of magnetic fields with intensity of $1.5H_B$, $2H_B$, $2.5H_B$, respectively.

3. Results and discussion

In order to further describe the variation of residual magnetic field, the gradient of the $H_p(y)$ curves, K, was given by Eq. (1) as following.

$$K = |\Delta H_p(y)/\Delta L| \tag{1}$$

where $\Delta H_p(y)$ is the differential value of magnetic signals between two points; ΔL the distance between the two points. The maximum gradient of $H_p(y)$ on the scanning line, K_{max}, was given by Eq. (2) as following.

$$K_{max} = max(|\Delta H_p(y)/\Delta L|) \tag{2}$$

Fig. 3 shows the variation of the residual magnetic field. It can be seen that the $H_p(y)$ is stable with the application of cyclic stress, and it increases with the increase of applied magnetic field intensity H. With the increase of stress cycles, stress concentration becomes more and more intensive at the location of the notch, where $H_p(y)$ changes sharply crossing zero value and appears maximum gradient value K_{max}. Nevertheless, the $H_p(y)$ curves have good linearity at the location away from the stress concentration area, and the gradient K is constant, nearly not affected by the stress cycles. It can be seen that K is only relevant to the applied magnetic field intensity H, as shown in Fig. 4. The gradient is approximately linear to the magnetic field intensity, which is described by Eq. (3)

$$K = aH + b \tag{3}$$

where a and b are both constant values related with the applied magnetic field, the material and shape of the specimen. In the experiment, a is 0.61, b is 0.45. It can be seen that the gradient K and magnetic field intensity H are well fitted by Eq. (3) in Fig. 4a. In the fatigue tests, applied maximum stress was very close to the yield limit of the material of Q345, thus plastic deformation appeared immediately under the effect of fatigue load. Known from ferromagnetics, the specimen comes into plastic deformation stage and appears many dislocations after a few stress cycles, which prevent the domain wall moving and weaken the magnetization [21]. Relaxation of internal stress occurs due to dislocation slip so that magnetic signals are independent on the loading cycles. These findings were consistent with the observations in both cyclic tensile and bending tests [10–11,22].

Fig. 4b indicates that K_{max} rises with the increase of either stress cycles or applied magnetic field intensities. It shows that the point of intersection of $H_p(y)$ curves is approximately crossing zero value, and recognizes the crack center where is the most serious stress concentration zone. The K_{max} increases with the increase of stress cycles, since the stress concentration at the zone approaching the notch of the specimen becomes more and more intensive, which was also observed in many tests [10–11,14–15]. Accordingly the K_{max} can be detected to identify the stress concentration in the specimen. Magnetic charge models were originally developed for simulating the self-magnetic flux leakage (SMFL) signal due to the existence of cracks [23–24]. As shown in Fig. 5, the permeability decreased sharply at the position of the notch of the specimens, and under the magnetization effect of the applied magnetic field,