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Characterization of spontaneous magnetic signals induced by cyclic tensile stress in crack propagation stage

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ABSTRACT

Influenced by the geomagnetic field, crack can induce spontaneous magnetic signals in ferromagnetic steels. The normal component of surface spontaneous magnetic signals of the center-cracked sheet specimens, $H_p(y)$, was measured throughout the tension–tension fatigue tests. The variation of $H_p(y)$ and its maximum gradient K_{max} in the crack propagation stage were studied. It shows that $H_p(y)$ began to change its polarity, just right on the crack position, in the intermediate stage of crack propagation. The cause for this phenomenon was also discussed. The peak-to-peak value, $\Delta H_p(y)$, of the magnetic signal when $H_p(y)$ changing its polarity was collected, and discrete wavelet transform (DWT) was further used to acquire high frequency components of the $H_p(y)$ signal. The results show that the K_{max} increased exponentially with the increase of loading cycles; an approximate linear relationship was found between K_{max} and crack length $2a$ in the intermediate stage of crack propagation; and the high-frequency component of $H_p(y)$ can be used to identify the late stage of crack propagation.

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1. Introduction

Generation of transient magnetic fields during tensile crack propagation and fracture of low carbon steels was first reported by Misra [1]. More detailed discussions on the fundamental mechanism and theoretical model have also been further given by Misra [2,3]. However, this signal was generated not just at the instant of fracture but prior to the fracture [2]. It should be noted that this spontaneous magnetic field also appears in the fatigue crack propagation stage when the ferromagnetic steels do not undergo large necking.

A fatigue crack is usually initiated by stress concentration or microdefects in a ferromagnetic component subjected to dynamic or cyclic loading, even under stress much lower than its ultimate strength [4,5]. These stress concentration and microcrack induced by cyclic stresses will produce leakage magnetic field in the surface of ferromagnetic materials, which has also been reported as one phenomenon of magnetic mechanical effect [6,7]. In the view of micro-structures of ferromagnets, the magnetic domain state in the deformation field changes irreversible, and the self-magnetic flux leakage is recorded as the form of spontaneous magnetic signals, which is also called as "magnetic memory signal" [8,9].

The magnetomechanical effect and its physical mechanism of the spontaneous magnetic phenomenon are discussed via both tensile and bending tests, and the variation of the magnetic signal induced by tensile stresses and cyclic stresses are also investigated in many experiments. Dong et al. [10,11], Shi et al. [12], Guo et al. [13], Yang et al. [14], Leng et al. [15] and Huang et al. [16] investigated the variation of magnetic signals induced during tensile tests of ferromagnetic steels. Leng et al. [17] and Huang et al. [18] conducted the bending fatigue experiments under different stress levels to investigate the magnetomechanical effect. The results show that the normal component of the magnetic field, $H_p(y)$, which is known as the metal magnetic memory signal, can be used to evaluate the materials' degree of damages in both elastic and plastic deformation stages, and the degree of stress concentration can be reflected by the $H_p(y)$ changing its polarity, tangential component $H_p(x)$ and gradient K reaching a peak value.

The magnetic memory signals show apparently different variation characteristics in the elastic and plastic ranges [19–21]. However, the physical mechanism of the spontaneous magnetic signal is still unclear so far. The regularity of magnetic memory signals was investigated in the fatigue crack propagation process under the dynamic bending load [18], though it is unknown that how magnetic signal induced by the cyclic tensile stress varies in the plastic deformation stage and in the crack propagation stage. So the spontaneous magnetic signals need to be analyzed further in order to identify whether and how the signal can be used to detect the crack propagation in the tensile fatigue process of

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ferromagnetic steels. This paper is prepared to explore the variation of the spontaneous magnetic signals in crack propagation stage of ferromagnetic steel. The fatigue crack propagation and corresponding magnetic field distributions at different loading cycles throughout the fatigue process were investigated; discrete wavelet transform (DWT) was adopted to analyze the magnetic memory signals, which has emerged to be a useful tool for the detection and analysis of the transient behavior of the signal; and the physical mechanism was discussed in detail.

2. Experiment

The specimen was made of Q345 low-carbon steel, which is commonly used in automobiles, pressure vessels, bridges and hoisting machineries. Its yielding strength is 358 MPa; ultimate strength is 484 MPa; elastic modulus is 206 GPa; shear modulus is 79.38 Gpa; and Poisson's ratio is 0.25–0.30. Its chemical constitution is shown in Table 1. Specimens were fabricated according to the Chinese Standard GB2975-1998, GB/T3273-2005 and GB/T6398-2000. Fig. 1 presents the shape of the sheet specimen, in which the length of the notch a_0 is 17.401 mm and the thickness is 6 mm. And three parallel scanning lines #1–#3 were labeled along the length direction. Scanning line #1 and #3 covered the initial crack tip; and scanning line #2 crossed the center of the notch.

To eliminate the impact of the initial magnetic field, specimens were demagnetized before loading. 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 192 MPa and load frequency at 10 Hz. The experiments were carried out at room temperature.

Table 1
Chemical composition (wt%) of the tested material.

Material	C	Si	Mn	P	S
Q345	0.12–0.20	0.20–0.60	1.20–1.60	≤ 0.035	≤ 0.035

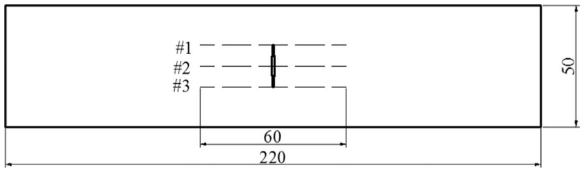

Fig. 1. Shape of sheet specimen (in mm), and the scanning lines.

The $H_p(y)$ values were measured by EMS 2000+ metal magnetic memory device in the geomagnetic field environment. The probe with a 1 A/m sensitivity based on Hall sensor was gripped on a non-ferromagnetic 3D electric scanning platform, and was placed vertical to the surface of specimen with a lift-off value of 1 mm. When loaded to the preset cycle number, the specimen was taken from the holders carefully and laid on the platform in south to north direction, and the $H_p(y)$ values at the three scanning lines were measured. And the length of the fatigue crack was measured by a JXD-250B reading microscope.

3. Results and analysis

3.1. Spontaneous magnetic signals

During the test, fatigue crack was initiated at the tip of notch and propagated gradually with the increase of loading cycles. And three stages of crack propagation were observed. In the early stage of crack propagation, the fatigue crack was only just observed by using the JXD-250B reading microscope at the loading cycle of 7000. In the intermediate stage, the crack had propagated to a certain length at loading cycles from 7500 to 12500. In the late stage, the crack propagated rapidly at loading cycles from 13,500 to 15,500, and the specimen was fractured at the loading cycle of 16,080.

The variation of magnetic signals measured on the #1 and #3 lines have identical features; therefore, only results from line #1 and #2 are presented. The relationship between magnetic memory signals on the scanning lines and loading cycles in the different stages of crack propagation is shown in Figs. 2 and 3. It can be seen that the $H_p(y)$ varied intensively in the crack area in all the three crack propagation stages, and the $H_p(y)$ value on the left end of the scanning lines varied with the increase of loading cycles, which was −30 A/m at the loading cycle of 10 and 90 A/m at the loading cycle of 15,500. Jiles developed a model to describe the stress dependence of magnetization, which shows the rate of change of magnetization depends not only on the tensile stress but also on the anhysteretic magnetization [6]. The magnetization is reduced with applied cyclic stress to overcome the internal friction forces so that it could approach its anhysteretic state, which was an irreversible process. More domain wall pinning sites appeared

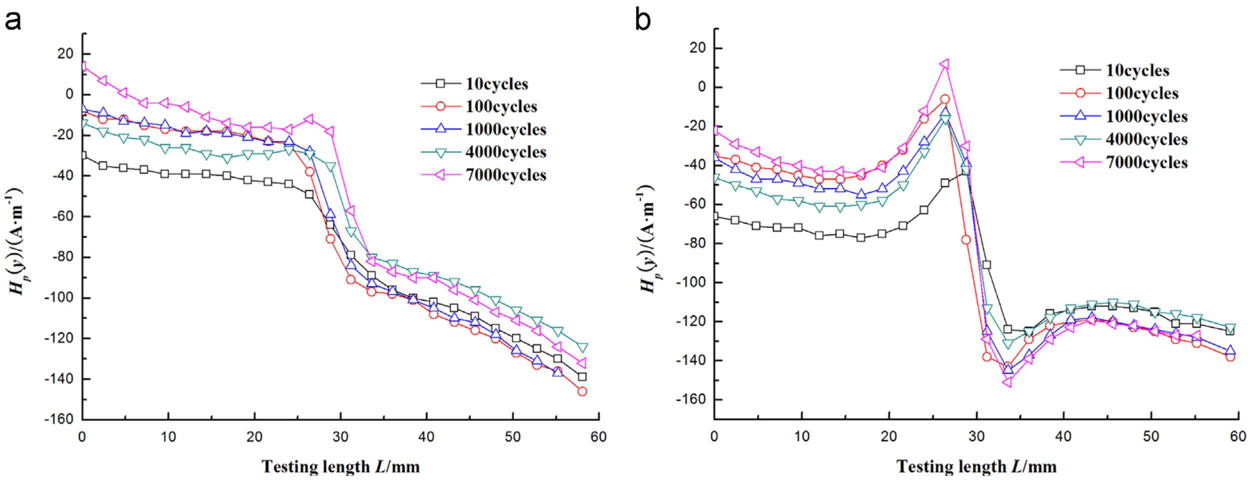

Fig. 2. Spontaneous magnetic signals at specimens in the early stage of crack propagation: (a) from scanning line #1; and (b) from scanning line #2.

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