Abnormal Magnetic Signals Characterization of Fatigue Crack Propagation Life

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Abstract. In this research, the abnormal magnetic signals were detected in dynamic tension tests on the ferromagnetic material specimens, in order to study the characterization method of abnormal magnetic signals for the crack propagation life. It is indicated that fatigue crack length $a$ is linear with the peak-peak value $\Delta H_{pa}(y)$ of abnormal magnetic signals. The $\Delta H_{pa}(y)$ of fatigue crack and the gradient of magnetic field intensity $k$ increase with the increase of fatigue cycle number. Therefore, $\Delta H_{pa}(y)$ and $k$ are confirmed as the key parameters of characterizing crack propagation life. Then, a life prediction model of abnormal magnetic signals for the crack propagation life is founded based on the Paris equation. The maximum error between measured values and calculated values is less than 15%.

1. Introduction

At present, most key components of machinery and equipment are made of ferromagnetic materials[1]. Because the components are subjected to repeated loads, fatigue fracture is prone to occur. Fatigue failure is one of the main failure modes for the components. Because the fatigue failure has a certain suddenness and contingency, it often leads to major accidents. Therefore, the fatigue life prediction is becoming more and more important[2]. The various defects in the ferromagnetic materials will be produced in the process of manufacturing. Under the action of fatigue load, these defects are easily becoming the source of crack, which leads to the fatigue fracture of the component. However, according to the fracture mechanics, it is found that even if there are cracks in some components, as long as we can monitor the crack growth and ensure that the crack will not expand to the critical size, the component can also be safely applied. Therefore, it is of great significance to study the fatigue crack propagation life for the components. In the field of engineering, conventional mechanical testing methods are very difficult to complete the monitoring tasks of the fatigue crack propagation. The nondestructive testing method is very suitable for monitoring the fatigue crack propagation, due to its sensitivity and diversity[3-5]. The metal magnetic memory testing is promoted by the Russian scholar Dubov in 1997 for the first time. The abnormal magnetic signals, which are affected by the geomagnetic field and stress, could be detected by the method. This novel nondestructive testing technology could be applied to detect the stress concentration and surface defect of ferromagnetic material[6,7]. Compared with the traditional nondestructive testing technology, the metal magnetic memory testing does not need to pretreat specimen, and it can be carried out when the specimen is in service. Meanwhile, the stress concentration area or micro defects can be detected in order to predict early warning of fatigue failure, unlike other traditional nondestructive testing methods only have the ability to detect macro defects[8,9].
Using metal magnetic memory testing technology, the loading history of ferromagnetic parts can be detected, and the stress concentration position can be measured. It is possible to characterize the stress concentration degree, damage degree and elastic-plastic state of the material. Therefore, metal magnetic memory testing technology has great potential in life prediction of ferromagnetic components. In this paper, the abnormal magnetic signals in metal magnetic memory testing were detected during dynamic tension tests on the ferromagnetic specimens with U notch. The relationship between abnormal magnetic signals and fatigue crack propagation was studied.

2. Experimental

2.1. Specimens

The base metal of specimens are 45 steel, which is a kind of medium carbon steel. The tensile strength of specimen is 679MPa, the yield strength is 386MPa and the elongation is 16.0%. The specimens were polished. Because the initial magnetic signals could be easily affected by the machining process and heat treatment condition, the specimens were demagnetized before testing in order to study the relationship between the stress, crack length and abnormal magnetic signals in the initial state.

2.2. Experimental Instruments

Instron-8801 hydraulic servo fatigue test machine were used, the dynamic load error was 1.0%. Tension–tension fatigue tests of sinusoidal waveform constant amplitude were carried out. The metal magnetic memory testing device is the EMS-2003 intelligent magnetic memory detector, and the detection probe is a two channel pen probe, the instruments are shown in figure 1. The normal component \( H_p(y) \) of the scattering magnetic field intensity can be tested using this equipment. The magnetic memory detection probe is clamped on the three-dimensional electronic control displacement platform made of aluminium alloy, and the detection step distance is 2.5 m. The fatigue crack propagation was monitored by Olympus i-speed high speed camera, and the length of fatigue crack could be detected.

![Figure 1. Testing instruments: a) Instron-8801 fatigue testing machine b) EMS-2003 detector.](image)

2.3. Testing Procedure

The tension-tension fatigue test were carry out on the flat U notched specimens (stress concentration factor \( K_t \) was 5). Under the cyclic loading (maximum stress was 80MPa, sine wave, stress radio \( R \) was 0.1, loading frequency \( f \) was 10), the number of cyclic loading sequentially increased. The specimen was removed from the fatigue testing machine and placed in the north to south direction on the platform after loading to the predetermined number of cycles. In the middle part of the test piece, 5 parallel lines, whose interval was 5 mm and length was 60mm, was drawn as the detection paths, shown in figure 2. The probe was gripped on the scanning platform, the lift-off value was 0.5mm, the testing speed was 10mm/s, and the sampling time interval was 30ms. The specimen was loaded again
to a higher preset circle value after metal magnetic memory testing, and the above procedure repeated until the specimen cracked.

![Figure 2. Scanning lines of the tension-tension fatigue testing specimen with U notch.](image)

3. Results and Analysis
The experiments are carried out in laboratory condition, so the environmental magnetic field is dominated by the relatively constant geomagnetic field. The abnormal magnetic signals $H_p(y)$ in different detection lines are detected after 1000 fatigue cycle times, shown in figure 3.

![Figure 3. Abnormal magnetic signals $H_p(y)$ in different lines of the specimen after 1000 cycle times.](image)

It is indicated that the gradient $k$ of the abnormal magnetic signal $H_p(y)$ increases rapidly near the U notch in the specimen, and the gradient $k$ of abnormal magnetic signals increases more when it is closer to the U notch. According to the material mechanics, the stress concentration degree increases nearby the U notch. The gradient $k$ increases with the increase of stress concentration\cite{8}, so the gradient $k$ dramatically increases near the U notch in the specimen and the stress concentration of the specimen can be qualitatively determined according to the gradient $k$ of the $H_p(y)$ detection curve. It can be seen that the change of abnormal magnetic signals $H_p(y)$ in $D_5$ detection path is the most obvious in figure 3. So the following analysis will be only around the results in $D_5$ detection path in order to facilitate the analysis and make it representative.

The abnormal magnetic signals $H_p(y)$ in $D_5$ detection path of the specimen after different fatigue cycle times is shown in figure 4. It is indicated that the abnormal magnetic signals $H_p(y)$ increase when the fatigue cycle times increase. The gradient $k$ of the abnormal magnetic signal $H_p(y)$ curves increases dramatically near the U notch in every fatigue cycle time, and the peak of $H_p(y)$ initiates. Therefore, the maximum value $k_{\text{max}}$ of the gradient and the peak-peak value $\Delta H_{\text{pp}}(y)$ of abnormal magnetic signals increase.
signals $H_p(y)$ could be the key parameters to reflect the relationship between the fatigue cycle time and the abnormal magnetic signals.

**Figure 4.** Abnormal magnetic signals $H_p(y)$ of specimen in D5 path after different fatigue cycle times. Firstly, the maximum value $k_{\text{max}}$ of the gradient was studied. The relationship between $k_{\text{max}}$ and fatigue cycle time $N$ is shown in figure 5. It is indicated that the maximum value $k_{\text{max}}$ of the gradient apparently increase at first when the fatigue cycle time increase, which is because the magnetic field strength will increase significantly with the increase of the load when the specimen is in the elastic region at the initial stage of fatigue. But when the cycle number increases to a certain extent, the maximum value $k_{\text{max}}$ trends in the stable, which is because the influence of fatigue load on the magnetic domain structure of the material reaches saturation.

**Figure 5.** Relationship between $k_{\text{max}}$ and fatigue cycle $N$.

With the increase of fatigue cycle time, the micro fatigue cracking is detected by the high speed camera at 8000 cycle times, then the maximum value $k_{\text{max}}$ increases dramatically to the maximum value until the specimen cracked at 18000 cycle times. Meanwhile, there is also the same relationship between peak-peak value $\Delta H_{pa}(y)$ and the fatigue cycle time $N$. According to the fracture mechanics\cite{4}, fatigue crack length increases when the fatigue cycle time increases. At the same time, the preliminary results indicate that the maximum value $k_{\text{max}}$ and the peak-peak value $\Delta H_{pa}(y)$ also increases with the increase of fatigue cycle time. Therefore, there must be some relationship between peak-peak value
\( \Delta H_{pa}(y) \) and the length of fatigue crack \( a \). In order to find the correlation, a fitted curve of peak-peak value \( \Delta H_{pa}(y) \) and the length of fatigue crack \( a \) is shown in figure 6.

![Figure 6. Fitted curve of \( \Delta H_{pa}(y) \) and \( a \).](image)

It can be seen that the peak-peak value \( \Delta H_{pa}(y) \) of abnormal magnetic signals gradually increases with the increase of length of fatigue crack \( a \). Then, the experimental data are fitted, and the fitting equation is shown in equation (1) as following.

\[
a = 0.12 \times \Delta H_{pa}(y) - 4.96
\]

(1)

According to the equation (1), there is a linear relationship between the peak-peak value \( \Delta H_{pa}(y) \) and the length of fatigue crack \( a \). In this research, the equation (1) is simplified to be equation (2) as following in order to be easy to analyze.

\[
a = A \times \Delta H_{pa}(y) + B
\]

(2)

Where \( A \) and \( B \) are constants, affected by material and stress.

At present, the fatigue crack growth life is mainly predicted by the fracture mechanics method \(^7\). In engineering practice, the method, which is most commonly used to the prediction of the fatigue crack propagation life, is the classical Paris formula, shown in equation (3) as following.

\[
N = \frac{1}{C(fA\sigma)^{a}(0, 5m - 1)} \left( \frac{1}{\Delta a_0^{0.5m - 1}} - \frac{1}{\Delta a_c^{0.5m - 1}} \right) \quad m \neq 2
\]

\[
N = \frac{1}{C(fA\sigma)^{a}} \ln \left( \frac{a}{a_0} \right) \quad m = 2
\]

(3)

Where \( C \) and \( m \) are constants, calculated by fatigue crack propagation test. \( f \) is the geometric correction coefficient.

The fatigue test is carried out in constant amplitude condition, so the equation (2) could be used in equation (3), shown in equation (4) as following.

\[
N = \frac{1}{C(fA\sigma)^{a}(0, 5m - 1)} \left( \frac{1}{(\Delta \Delta H_{pa}(y)_0 + B)^{0.5m - 1}} - \frac{1}{(\Delta \Delta H_{pa}(y)_c + B)^{0.5m - 1}} \right) \quad m \neq 2
\]

\[
N = \frac{1}{C(fA\sigma)^{a}} \ln \left( \frac{(\Delta \Delta H_{pa}(y)_0 + B)}{(\Delta \Delta H_{pa}(y)_c + B)} \right) \quad m = 2
\]

(4)
Where $H_{pa}(y)_0$ is the origin $H_{pa}(y)$, $H_{pa}(y)_c$ is the critical $H_{pa}(y)$.

In order to verify the accuracy of the equation (4), the test parameters are used as geometric correction coefficient $f$ is 1.12, maximum stress is 80MPa, minimum stress is 8MPa, $m$ is 2.32 and $C$ is $2.47 \times 10^{-12}$. The test parameters are brought into the equation (4), and the calculated values of the fatigue crack propagation life could be obtained, which are compared with the measured values, shown in figure 7.

![Figure 7](image)

**Figure 7.** Measured values and calculated values for propagation life of the specimen.

| Peak-peak value $\Delta H_{pa}(y)$ (A/m) | 121  | 114  | 109  | 100  | 95   | 90   | 84   | 76   |
|----------------------------------------|------|------|------|------|------|------|------|------|
| Calculated value (time)                | 490  | 1000 | 1450 | 1860 | 2460 | 3200 | 4590 | 6720 |
| Measured value (time)                  | 500  | 1000 | 1700 | 2000 | 2500 | 2900 | 4000 | 6000 |
| Relative error (%)                     | 2.00 | 0.00 | 14.70| 7.00 | 1.60 | 10.34| 14.75| 12.00|

Validity analysis based on the actually measured value demonstrates that the measured values fit well with the calculated values, and the maximum error is less than 15%, shown in Table 1. The error is related to the constant $A$ and $B$ in equation (2). The better the linear fitting is, the smaller the error is. The equation (4) is obtained in the conditions of this paper, and there are more restrictive conditions. Although the method is obtained in laboratory conditions, it can direct the prediction for fatigue crack propagation life of ferromagnetic materials by the abnormal magnetic signals, and it can greatly promote the development and perfection of the components reliability.

### 4. Conclusions

In this research, the gradient $k$ of the abnormal magnetic signals increases when the stress concentration increases. The gradient $k$ and the peak-peak value $\Delta H_{pa}(y)$ of the abnormal magnetic signals increase with the increase of fatigue cycle times. The maximum value $k_{max}$ of the gradient and the peak-peak value $\Delta H_{pa}(y)$ of abnormal magnetic signals are the key parameters to reflect the relationship between the fatigue cycle time and the abnormal magnetic signals. There is a linear relationship between the peak-peak value $\Delta H_{pa}(y)$ and the length of fatigue crack $a$. A predictive model for fatigue crack propagation life of ferromagnetic material is established, combined with the classical mechanics Paris formula. Validity analysis based on the actually measured value demonstrates that the measured values fit well with the calculated values and the maximum error is less than 15%.
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