Distinguishing Stress Concentration or Cracking in Ferromagnetic Material Using Abnormal Magnetic Signals

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In the geomagnetic field, spontaneous magnetic signals in ferromagnetic materials can be induced by stress, which can be potentially applied to estimate the damage degree. In this research, a method of distinguishing stress concentration or cracking in ferromagnetic material was proposed. The normal component of magnetic field, $H_p(y)$, was measured on the surfaces of ferromagnetic specimens with notch. The results indicated that the shapes of $H_p(y)$ curves of stress concentration and cracking were different, there was abnormal magnetic peak in the $H_p(y)$ curve of cracking. Meanwhile, the effect of lift-off on abnormal magnetic peak was studied, and the optimal lift-off value was also presented. [doi:10.2320/matertrans.M2012393]

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1. Introduction

For the good mechanical properties, ferromagnetic materials are widely used in welding. Many ferromagnetic welding components are subjected to fatigue, causing lots of catastrophic accidents.\textsuperscript{1–3} Fatigue crackings are often initiated from components’ surfaces which have stress concentration zone,\textsuperscript{4–6} so it is very important to use a method for evaluating the stress concentration degree. At present, a novel non-destructive testing method named metal magnetic memory testing (MMMT) was created by Russian professor Doubov in 1997.\textsuperscript{7,8} The MMMT is based on magneto-mechanical effect. Under geomagnetic field, load can lead to the generation of spontaneous weak magnetic signals without any other extra magnetic field. In stress concentration zones, the tangential component of stray field, $H_p(x)$, has a maximum value, meanwhile, the normal component, $H_p(y)$, changes positive-negative symbols and has a zero value. Therefore, the stress concentration zones can be detected by measuring the $H_p(y)$ values and their variable gradient without any other extra magnetic field. Compared with other non-destructive testing methods, such as ultrasonic testing, eddy-current testing and magnetic particle inspection, the MMMT has no use for surface pretreatment and special magnetic equipment. It can be applied in inservice inspection, it can be effectively used to detect stress concentration zones and microdefects.

Lots of experiments on MMMT have been done by national and international academicians,\textsuperscript{9–11} it is reported that there are some relationship between stress concentration degree and the gradient of $H_p(y)$, and the $H_p(y)$ signals of stress concentration zone is similar with the signals of cracking, but there are few investigations to find the difference. In this paper, the tension to tension fatigue test of 18CrNi4A steel specimen with notches was carried out until cracking appeared, the normal component of stray field, $H_p(y)$, on surface of the specimen were detected. The differences between $H_p(y)$ signals of stress concentration zone and cracking was discussed.

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2. Experimental

The testing material is 18CrNi4A steel, which is a kind of case-hardened steel. Many factors, such as machining process, heat treatment condition and transport situation, intensively affect the initial magnetic signal, so all specimens were demagnetized by pulse demagnetization machine in order to reduce the processing magnetization.

The shape of specimen is given in Fig. 1(a). Stress concentration factor $\alpha$ of the notched specimen is 5. Their surface roughness $R_s$ was 3.2 $\mu m$. One horizontal line AB was drawn on the surface of specimen before cracking, whose length was 60 mm. Four parallel lines marked by numbers $d_1$, $d_2$, $d_3$ and $d_4$ with 5 mm intervals were drawn on the surface of specimen after cracking.
The dynamic tension tests were done with MTS810 servo hydraulic testing machine, whose dynamic load error was ±1.0%. Tension-tension fatigue tests of constant amplitude (sinusoidal waveform) were performed. The stress was 900 MPa, ratio \( R \) was 0.1, and load frequency \( f \) was 3 Hz. \( H_p(y) \) values were measured by an EMS2003 intelligent magnetic memory device. A probe was fixed on 3D electrical scanning platform made of non-magnetic materials and placed vertical to the surface of specimen with different lift-off values. The diameter of probe was 6 mm. The end of probe was soft cushion to prevent scratching the sample surface. The testing system is shown in Fig. 2.

In the fatigue testing, the specimen was positioned vertically between the upper and lower holders of the testing machine. When the specimen was loaded to a preset cycle number, it was taken from the holders and laid on the platform in south (A) to north (B) direction. Then, the \( H_p(y) \) values of scanning line were detected. After detection, the specimen was loaded again to a more preset cycles, as well as the above procedure was repeated until the cracking appeared. Then the \( H_p(y) \) values of scanning line \( d_1, d_2, d_3 \) and \( d_4 \) were detected.

3. Results and Analysis

Figure 3 shows the magnetic signals of specimen from line AB at different cycles with lift-off 0.5 mm. The results indicate that magnetic signals sharply change and the gradient \( |k| \) intensely increase near the notch along the scanning line. It proves that there is close relationship between stress concentration degree and the gradient of \( H_p(y) \). At the same time, the gradient \( |k| \) of the abnormal signals go up with the increase of loading cycles approaching to a stable value until cracking appeared at 4300 cycles. When the cracking happened, the gradient \( |k| \) suddenly increased and the abnormal magnetic peak of \( H_p(y) \) appeared.

In order to study the character of \( H_p(y) \) curves of cracking, the magnetic signals of specimen after cracking from line \( d_1, d_2, d_3 \) and \( d_4 \) were detected with lift-off 0.5 mm, shown in Fig. 4. Line \( d_1 \) and \( d_2 \) go through the stress concentration zone of cracking, while line \( d_3 \) and \( d_4 \) go through the cracking. It is indicated that the magnetic signals of cracking and stress concentration both sharply change and their gradient \( |k| \) intensely increase, but there are abnormal magnetic peaks only in the magnetic signals of cracking. Therefore, the abnormal magnetic peak is the key to distinguish the magnetic signals of stress concentration or cracking. Because the diameter of probe is 6 mm, the efficient detecting zone is about 80%, so the minimum value of cracking which can be detected in this method just appears along line \( d_3 \), the value is 0.2 mm inspected by visual microscope.

The results could be explained by the theory of interaction energy in ferromagnets.\(^{12}\) When test temperature is far below Curie point, total free energy of ferromagnet includes magnetocrystalline anisotropy energy \( E_k \), stress energy \( E_s \) and demagnetization energy \( E_d \) provided that total free energy is equal to internal energy as eq. (1):

\[
E = E_k + E_s + E_d
\]

Stress energy \( E_s \) is far greater than \( E_k \) and \( E_d \) under the applied axial tensile stress. When the applied load reached to the ultimate strength, fracture happened and stress energy released immediately. Meanwhile demagnetization energy increased dramatically to recover system balanced state. So the abnormal magnetic peak occurred in the fracture zone and the amplitude of magnetic signals changed sharply.

It is known that the lift-off affects the magnetic signals of \( H_p(y) \), but there are few research to study the relationship between lift-off and magnetic signals, which is very important for the application of MMMT. In this paper, the
magnetic signals of specimen from line d4 with different lift-off were detected, shown in Fig. 5.

Figure 5 shows that the value and gradient $|k|$ of $H_p(y)$ both decrease with the increase of lift-off value. When the lift-off is between 0.0 and 1.0 mm, there is abnormal magnetic zone near cracking, meanwhile, abnormal magnetic peaks exist in the zone. When the lift-off is between 1.0 and 20.0 mm, the abnormal magnetic zone exists, but the abnormal magnetic peaks disappear. While the lift-off is higher than 20.0 mm, the abnormal magnetic zone and abnormal magnetic peaks both disappear, the $H_p(y)$ curve becomes linear. As we all known, the gradient $|k|$ and abnormal magnetic peak are the key parameter for expressing the stress concentration degree and cracking, therefore, the lift-off should be less than 1.0 mm in practical testing, otherwise, the magnetic signals will be distortion. Meanwhile, the lift-off should not be too low, inducing the friction of probe. The value of lift-off should be decided by the roughness of surface.

Thus a simple and fast method for detecting of stress concentration degree and cracking is proposed. The gradient $|k|$ and abnormal magnetic peak are the key parameter for expressing the stress concentration degree and cracking. The lift-off should be less than 1.0 mm and decided by the roughness on the surface of components in practical application.

4. Conclusions

There is close relationship between stress concentration degree and the gradient of $H_p(y)$. When the cracking appeared, the gradient $|k|$ intensely increased and the abnormal magnetic peak of $H_p(y)$ occurred, which is the key to distinguish the the magnetic signals of stress concentration or cracking. The theory of interaction energy in ferromagnets can be used to explain the effect of abnormal magnetic peak on cracking. Meanwhile, the suitable value of lift-off in practical testing is proposed. The lift-off should be less than 1.0 mm and decided by the roughness on the surface of components in practical application. However, there is a lot of basic experimental work to apply the novel method in practical detecting because of many influencing factors, such as load type, extra magnetic field and heat treatment conditions. Further more work will focus on quantitatively estimating the stress concentration degree by magnetic signals and excluding the effect of influencing factors.

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