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Influence of Stress Concentration Factor on Magnetic Memory Effect of Steel Samples under Dynamic Tension Load

Chang-liang SHI [1,2], Shi-yun DONG [2], Peng HE [1], Bin-shi XU [2]
[1]State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology; Harbin, China; Phone: +86-10-66718541; e-mail: barrystone@163.com, hlx11111@163.com
[2]National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering; Beijing, China; e-mail: barrystone@163.com, syd422@sohu.com

Abstract:

Under the excitation of geomagnetic field, normal component of surface scattering magnetic field intensity $H_p(y)$ changes of steel tensile samples with different stress concentration factors α were studied. Constant amplitude sinusoidal tensile load cycles were applied on 18CrNi4A steel plate samples whose α were respectively 1, 3 and 5. Then the correlation of $H_p(y)$ value changes with loading cycles was reported. The results indicated that stress concentration factor extremely affected the magnetic signals, the absolute values $|K|$ of the gradient of the $H_p(y)$ curves increased with the rise of α. Meanwhile, $|K|$ also went up when loading cycles increased in the initial state. However, after a few cycles, those $H_p(y)$ curves corresponding to different cycles became similar before cracking happened.

Keywords: stress concentration factor, magnetic memory effect, dynamic tension load, geomagnetic field, loading cycles

1. Introduction

Many military equipments often must be served under the circumstances of high temperature, high speed and corrosion surroundings with their development to higher level of mechanization and communication, which request for their higher quality[1]. Some components of military equipments are made of ferromagnetic materials, such as the key parts in artillery, guided missile, aerocraft, ship, armored vehicle and space instrumentation. Damage would occur and develop in these parts under the influence of applied load and lead to failure finally. Assessment for degree of ferromagnetic materials damage, especially early damage, and residual life prediction of equipments play an important role in remanufacturing engineering[2].

At present, the non-destructive diagnosis of equipments and work pieces made of ferromagnetic materials are widely carried out because of many merits of these materials. However, the conventional non-destructive testing methods, such as X-ray testing, ultrasonic wave and eddy current testing, can only be used to find existing defect s and do nothing to assess early damage. The situation has been changed when a new method of non-destructive testing, namely the metal magnetic memory testing technology, was created by the scholars of Russia in 1990's[3]. It is considered having the ability of early diagnosis and pre-warning, can effectively measure early damage zones that are usually stress concentration zones in ferromagnetic materials, and can help to find dangerous areas before the formation of macro-cracks when the work piece is loaded until destruction.

Though the theory and judgment principle had been founded , the method is still imperfect. Therefore, lots of experiments on ferromagnetic materials have been done at home and abroad in order to establish the real relation between external stress and magnetic field change inside materials[4-8]. In this paper, the changing regularity of magnetic signals of 18CrNi4A steel samples with different stress concentration factors was studied by the dynamic tensile experiments.

2. Experimental

The samples are made of 18CrNi4A, a kind of case-hardened steel, which has high tension strength and good integrated mechanical property by means of quenching and lonnealing. This material is usually applied in manufacturing critical heavy-duty gear and shaft item, also used as carburized bearing steel. Table1 shows the chemical constitution and mechanical property of 18CrNi4A.

Table 1. chemical constitution (wt.%) and mechanical property of 18CrNi4A

C	Mn	Si	S	P	Cr	Ni
0.15~0.20	0.30~0.60	≤0.35	≤0.010	≤0.015	0.80~1.10	3.75~4.25

Heat treatment	σ_b/MPa	$\sigma_{P0.2}$/MPa	δ_5/%	a_{KU}/(kJ/m^2)
810~830℃ , 1h , oil cooling 170~190℃ , 2h , air cooling	1325~1520	≥980	≥8	≥600

Many factors, such as machining process, heat treatment condition and transport situation, intensively affect the initial magnetic signal, so all the samples were under inductive demagnetization before experiments in order to study the relationship between work loads and magnetic memory signals in ideal condition.

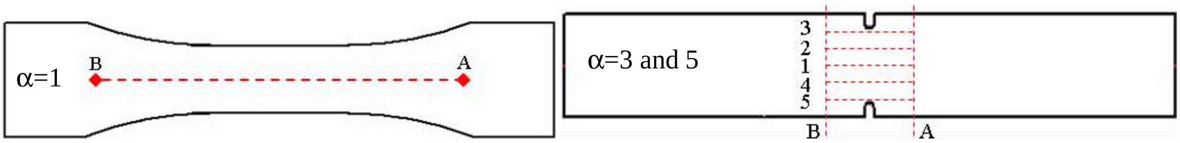

Figure 1. Testing paths of samples with different stress concentration factors

Table 2. The parameters of fatigue test

Specimen	Stress concentration factor α	Maximum stress σ_{max}/MPa	Stress ration R	Load frequency f /s^{-1}
1	1	1100	0.1	3
2	3	667	0.1	3
3	5	667	0.1	3

The experiments were done by MTS810 hydraulic servo machine, whose dynamic load error is ±1.0%. $H_p(y)$ values were measured by EMS2003 intelligent magnetic memory system. The samples were on load, shown in Table 2, until preset cycles, lifted down and laid in north to south direction. To ensure the precision of testing, the parallel lines averaging the broad of the testing region of the specimen were drawn on the specimens, and testing was accomplished along these lines from A (north) to B (south), shown in figure 1, by the nonferromagnetic displacement equipment of electrical controller.

3. Results and analysis

The specimen 1 experienced 43329 fatigue load cycles before its failure. The curves of magnetic signals of the specimen before loading and after fracture are shown in figure 2, which indicates that initial magnetic signal state of specimen 1 surface is almost uniform without any zero-crossing point because of the inductive demagnetization before experiments. However, Necking occurs on a certain position of the specimen at 43329 cycles to which zero-crossing point of magnetic signals was measured by the probe. The $H_p(y)$ value of magnetic signals on the fracture zone of fatigue specimen increases dramatically. Zero-crossing point of the curves exists on the boundary of the fracture, magnetic signals far from the fracture become to approach stable value.

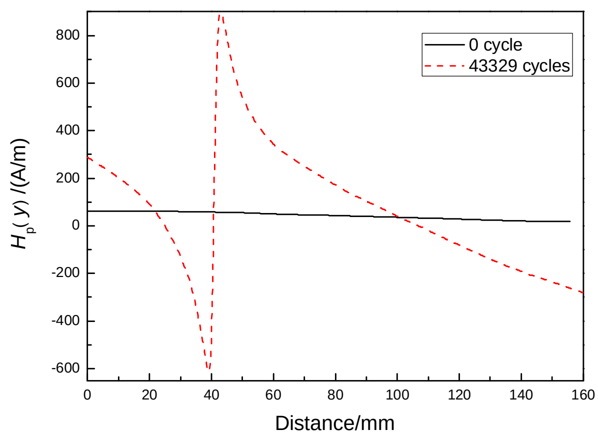

Figure 2. Magnetic signals of specimen 1 before loading and after fracture

This result could be analyzed in terms of interaction energy in ferromagnet[9]. When test temperature is far below Curie point, total free energy of ferromagnet includes magnetocrystallien anisotropy energy F_k, stress energy F_σ and demagnetization energy F_d provided that total free energy is equal to internal energy:

$$F = F_k + F_\sigma + F_d \quad (1)$$

where F_σ is far greater than F_k and F_d under the applied axial tensile stress. When the applied load reached to the ultimate strength, specimen was broken and stress energy released immediately. At the same time demagnetization energy increased dramatically to recover system balanced state according to thermodynamic equilibrium view point. So positive-negative magnetic poles occurred on the fracture zone and the amplitude of magnetic memory signals increased violently.

The curves of magnetic signals corresponding to different fatigue cycles of the specimen are shown in figure 3. It can be seen that every magnetic signal curve is almost linear, with only one zero-crossing point. There exists an obvious regularity between loading cycles and the absolute values $|K|$ of the gradient of the $H_p(y)$ curves, presented in figure 4. The results show that the absolute values $|K|$ of the gradient of the $H_p(y)$ curves increase intensively when the loading cycles go up in the initial state. The $|K|$ of magnetic signals after 1000 cycles are transformed to regular pattern with the stable value. The relation between $|K|$ of magnetic signals and loading cycles can be fitted by the following equation:

$$|K| = aN^{b} \tag{2}$$

where $|K|$ is the absolute values of the gradient of the $H_p(y)$ curves, N is the loading cycles, a and b are both constant values related with the loading form and value. In the experiment, a is 2.82 and b is 0.039. It can be seen that the $|K|$ and loading cycles are well fitted by the fitting curve, shown in Figure 4.

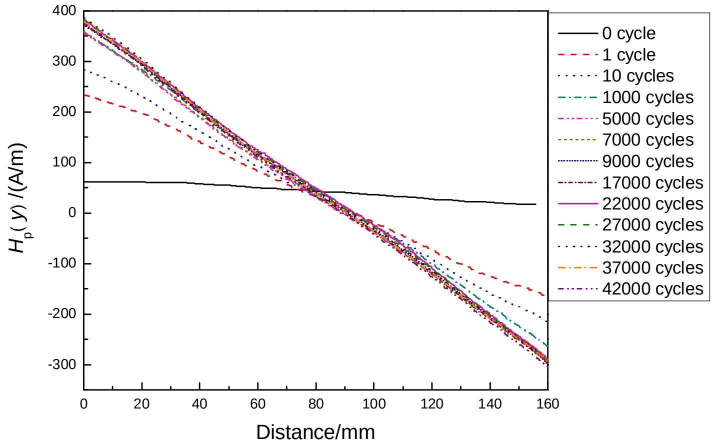

Figure 3. Magnetic signals from measured line at different fatigue cycles of specimen 1

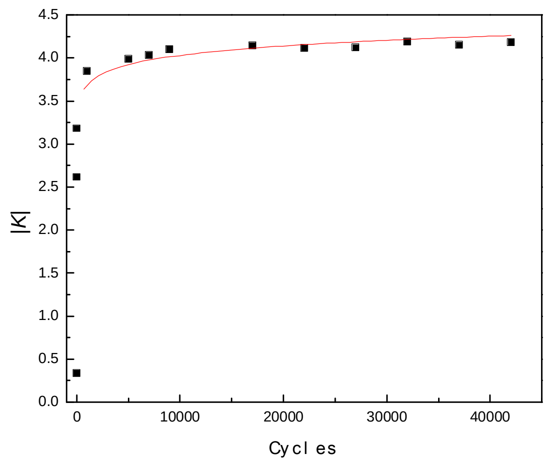

Figure 4. Gradient $|k|$ of magnetic signals from line at different cycles of specimen 1

The $|K|$ of magnetic signals are transformed to be stable with the increase of the loading cycles in the results. Known from ferromagnetics[10], the direction of the magnetic domain of ferromagnetic materials is rotated to uniform with the increase of loading cycles. Therefore, at the beginning, the specimen is in elastic deformation stage with few dislocations, the magnetic signals become more and more intensive when cycles increase. After a few cycles, the specimen comes into plastic deformation stage when many dislocations appear, interacting with domain wall. Dislocation density rises when the loading cycles increases. Dislocation blockings, for the increase of dislocations, intensively prevent the domain wall moving, which obviously weakens the spontaneous magnetization effect. Relaxation of internal stress occurs in plastic deformation stage due to dislocation slip and then magnetic signals are uniformed which are clearly independent on the applied loading cycles in this stage. $H_p(y)$ value of magnetic signals varied less with applied loading cycles increasing. In the tension-tension fatigue test applied maximum stress σ_{max} was controlled to 1100 MPa, which is well close to yield limit of the experimental material. Plastic deformation appeared immediately under the effect of fatigue load. Therefore, the shape and distribution of magnetic signal curves was very similar corresponding to different cycles after a few load cycles.

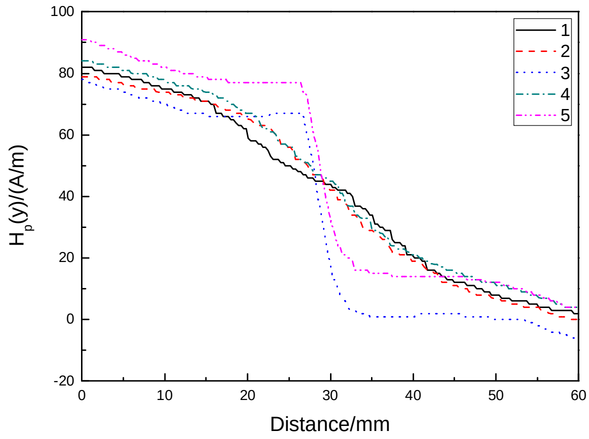

Figure 5. Magnetic signals of specimen 2 from different measured lines at 1000 cycles

The specimen 2 and 3 experienced 20109 and 9210 fatigue load cycles respectively before their failure. Meanwhile, the $H_p(y)$ values of magnetic signals on the fracture zone of fatigue specimens go up dramatically as same as the results of specimen 1. Figure 5 shows the magnetic signals of specimen 2 from different measured lines at 1000 cycles. The results shows that magnetic signals change dramatically and the gradient $|k|$ increase a lot near the notches along the same measured line. For the magnetic signals in different measured lines, the gradient $|k|$ corresponding to the notches are also different. The gradient $|k|$ from measured line 3 and 5 are more than others. The same situation happened in specimen 3. For the shape of specimen with stress concentration, the degree of stress concentration becomes more and more intensive with the decrease of the distance from the notches. Therefore, it is can be seen that the gradient $|k|$ is related with stress concentration.

Shown in figure 5, the gradient $|k|$ from measured line 3 and 5 are higher than others. The magnetic signals of specimen 2 and 3 from measured line 5 were respectively provided in figure 6 and 7 in order to conveniently study the relationship between the gradient $|k|$ and the degree of stress concentration.

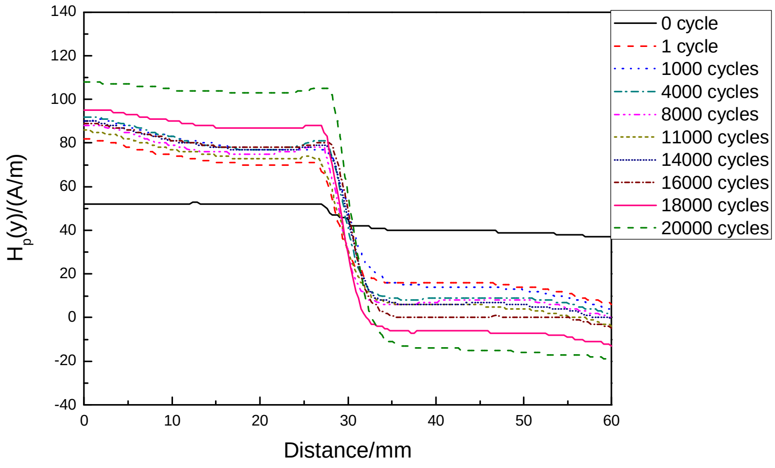

Figure 6. Magnetic signals of specimen 2 from line 5 at different cycles

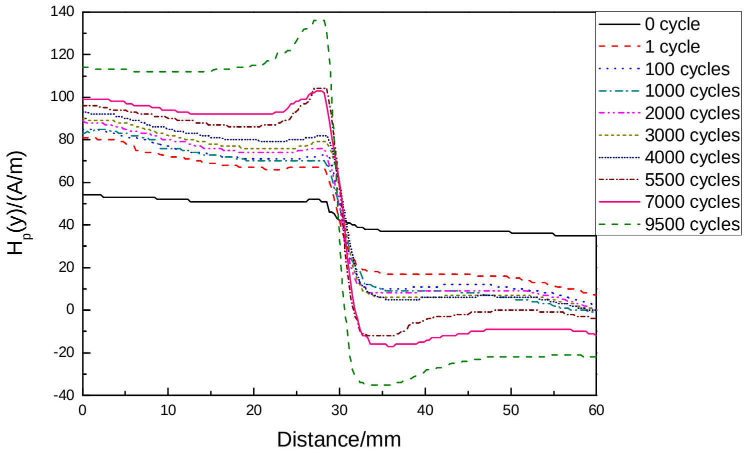

Figure 7. Magnetic signals of specimen 3 from line 5 at different cycles

Seen from figure 6 and 7, the magnetic signals change extremely in stress concentration zone at different cycles. At the same time, the gradient $|k|$ go up to a stable value with the increase of loading cycles as the same reason for specimen 1. Compared with specimen 2, the stable value of $|k|$ for specimen 3 is higher because the stress concentration factor of specimen 3 is higher than specimen 2. Therefore, the gradient $|k|$ can be used to describe the degree of stress concentration. So far, the degree of stress concentration just can be qualitatively characterized by magnetic signals. The stable value of $|k|$ increases with the rise of stress concentration factor.

4. Conclusions

(1) Magnetic domain structure is changed due to the influence of applied load combined with earth magnetic field, which induces magnetic leakage field signals.

(2) The $H_p(y)$ value of magnetic signals on the fracture zone of fatigue specimen increases dramatically and positive-negative magnetic poles occur on the fracture zone.

(3) The absolute values $|K|$ of the gradient of the $H_p(y)$ curves increase intensively when the loading cycles go up in the initial state. But the $|K|$ after a few cycles are transformed to regular pattern with the stable value until cracking.

(4) Stress concentration factor extremely affected the magnetic signals, the absolute

values $|K|$ of the gradient of the $H_p(y)$ curves increased with the rise of stress concentration factor.

Acknowledgements

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