Experiments of Influencing Factors in the Magneto-mechanical Effect

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Based on the magneto-mechanical effect, the surface magnetic field of ferromagnetic materials can be used to evaluate their stress status or defects. However, there are several factors which affect the magnetic field distribution. In the last 10 years, we have carefully studied the effect of stress, the environmental field, and the material of the specimens. The experimental results pointed out some relationships between the surface field and the structural safety of ferromagnetic materials:

1. The abnormal change of surface field will be larger in higher carbon content steel as well as the magneto-mechanical effect coincide with magnetic hardness density of ferromagnetic properties.
2. The environmental field is critical to the surface magnetic field distribution. This includes the tendency towards magnetization when the stress increases.
3. In specific environments, the magnetic field change caused by stress concentrations can be approximated by the law of approach by Jiles. DC.

Key Words: Magneto-mechanical effect, stress, environmental field, material

1 Introduction

Stress concentration caused by loading or fatigue is a potential safety hazard to metal materials; its testing method is always a focus of nondestructive testing researchers. Since it was discovered that stress in ferromagnetic material can cause magnetization changes, researchers have tried to use weak magnetism technology in nondestructive stress testing [1]. Examples of this include the metal magnetic memory method and the weak magnetic method [1][2][3]. The law of approach had analyzed the magneto-mechanical effect and summarized a mathematical model for the magnetization change under the conditions that the stress and material are uniformly distributed and the environmental field is weak[5][6]. However, since the conditions in this model were simplified, it is hard to use this model to predict the effect of stress concentration when the stress is nonlinearly distributed and the environmental field is complicated. In order to determine whether the weak magnetism methods are valid for evaluating the safety status of stress concentration, in the last ten years, experiments have been carried out to study the key factors in magneto-mechanical effect which are stress[9][10][11]、 environmental field[11][12], and material. The results showed that there are laws based on these factors which govern the abnormal change of magnetic field caused by stress concentration. Furthermore, it is possible to roughly predict the stress concentration status by using these laws.

2 Theory

Using the finite element method, ferromagnetic metal parts can be viewed as being composed of many small elements. The distribution of stress and material in each element is uniform, which means that the law of approach can used to predict the magnetization change of each element. Formula 5-1 is one key formula in the law of approach introduced by Jiles.D.C [5]:

$$\begin{aligned} H_{eff} &= H + \alpha M + \frac{3\sigma}{\mu_0}\sum_{i=0}^{\infty} i\gamma_i(0)M^{2i-1} \\ &= H + \alpha M + \frac{3\sigma}{\mu_0}\sum_{i=0}^{\infty}(iM^{2i-1}\sum_{n=0}^{\infty}\frac{\sigma^n}{n!}\gamma_i^n(0)) \end{aligned} \quad 5\text{-}1$$

where H is the environmental field, M is the intensity of magnetization, σ is the strain, and $iM^{2i-1}\sum_{n=0}^{\infty}\frac{\sigma^n}{n!}\gamma_i^n(0)$ is the Taylor series expansion of magnetostriction. In the formula, the magneto-mechanical effect is viewed as an equivalent magnetizing field.

The effect of stress is described as a polynomial in formula 5-1. When the strain increases, H_{eff} becomes larger. Since the relationship between σ and H_{eff} is nonlinear, effects from stress concentration should be more significant when the strain increases. The effect of magnetostriction is similar but not the same, though it is divided into Taylor series expansion.

Environmental field is the third factor. However, it is only considered as a linear component and the effects of the environmental field can cancel each other out in nearby elements. Since the leakage surface field tested with the weak magnetism method is the differing results of the magnetization among elements, the abnormal surface field change may be stable when the environmental field is in a high level. However, it should be noted that the abnormal changes are obvious when the environmental field is increasing from zero because the magnetic distribution in weak magnetic environment also depends on the surface shape and totally different from the uniform distribution when the environmental field is zero.

Using "H_{eff}" as solved for in formula 5-1, the magnetization value can be calculated with formulas 5-2 and 5-3:

$$M_{an}(H,\sigma) = M_s\left[\coth\left(\frac{H_{eff}}{a}\right) - \frac{a}{H_{eff}}\right] \quad 5\text{-}2$$

$$\frac{dM}{dW} = \frac{1}{\xi}(M_{an} - M) + c\frac{dM_{an}}{dW} \quad 5\text{-}3$$

where $a = k_B/\mu_0 M$[5], ξ is a coefficient with dimensions of energy per unit volume, and W is the elastic energy per unit volume.

However, the magnetization intensity "M" is also a variable in formula 5-1, which means that the effects of these factors are compounded and their influence becomes more complicated than what is discussed in this section.

3 Experiments

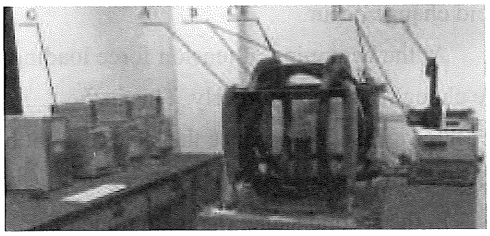


Figure 3.1 Experiment System

The experimental system we used to study the magneto-mechanical effect is as shown in Figure 3.1, which is made up by following parts: A: 3D Helmholtz Coil to control the environmental field; B: Portable Tensile Means to apply a controllable tension force; C:Specimens; D: Flux Gate Magnetometer and Tesla Magnetometer to test the environmental field produced by the 3D Helmholtz Coil; E: 3D Displacement Controller to hold the testing sensor and scan the surface field automatically; F: Wireless Micro-magnetic Detector and the GMR Sensor which were self-developed with a testing accuracy of 50nT; G:Computer to control the sensor movement and analyze the testing results.

The flat-type specimen as shown in Figure 3.2 has a regular round hole in center, and stress concentration is generated around the hole when tensile force is applied to the specimen by the portable tensile means.

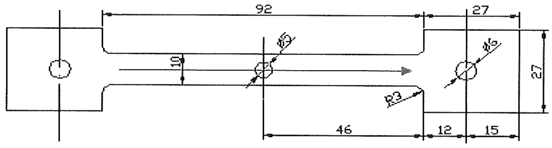


Figure 3.2 Specimen dimensions and scanning line

3.1 Effect of Stress and Materials

Figure 3.3 is the p-p value of the abnormal change near the stress concentration. When the tension force increases, three stages of surface field change occur.

1 At the beginning of tension force loading, the change is quite disorderly. This is the expected reaction because the states cannot be the same before undergoing tension.

2 In the second stage, the magnitude of abnormal change becomes proportional to the tension force. The starting point and the duration of this stage depend on the materials.

3 When the tensile force is high enough, the change becomes stable. As pointed out by Jiles.D.C "the rate of change of magnetization with elastic energy is proportional to the displacement of the magnetization from the anhysteretic", thus, if the displacement is very small, the change rate is close to zero.

Studies done by S.habermehl [8] illustrated the relationship between the carbon component and the ferromagnetic properties. These studies also indicate that the carbon component plays an important role in the magneto-mechanical effect. In our experiment, the magneto-mechanical effect in 0.45% carbon steel is much stronger than that in 0.25% carbon steel. Furthermore, the second stage mentioned above also lasts much longer in 0.45% carbon steel.

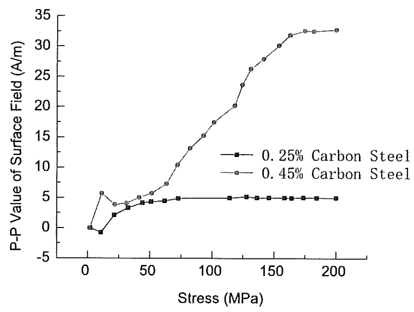


Figure 3.3 P-P value of surface field change between different steel

3.2 Effect of Environmental Field

The effect of environmental field can be analyzed in the following three ways:

1 The direction of environmental field;

2 The Magnitude of environmental field during stress loading;

3 The magnitude of environmental field after stress loading [9];

In order to study the effect of environmental field, a series of experiments were carried out, and Figure 3.4-Figure 3.6 show the results of these experiments. Figure 3.4 pertains to an experiment which investigates the direction effect of the geomagnetic field. The corollary is that the magnetic change is the largest when the environmental field direction is the same as the principal strain [9]. Based on this result, when the magnitude of environmental field was studied, the directions of the environmental field and the tensile force were set the same.

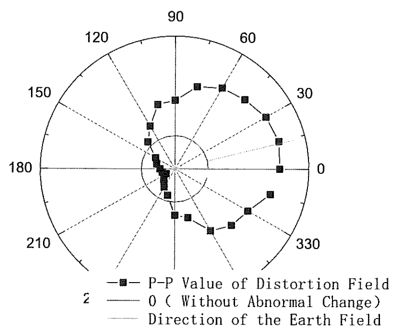
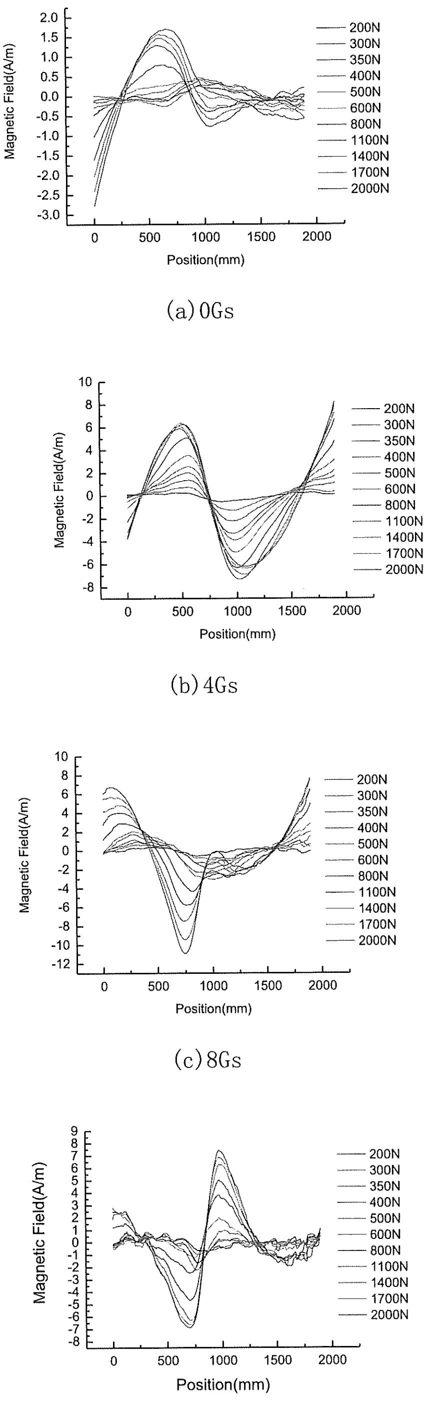


Figure 3.4 Relationship between the environmental field direction and the abnormal field change

Figure 3.5 is the experimental result from the study of the environmental field effect during the tension force loading. In this experiment the environmental field plays the roles of both the magnetizing field and the environmental field of the magneto-mechanical effect. The change is weak when the environmental field is near zero, but it strengthens as the environmental field increases. As discussed in Section 2, the effect of environmental field is almost a linear component for H_{eff}. When the field increase from zero, the effect of the environmental field increases quickly because of the uneven magnetization distribution caused by the shape. But after the environmental field reaches roughly 4Gs, the magnitude of abnormal change becomes stable because the changes cancel each other out.

Figure 3.6 shows the field effect after force loading. The environmental field here is just a magnetizing field, without magneto-mechanical effect, which can increase or decrease the abnormal change. Figure 3.5 and Figure 3.6 both show a phenomenon that the direction of abnormal changes becomes opposite while the environmental field is increasing. A plausible explanation for this is that the magneto-mechanical effect tends to demagnetize in weak environmental field which is just opposite to the simply magnetizing effect.



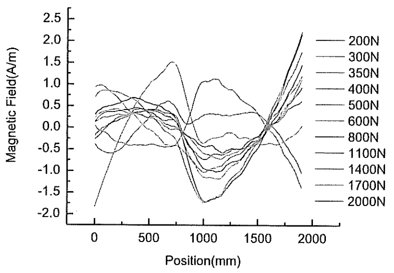
(a) 0Gs

(b) 4Gs

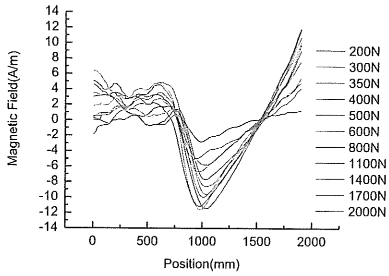
(c) 8Gs

(d) 12Gs

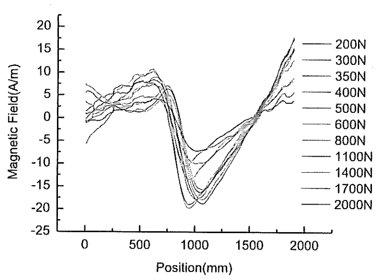
Figure 3.5 Environmental field effect during stress loading



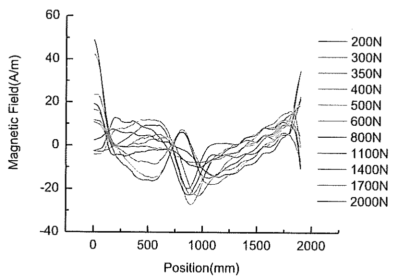
(a) 0Gs



(b) 4Gs



(c) 8Gs



(d) 12Gs

Figure 3.6 Environmental field effect after stress loading

4 Summary

Based on the test results and the comparison to the law of approach, it can be seen that the abnormal change of magnetic field caused by stress concentration is quite different from that caused by uniformly distributed stress, but the change tendency predicted by the law of approach can still be used as a reference value.

In different materials, the carbon component is strongly correlated to ferromagnetic properties. The abnormal field will be lager in higher carbon steels because of its magnetic hardness density.

During tensile force loading, the environmental field is the magnetizing field and the magnetic environment of the magneto-mechanical effect. This relates to the point where magnetization begins moving from a hysteresis curve to an anhysteretic curve in the magneto-mechanical effect. After loading, the environmental field is still a magnetizing field that can increase or decrease the abnormal change.

In specific environments, the magnetic field changes caused by stress concentration can be approximated by the law of approach. There is a stage during the stress magnetizing process where the abnormal change is roughly proportional to the magnitude of stress. This stage may be helpful in stress testing, even if the duration of this stage depends on the materials being tested.

5 Acknowledgement

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6 Reference

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