

Analysis of Damage's Influences on Metal Magnetic Memory Signal

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Abstract. Metal Magnetic Memory (MMM) technique has been extensively used as a qualitative method to test the position of possible damages in ferromagnetic metal structures, a bottleneck in further development of MMM technique is the quantitative relationship between MMM signal and damage characteristic has not been fully revealed. In this paper, analysis of influences of stress and discontinuous structure on MMM signals is presented. Samples of diverse types of structural defects were made and then loaded with different series of stress. The resulting residual deformations and gradients of the magnetic field were measured. Analysis of the quantitative relationship between MMM signals and stress was conducted. The results show: 1) The magnetic field gradient above the structure-continuous zone increases with stress. Therein lies the potential to estimate the stress level point by point. 2) The second-order gradient of the magnetic field near the structure-discontinuous zone increases with the maximum strain in a similar way for different types of discontinuous structures, implying a possibility that the second-order gradient of the magnetic field may be conceive some information about the maximum stress at the edge of discontinuous structures independent of their geometry characteristics.

Keywords. Damage's influences, metal magnetic memory signal, magnetic field gradient

1. Introduction

In real world engineering, there has been a higher demand for non-destructive testing (NDT) methods to determine the state of stresses and deformations in structures. Because the motion of magnetic domains in ferromagnetic material can be influenced by stress and deformation, corresponding magnetic field signals carry information about the status of stress and deformation, some electromagnetic NDT methods, such as magnetic flux leakage (MFL), magnetic barkhausen noise (MBN) and metal magnetic memory (MMM) [1], have attracted much attention and are developing fast in recent years. Among them, MMM technique is time-saving and easily operated, it has been wildly applied in engineering to qualitatively assess the early damage, especially the micro-damage due to local stress concentration in ferromagnetic structure. Its

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capacity for quantitative detection of stress, however, is insufficient because the quantitative relationship between MMM signal and damage characteristic has not been fully revealed, which interest many scholars and arouse their research enthusiasm lately [2-5].

The physical basis of MMM technique is magneto-mechanical effect [6] under the stimulation of the Earth's magnetic field. The magneto-mechanical effect and the leakage of magnetic field caused by the discontinuity of structure are largely regarded as two of the critical factors influencing MMM signal. On the issue of the magneto-mechanical effect of MMM technique, Dong et al. discovered the magnetic gradient (the gradient of the normal component of the residual magnetic field (RMF)) shows a good linearity with evenly distributed elastic stress [7]. Wang et al. proposed a magnetic charge model which established the relationship between stresses and the MMM signal for unevenly distributed stresses [8], whereas whose validity still needs to be tested by further studies.

In addition to the magneto-mechanical effect, another important factor that affects MMM signals is the discontinuous structure which causes the emergence of stress concentration in most case, and promotes each other. Discontinuity cuts off the magnetic circuit within the ferromagnetic structure, the insertion of air increases the intensity of magnetic resistance between the parts of the discontinuous structure, ultimately, affects the tested MMM signals. Roskosz et al. compared the distributions of RMF signals with stress distribution, finding that there are correlations between the discontinuous structure and the RMF signals [9-10], yet the quantitative relationship between them is not clear.

Based on the above background, this paper aims to present some quantitative analysis on how those two factors influence the RMF signals, and further to explore the NDT characterizations of MMM technique to stress concentration.

2. Experimental

The samples are 3-mm thick flat bars made of Q195 steel with a yield stress of 195Mpa. The samples are of different shapes and sizes, type-A, B and C. As shown in Fig.1, type-A sample is made without any artificial defect, type-B sample has a circular hole of 10-mm in diameter in the middle, type-C sample has two 2-mm wide notches on both edges.

The samples are demagnetized by a degauss device and then loaded on a tensile testing machine MST 880. Fourteen samples were tested in total, including five type-A, three type-B and six type-C. Numbers attached on each sample indicate the type of sample and the degree of nominal stress applied, greater number means more stress. Fig.2 shows the stress (σ)-strain (ϵ) curve of A5 sample. The applied nominal stresses are given in Table 1. Each sample is loaded into the plastic deformation range.

According to the knowledge of mechanics of materials, the increase of applied stress during the range of plastic deformation for the tested materials will lead to a faster increase in plastic strain, thus the level of plastic strain is used to quantify the intensity of applied stress hereafter.

During loading, changes of surface deformations within the measuring fields (as shown in Fig.1) of samples are recorded by an ARAMIS V5.4.1 deformation testing device. After loading, samples are removed from the tensile machine, magnetic gradients of the RMF in the measuring fields are scanned by a Bartington Mag-01H

flux gate magnetometer, surface plastic residual strains in the measuring fields are computed by the ARAMIS V5.4.1 deformation testing system. Here, the magnetic gradient (dB/dY) denoted by

$$dB/dY = \frac{\partial B_n}{\partial Y}$$

(1)

Where, B_n is the normal component of RMF, Y the coordinate of the testing position along the Y axis of the sample (as shown in Fig. 1).

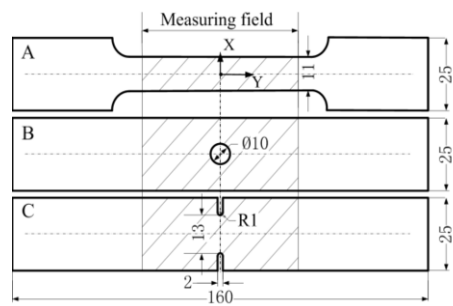


Fig.1. Shapes and sizes of samples

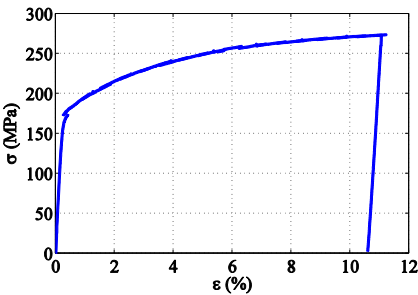


Fig.2. Stress (σ)-strain (ε) curve of A5 sample

Table 1. Applied nominal stresses to samples

Sample		Sample number: Nominal stress (MPa)				
Type A	A1:220.9	A2:248.6	A3:260.0	A4:266.2	A5:273.1	
Type B	B1:200.9	B2:234.2	B3:237.6			
Type C	C1:267.6	C2:297.8	C3:333.1	C4:347.0	C5:351.8	C6:344.2

3. Results

Because the distributions of residual plastic strain for the same-type of samples are similar but with different intensities, Fig.3 just shows the residual strain (ε) distributions of samples of A5, B3 and C5. For the same reason, Fig.4 shows the magnetic gradient (dB/dY) distributions of samples of A5, B3 and C6. Comparing the results displayed in Fig.4 with those of Fig.3, the magnetic gradient distributions look very similar to their strain distributions for each type of sample. The magnetic gradient distributes almost evenly for type-A samples with evenly distributed stress. For type-B and C samples with discontinuous structure, there are stress concentration zones (SCZ) appearing near the hole of type-B sample and the notches of type-C sample, the intensities of magnetic gradient above SCZ are obviously stronger. Especially, above the structure-discontinuous zone, i.e., the hole of type-B samples and the notches of type-C samples, the magnetic gradient intensities reach the maximum value, just like the results shown in Fig.5.

To explore the quantitative relationships of magnetic gradient with stress, 14 sets of dB/dY data on midlines of Y=0 of samples are picked and shown in Fig.6. For different type of samples, there has been a common phenomenon that the magnetic gradient where Y=0 always increases with the applied stress.

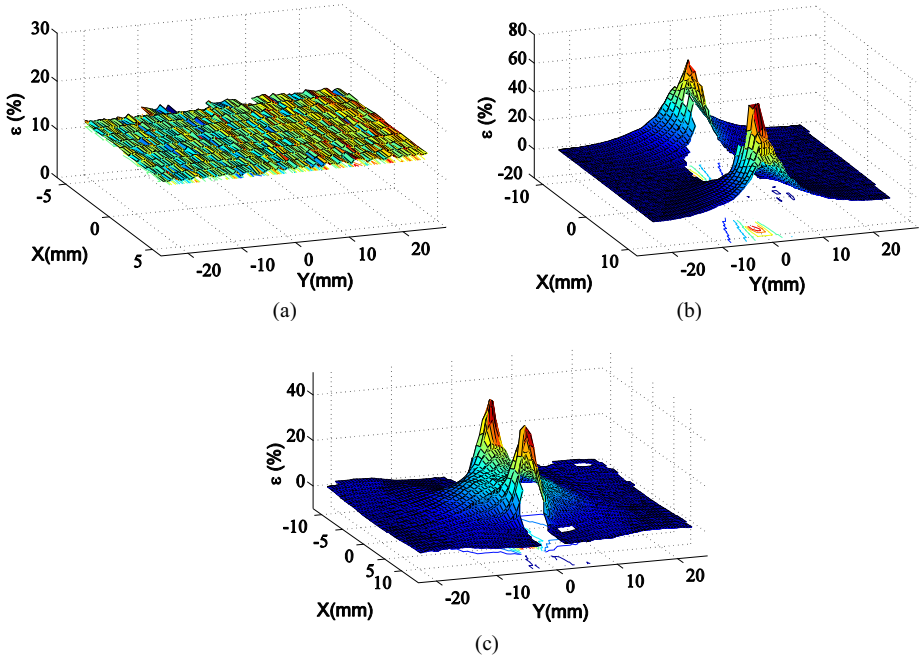


Fig.3. Strain distributions of samples of (a) A5, (b) B3 and (c) C5

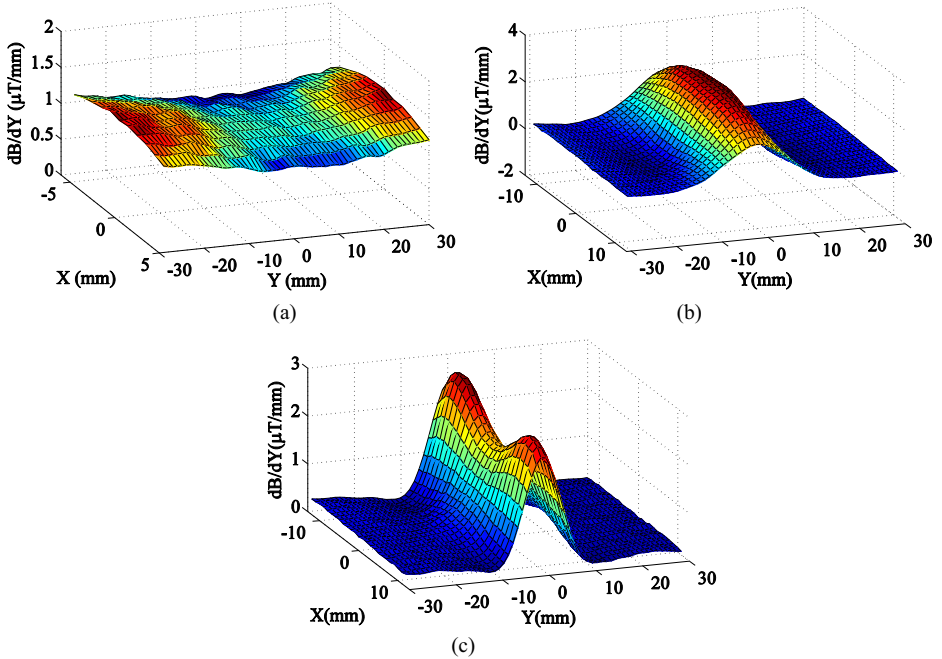


Fig.4. Magnetic gradient distributions of samples of (a) A5, (b) B3 and (c) C6

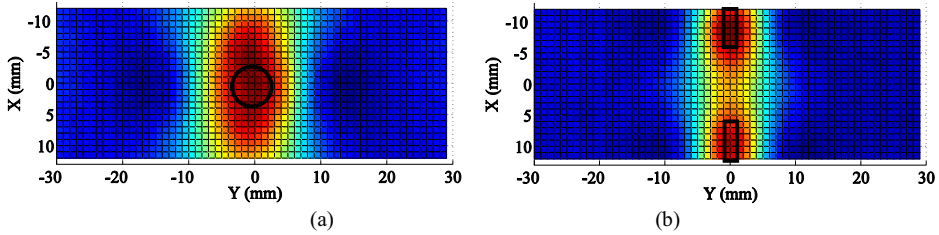


Fig.5. Magnetic gradient distributions above the structure-discontinuous zones of (a) B3, (b) C6 samples

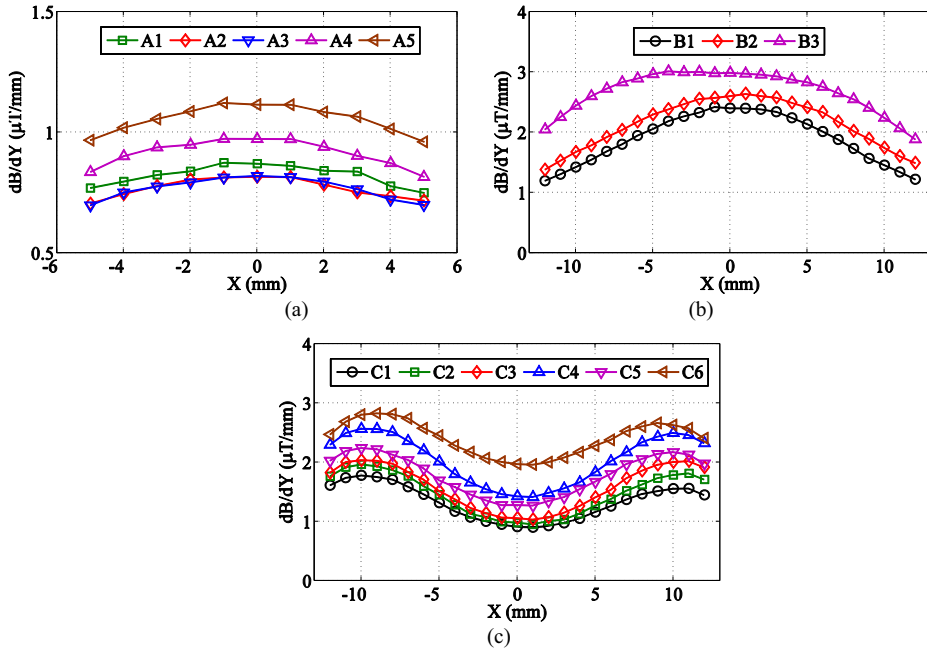


Fig.6. Magnetic gradients where $Y=0$ for samples: (a) Type-A; (b) Type-B; (c) Type-C.

4. Analysis

Analyze the results shown in Fig.3 to Fig.6, the magnetic gradient is stronger where the stress is large as shown in Fig.4, the magnetic gradient increases with the applied stress for each type of sample as shown in Fig.6, it is easy to conclude that the increase of stress leads to the increase of magnetic gradient. But the problem is not that simple when the effect of the discontinuous structure is considered. It is generally known that the discontinuous structure plays an important role in influencing the distribution of MFL signal for the MFL technique. Discontinuous structure breaks the magnetic circuit within the ferromagnetic structure, resulting in the leakage of the magnetic field into the air and thus affects the MFL signal. For MMM technique, it is the same case. Therefore, the RMF signal of MMM technique is affected not only by the stress concentration, but also by the discontinuous structure. In summary, the quantitative relationship between RMF and stress should be analyzed from two aspects:

1) for structure-continuous zone to test the effect of stress; 2) for structure-discontinuous zone to test the effect of the discontinuous structure.

For the structure-continuous zone, to test whether the relationship between the magnetic gradient and stress is the same for different types of sample, points at the center of type-A and C samples are used for the continuity of their structures. The measured magnetic gradients and strains at the center points of type-A and C samples are singled out, the relationship between the magnetic gradient and strain of the center points of type-A and C samples for structure-continuous zone is plotted in Fig.7. The figure shows that the relationship of magnetic gradient with stress is almost the same under two different conditions: evenly distributed stress of type-A, and concentrated distributed stress of type-C. The results give a further confirmation that the magnetic gradient increases with stress disregarding the form of stress distribution, and may be used to estimate the stress level point by point.

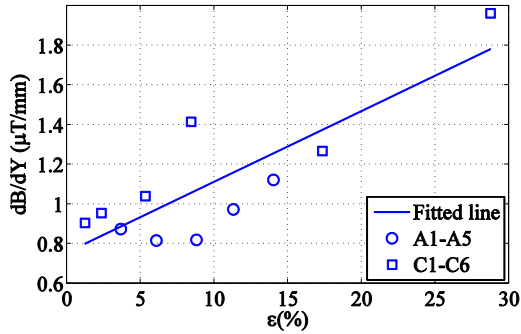


Fig.7. Relationships between magnetic gradient and strain for structure-continuous zone

For the structure-discontinuous zone, based on the previous conclusion that the magnetic gradient increases with stress point by point, it is easy to deduce that the magnetic gradient will change a lot near the edge of the discontinuous structure because where the stress changes to zero. To test this idea, the second derivatives of the magnetic field versus Y position (d^2B/dY^2) of type-B and C samples are calculated and shown in Fig.8 and Fig.9.

$$d^2B/dY^2 = \frac{\partial^2 B_n}{\partial Y^2} \quad (2)$$

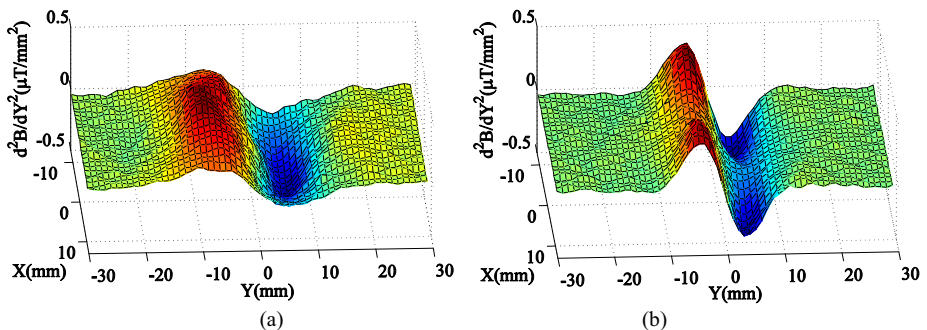


Fig.8. Second derivatives of magnetic field of (a) B3 and (b) C6 samples

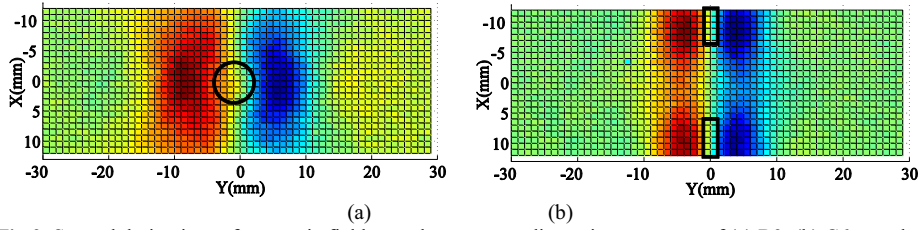


Fig.9. Second derivatives of magnetic field near the structure-discontinuous zones of (a) B3, (b) C6 samples

The results show that the d^2B/dY^2 sure has changed a lot near the edge of the discontinuous structure. To test whether the change rule of d^2B/dY^2 with stress is the same for different types of discontinuous structure, the peak-to-peak value of d^2B/dY^2 (amplitude of d^2B/dY^2) and the maximum strain (used to quantify the degree of stress concentration) for all type-B and C samples are picked out. The relationship between amplitude of d^2B/dY^2 and maximum strain for different discontinuous structures is shown in Fig.10. It shows that the relationships of d^2B/dY^2 with maximum strain for different types of discontinuous structure change with similar rules, which implies a possibility that the RMF characteristic: d^2B/dY^2 may be qualified as a unified quantitative criterion to estimate the maximum stress near the discontinuous structure independent of its geometry.

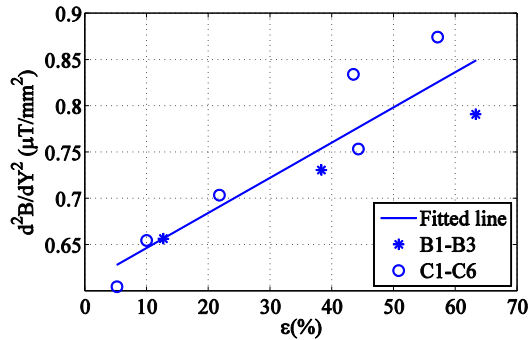


Fig.10. Relationships between second derivative of magnetic field and maximum strain for the structure-discontinuous zones

5. Conclusion

Stress and discontinuous structure are two of the principal factors influencing RMF signal of MMM technique, to get characteristic parameters from RMF signals to quantitatively detect the stress degree, the quantitative relationship between RMF signal and stress, which is quantified by the strain, are studied in this paper. First, it has been found that the magnetic gradient distributes stronger where the strain is larger, the magnetic gradient increases with the applied stress for each type of samples, and the magnetic gradient above structure-continuous zone increases with stress in a similar way for different stress distribution. These results suggest that the magnetic gradient increases with stress disregarding the form of stress distribution, which may be used to assess the stress level point by point. Second, based on the above conclusion, a RMF characteristic: second derivative of magnetic field has been presented. It has been observed that the rules of how the second derivative of magnetic field changes with

maximum strain for different types of discontinuous structure are similar, which implies the second derivative of magnetic field may be qualified as a unified quantitative criterion to estimate the maximum stress in a discontinuous structure.

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