METAL MAGNETIC MEMORY NDT METHOD: EXPERIMENTAL, THEORY AND NUMERICAL SIMULATION

Zhengdao Wang[a)] Kai Yao & Bo deng
Department of Mechanics, School of Civil Engineering, Beijing Jiao-Tong University, Beijing, 100044, China

Summary Metal magnetic memory (MMM) is a new weak magnetic NDT method, which can be used to inspect the macro-cracks as well as the mechanical degradation and early damage of engineering structures. With the aim of developing MMM method from a qualitative NDT technique to quantitative technique, we have (i) conducted the residual magnetic field (RMF) measurement and proposed a new criterion to characterize ferromagnetic samples subjected to different deformation states; (ii) numerically simulated the RMF distribution and given a reasonable explanation about the experimental results; (iii) derived a physical magnetic-elastic-plastic coupling model for analyzing the MMM phenomenon.

MANUSCRIPT PREPARATION

Metal Magnetic Memory (MMM) is a newly developed magnetic non-destructive (NDT) testing method. It is effective in characterizing the early damage of widely-used ferromagnetic materials and structures in engineering. However, due to the short history, lack of robust theoretical basis and varied effect factors on testing results, to date this technique is still under the state of the mechanism investigation and applied as a qualitative NDT tool. This paper aims to present a systematic experimental, numerical and theoretical research on this technique.

Fig. 1 presents the experimental results of the variations of normal RMF amplitude, $H_p(y)$, along the three measurement lines when Q235 low-carbon steel is subjected to elastic deformation, plastic deformation and fracture[1]. A small hole is machined in the middle of the specimen to produce a local stress-concentration during the loading process. Lines 1, 2 and 3 are along the loading direction and depart the hole from 1 mm, 3 mm and 5 mm, respectively. Fig. 1 shows the different features of $H_p(y)$ in different deformation stages: linear change in the elastic deformation; non-linear deformation in the middle stress-concentration zone when the sample is plastically deformed; and positive-negative change after the fracture.

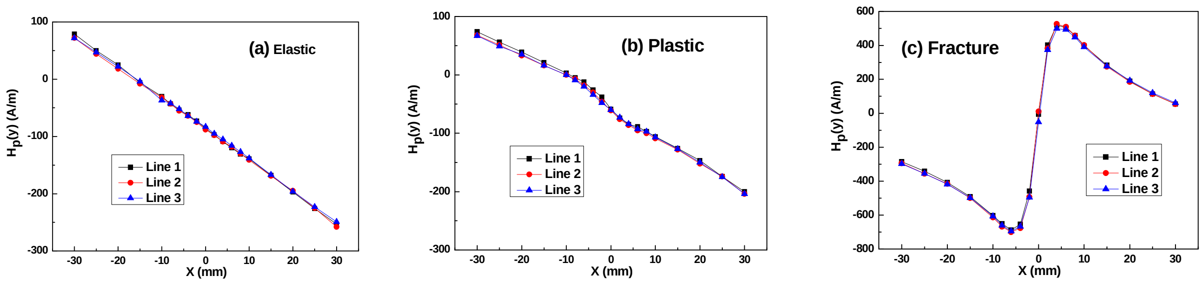

Fig. 1 Experimental normal RMF amplitudes of ferromagnetic materials under different deformation stages[1].

In order to give an explanation about the experimental results, Fig. 2 shows the numerical simulations of ferromagnetic materials under different deformation stages. Due to the magnetization of ferromagnetic materials during the fabrication and machine process, an initial magnetic strength of 200 A/m is assumed in the FE simulation, which causes a linear change of $H_p(y)$ along the initial magnetization direction. The elastic deformation changes the permeability in ferromagnets due to magnetomechanical effect. However, the effect of the elastic deformation on the permeability is no more than a few times. As considering about two orders of the permeability in ferromagnets larger than that of the air, the elastic deformation has no o much influence on $H_p(y)$ (Fig. 2b).

Different from the elastic deformation, the plastic deformation leads to the accumulation of the dislocation density acting as pinning sites and causes irreversible orientated movements of domains. Thus, the plastic deformation will decrease the magnetic permeability and develop a local coercive field, which causes a non-linear change as shown in Fig. 2c. The fracture inside ferromagnets can cause macro-cracks and significant accumulation of magnetic charges between broken parts, which causes a change of positive-negative symbols of $H_p(y)$ in the broken area, and the amplitude has a remarkable increase as compared to the elastic and plastic deformations (Fig. 2d). It is clear that the numerical simulation in Fig. 2 agrees well with the experimental results in Fig. 1.

Fig. 3 shows the gradient curves of $H_p(x)$, and $H_p(y)$ under the plastic deformation. According to our experimental and numerical results, a new criterion is proposed for justifying whether or where ferromagnets are under the plastic deformation by MMM technique: the tangential gradient component $H_p(x)/dx$ experiences a peak-peak change and

a) Corresponding author. Email: zhdwang@bjtu.edu.cn.

passes through zero, while the normal gradient component $H_p(y)/dx$ reaches a peak value in the maximum plastic-deformation zone.

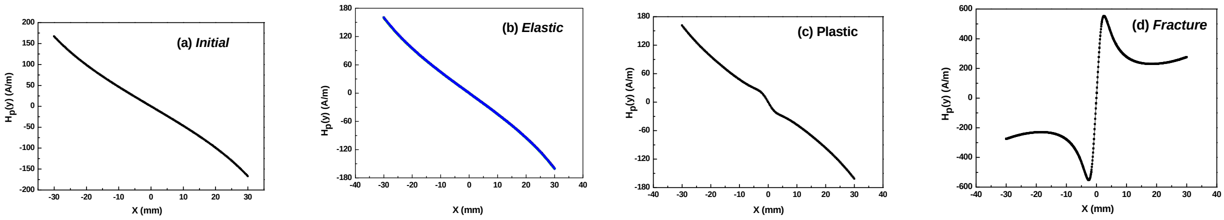

Fig. 2 Numerical simulations of ferromagnetic materials under different deformation stages.

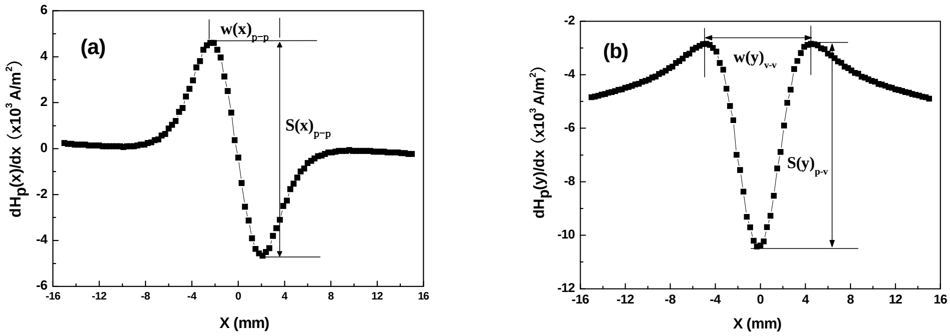

Fig. 3 Tangential and normal RMF gradients of ferromagnetic materials after the plastic deformation.

The physical basis of the MMM technique is the plastic-based magnetic-stress coupling effect. Thus, plastic-based magnetic-stress coupling models are required. As considering the plastic-induced pinning effect, a new physical-based magnetic/stress coupling model is proposed as follows[2]:

Magnetization strength: $$M = M_s\left(\coth\left(\frac{H_{total}}{\mu_0 a}\right) - \frac{\mu_0 a}{H_{total}}\right); \qquad (1)$$

Effective field: $$H_{total} = H_H + H_\sigma^e + H_\sigma^p;$$

Magnetic-induced effective field: $$H_H = H + \alpha M;$$

Elastic-induced effective field: $$H_\sigma^e = \frac{3\sigma_{eq}\cos^2\beta}{\mu_0}\left[(\lambda_{11} + \lambda_{12}\sigma) + 2(\lambda_{21} + \lambda_{22}\sigma)M^2\right]M;$$

Plastic-induced effective field: $$H_\sigma^p = -k\left|\varepsilon^p\right|, \text{ where } k = \frac{1}{\mu_0}\frac{b\langle\varepsilon_\pi\rangle}{2m}.$$

Eq. (1) presents the magnetization solution of ferromagnetic materials under the applications of applied field, elastic deformation and plastic deformation. The total field includes three terms. The first one is due to the applied magnetic field; the second is due to the elastic deformation, where a complex stress state is considered instead of a commonly uniaxial load state; and the third is due to the plastic deformation, which is determined in terms of the concept of the pinning energy coming from dislocation accumulation.

References

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