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Three-dimensional finite element analysis of residual magnetic field for ferromagnets under early damage

Kai Yao*, Kai Shen, Zheng-Dao Wang, Yue-Sheng Wang

Department of Mechanics, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

In this study, 3D finite element analysis is presented by calculating the residual magnetic field signals of ferromagnets under the plastic deformation. The contour maps of tangential and normal RMF gradients are given, and the 3D effect is discussed. The results show that the tangential peak–peak amplitude and normal peak–vale amplitude are remarkably different in 2D and 3D simulations, but the tangential peak–peak width and normal peak–vale width are similar. Moreover, some key points are capable of capturing the plastic-zone shape, especially when the lift-off is small enough. The present study suggests an effective defect identification method with Metal magnetic memory (MMM) technique.

1. Introduction

Traditional non-destructive testing (NDT) techniques focus on monitoring macro-defects. However, early damage or material degradation occupies the most part of the service life of engineering structures. Therefore, evaluation of early damage is receiving more and more attention recently. For ferromagnets, the magnetic technique is expected to be one of the candidates for early damage evaluation. Although magnetic flux leakage (MFL) technique has been widely used as an inspection technique in the petrochemical engineering and transportation, energy and metal industries [1–4], it is incapable of capturing early damage, because the applied strong field forcibly re-orientates all domains and recovers the deformation-induced domain movement. In this aspect, the weak magnetic method may overcome this difficulty. The first weak magnetic NDT method is metal magnetic memory (MMM) technique which was proposed by Doubov [5]. Different from traditional strong magnetic NDT techniques where the magnetic-induced field is measured, the MMM method measures the stress-induced residual magnetic field (RMF). Thus it is regarded as an ideal candidate in assessing the early damage of ferromagnets [6].

MMM method has received great interests in both scientific investigations and engineering applications in the last two decades. Doubov and Chechko [7–9] reported extensive engineering cases in diagnosing defects of engineering structures such as boiler, power station, pressure vessel, rail track, etc. Roskosz et al. [10,11] analyzed the quantitative relationships between the RMF component gradients and equivalent residual stress based on the measurements of samples with different geometries. Wang et al. [12,13] analyzed the RMF distributions by a modified magnetic charge model. Ren et al. [14] reported the influence of the environmental magnetic field on RMF signals. Wilson et al. [15] introduced a novel tri-axial magnetic sensor to confirm that the parallel component has a much greater correlation to the applied stress than the perpendicular component. Moreover, enormous static and fatigue experiments were performed by MMM method [16–26].

Although great endeavors have been put forward on MMM technique, quantitative determination of damage is not reached due to difficulties in mechanism analysis. Our previous work presented a finite element analysis (FEA) about the RMF signals under different plastic-zone sizes, lift-off values and testing directions. Some RMF parameters in characterizing the local plastic deformation were defined. However, the defects in that model were treated as two-dimensional (2D) profile instead of actual three-dimensional (3D) geometry; and the RMF signal is of single channel whereas the actual signals are multi-channel. In this paper, 3D FEA is presented. Some typical defects, e.g. round and diamond, are modeled and RMF signals are calculated. An effective method to image the defects is proposed.

2. FEM modeling

The calculations are completed by using the ANSYS finite element software. Fig. 1 shows the sketch of the 3D FEM model with a local plastic zone (defect) located at the center of the specimen. The lengths (in x-direction), depths (in y-direction) and

* Corresponding author. Tel.: +86 10 51688417; fax: +86 10 51682094.
E-mail addresses: 09115274@bjtu.edu.cn (K. Yao), yswang@bjtu.edu.cn, yueshengwang@hotmail.com (Y.-S. Wang).

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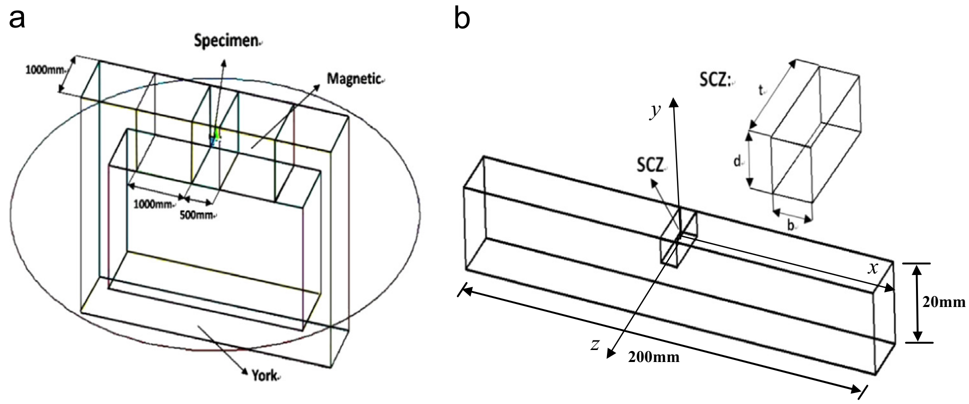

Fig. 1. Sketch map of the 3D FEM model (a) and the geometrical sizes of the specimen (b).

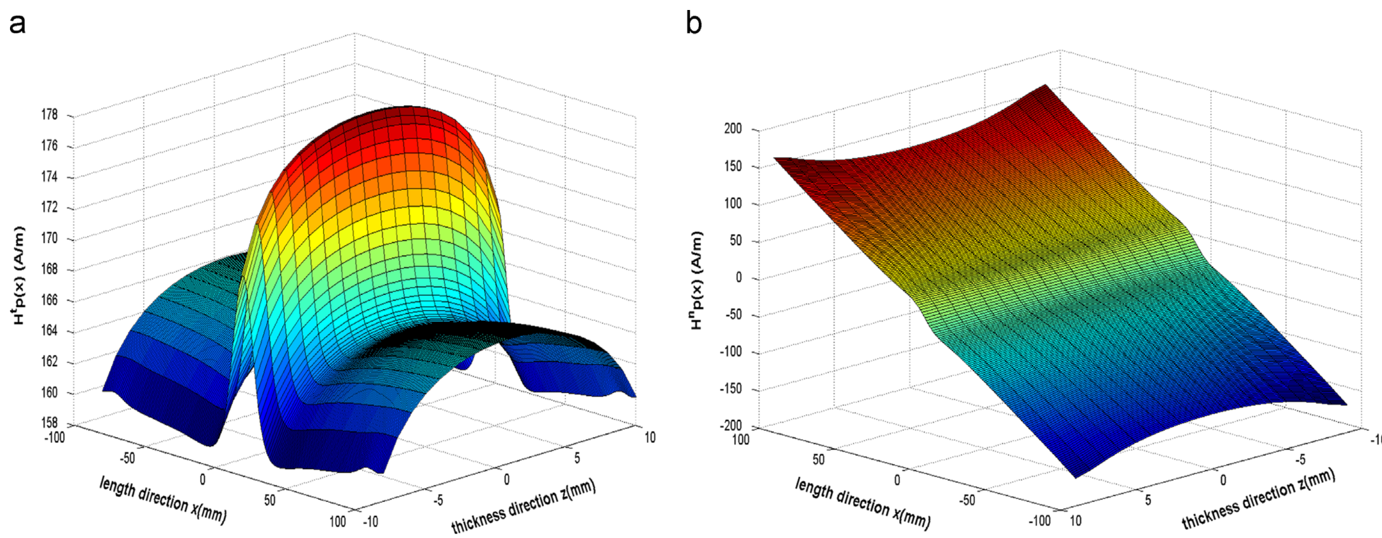

Fig. 2. Contour maps of tangential (a) and normal (b) RMF components for $b=4$ mm, $d=3$ mm and $L=1$ mm.

thickness (in z-direction) of local stress-concentration zone (SCZ) are denoted by b, t and d. In order to get accurate results, fine mesh was made within the plastic zone. The FEM elements for this simulation are about 120,000, and the computing time for one case is about 1200 min by a personal computer with Intel(R) Core (TM) i5-2500K CPU @3.30 GHz 3.60 GHz and 16.0 GB memory. The Earth magnetic field is simulated by two large magnets to produce a homogenous environmental magnetic field with the amplitude of 40 A/m.

Plastic deformation in the middle of the specimen leads to the accumulation of the dislocations acting as pinning sites and causes irreversible orientated movements of domains, which consequently decreases the magnetic permeability μ_r and develops a local coercive field H_c in the plastic zone. In this study, we assume a constant plastic strain with 8% in the middle of the specimen, where $\mu_r=270$ and $H_c=335$ A/m. For details, we referred to Yao et al. [19].

3. Simulation results and discussions

3.1. Effect of plastic-zone size

Measurement is performed along the x-direction from one end of the specimen ($x=-100$ mm) to the other end ($x=100$ mm). The lift-off value, L, which is defined as the distance between the RMFs measured surface and the specimen surface, is 1 mm. Fig. 2 shows the contour maps of the tangential and normal RMF components for a 3D specimen with a plastic zone of width $b=4$ mm. Fig. 3 shows the curves of tangential and normal RMF gradients, which are calculated from using the results in Fig. 2. One may observe that the curves of RMF gradients (Fig. 3) exhibit more pronounced characteristics in the plastic zone than RMF themselves (Fig. 2). It is worth notice that although the MMM testing method generally makes use of the RMF gradient absolute values, the RMF gradients with the positive/negative sign other than their absolute values are used here. This is because the RMF gradients experience the change of the signs in the plastic zone. Their absolute values cannot characterize this feature.

In order to understand the impact of the plastic zone on the RMF characteristics, we plot curves of the tangential and normal RMF gradients varying with x for different thickness in Fig. 4. It is seen from Fig. 4(a) that the tangential gradient component, $dH_p^t(x)/dx$, vanishes at points far from the plastic zone. It first increases from zero to a peak with x approaching the edge ($x=x^t_{-p}$) of the plastic zone, and then decreases and passes through zero at the center ($x=0$) of the plastic zone, reaching the minimum value with x approaching the other edge ($x=x^t_{+p}$) of the plastic zone, The normal gradient component $dH_p^n(x)/dx$ shows double peaks at $x=x^n_{-p}$ and $x=x^n_{+p}$, and reaches the minimum value at the center ($x=0$) of the local plastic zone. This behavior agrees with the previous experimental observation [18] and 2D simulation [19].