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A magnetomechanical model for the magnetic memory method

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ABSTRACT

Steel and other metal alloys are widely used in various industries of the national economy. The structure failure often causes great economic losses, and threatens people's life seriously, therefore the early warning of defect becomes essential to prevent malignant accidents fundamentally. Magnetic memory method is a nondestructive testing technology that can realize the early diagnosis for the ferromagnetic material. One key issue on the magnetic memory method is to establish the quantitative relationship between the shape and size of defect and the surface magnetic memory signals. However, little investigation of this issue restricts its applications in the engineering seriously. In this paper, based on a nonlinear constitutive relation for ferromagnetic materials under a constant weak magnetic field, a magnetomechanical model is established for the magnetic memory method, and its quantitative analysis is also completed by the finite element method. Comparisons of the theoretical results for different magnetomechanical models and experimental data are presented. It shows that theoretical results obtained from the proposed model are more consistent with experimental data, and the proposed magnetomechanical model is applicable for various ferromagnetic materials. A detailed study has also been performed to reveal the effects of load magnitude, defect size, lift-off value on the magnetic memory signals. In addition, a theoretical analysis for the stress concentration problem is presented to demonstrate its feasibility for the early diagnosis.

1. Introduction

Steel and other metal alloy are the most widely used kind of structural materials in the national economy. For instance, the rail steel U71Mn and U75V are all metal alloy generally used in high-speed train rails [1]. The high speed rails undertake the function of guiding the wheels move forward and withstanding the enormous pressure from the wheels. As an essential component of the track structure, high-speed train rails play a key role for the high speed, secure and smooth train running. In the design, fabrication and application process, stress concentration caused by defects is a major cause of metal structure failures. The structure failure can affect the structural safety and service life, and then, causes a great economic loss and threatens the safety of the human seriously. For example, the existence of rail defects may cause rail breakage, and then causes the train derailment accident. The damage inspection for the high-speed rails has become a important worldwide subject of nondestructive testing. At present, the rail damage inspection methods mainly include ultrasonic testing, radiographic testing, magnetic flux leakage testing, eddy current testing, etc. [2–4]. However, these nondestructive testing methods can only detect the defects with a certain scale, but it cannot evaluate the early damage, especially the stress concentration and the recessive discontinuity. The effective detection in the early stages of rail defects can avoid the malignant accidents caused by fatigue damage development fundamentally. Magnetic memory method is regarded as a new nondestructive testing technology in the 21st century [4]. It not only can detect the position of the defect, but also can realize the early diagnosis for the ferromagnetic material and structure. At present, researchers have started trying to apply magnetic memory method on the railway detection.

Magnetic memory method is a passive magnetic testing technique different from the traditional magnetic flux leakage method, which can determine the exact location and degree of stress concentration or defects through the spontaneous surface micro magnetic signals of ferromagnetic materials [5,6]. One key issue on the magnetic memory method is to establish the quantitative relationship between the shape and size of defect and the surface micro magnetic signals. Jiles established a phenomenological model to explain the magnetomechanical constitutive relationship based on the law of approach and effective field theory [7,8]. This phenomenological model has a clear physical mechanism, and can build a bridge between the mechanical quantities and magnetic quantities, which is often used in the qualita-

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tive analysis of the magnetic memory experiments. For instance, the direction of the field gradient reverses under different stress condition from a tensile experiment, and this reverse phenomenon is explained by using Jiles constitutive relation successfully [9]. Using Jiles constitutive relation [8], the normal component of signals through a sheet specimen without damage is measured, and a qualitative explanation is given to explain that the slope of normal component increases as increasing loading [10]. The test of magnetic memory signal for the steel specimens under fatigue load shows that the magnetic memory signals become stable after cyclic loading. And then, a qualitative explanation of this phenomenon is made through using the Jiles constitutive relation to analyze the influence of the initial magnetization state on the magnetic signals [11,12]. The rule of magnetic memory signals of thin shell structure is studied by using Jiles constitutive relation [13,14]. Exhaustive experimental results between the stresses and magnetic memory signals is completed, and a quantitative statistics and analysis is given based on Jiles model [15,16]. In addition, the bending experiment of round iron bar has been analyzed based on Jiles constitutive relation [17].

However, it is noteworthy that the experimental results can only reflect the influence of single factor (e.g. defect size or load magnitude) on the magnetic memory signals, but cannot describe multi-factor combined effects (e.g. environmental magnetic field, initial magnetization condition, defect type and size, load type and magnitude) on the signals. However, the basic key issue on the quantification research for magnetic memory method is the quantitative rules between of the multiple factors and magnetic memory signals. Therefore, it is necessary to study the theoretical model of magnetic memory method. As yet, these numerical investigations of magnetic memory method can only describe qualitatively the basic morphology of magnetic memory signal, further, how to establish the quantitative relationship between the damage and the micro magnetic signals has been widely concerned by researchers [18–25]. However, the previous theoretical study has some limitations quantitatively. For instance, for the magnetic charge method [19,20], it becomes more difficult to determine the value of the magnetic charge density. And the body magnetic charge caused by inhomogeneous stress distribution is often overlooked in the magnetic charge method. The existing experimental shows that the fact that magnetic memory signal increases with stress increases, but the results of finite element analysis fail to portray experimental phenomenon [21,25]. Recently, by using Jiles model as constitutive relation, the analysis of the magnetic memory signal caused by a non-uniform magnetization body is completed, and the quantitative relation between of the stress distribution of ferromagnetic materials and the surface magnetic memory signals is established [26–29]. However, there results still exist a gap between their theoretical results and the corresponding experimental results [26–28]. For example, there is a gap of 70% in amplitude difference between the experimental data and the theoretical results for the peak value of radial component of signal [26]. In addition, in another study [28], the theoretical result is 46% less than the experimental results when the test specimen is in the low stress state (it corresponds the stress is less than 35 MPa).

"The remanence of a ferromagnet is formed under the influence of many factors," says professor Gorkunov, director of institute of engineering science in Russia, "and the method of magnetic memory, without taking into account the conditions of the formation of the remanence state in a product area under testing will have low assessment reliability" [30]. As shown in Fig. 1, the theoretical results based on the energy conservation relation, the mean value of the tangential component and the slope of the normal component of magnetic memory signals do not vary with the stress. The theoretical results based on Jiles hysteresis and Jiles magnetomechanical constitutive relations can both reflect the variation trend of characteristic value with the increasing stress, but there has a significant difference between the theoretical results and the experimental data for the low stress state. This gap between of the theoretical results and experimental data may be due to the lack of quantitative study on the constitutive relation. As pointed out in literature [9], the Jiles constitutive relation has some deficiencies in quantification, for instance, there is a visible difference between theoretical and experimental results [31] on stress magnetization curve, and the relative error is greater than 40% in half of the cases. Based on the thermodynamic relations and the approach law of irreversible magnetization, a nonlinear constitutive relation has been proposed for the quantitative evaluation of magnetomechanical effect [32]. As shown in Fig. 2, in comparison with Jiles constitutive relation, excellent agreement has been achieved between the predictions from the proposed nonlinear constitutive relation and the experimental results, which means that this nonlinear constitutive relation can predict the magnetomechanical behavior quantitatively under different magnetized conditions [32]. It is evident that the material parameters in the general nonlinear constitutive relation can also be determined by the measure experiments in mechanics and physics easily.

Using the proposed nonlinear constitutive relation [32], in this paper, the quantitative analysis of the magnetic memory signals is realized through the finite element method. In Section 2, the basic equations for magnetic memory method are introduced in detail. After that, through comparing the theoretical results and experimental results, the effectiveness of the theoretical model is verified in Section 3. In Section 4, a detailed study is performed to reveal the effects of the load magnitude, defect size, structure size, lift-off value on the magnetic memory signals. Finally, some remarks and conclusions are drawn in Section 4.

2. Theoretical framework

Mechanical equations, magnetism equations, and the constitutive relation are given together to form the theoretical model for magnetic memory method. Magnetism equations contain Maxell's equations, jump condition on the interface, magnetization relation. For the mechanical equations, there are the deformation equilibrium, constitutive equation, equilibrium equation and boundary conditions. Here, in the proposed magnetomechanical model, the proposed nonlinear constitutive relation [32] is applied to describe the magnetization changes induced by the loaded process. In the following sections, these equations are listed to establish the theoretical model for magnetic memory method.

2.1. Mechanical equations

The three-dimensional elasticity mechanical equations are applied for the mechanics analysis of ferromagnetic structure, because the mechanical response due to the weak geomagnetic field is approximately two orders of magnitude lower than the mechanical response caused by the stress load. And the whole process can be approximated as a static process for the low deformation speed case. Furthermore, the material is assumed as an isotropic medium. All of the mechanical equations are listed as follows.

The equilibrium equations are

$$\sigma_{ij,j} + F_i = 0 \tag{1}$$

where σ_{ij} is the stress tensor, and F is the body force.

These strains are related to the displacement by Cauchy equations

$$\varepsilon_{ij} = (u_{i,j} + u_{j,i})/2 \tag{2}$$

where ε_{ij} is the strain tensor, and u_i is the displacement tensor.

To close system (1) and (2), it is necessary to add the constitutive relations

$$\varepsilon_{ij} = \frac{1}{E'}[(1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij}] \tag{3}$$

where E' is the Young's modulus, and ν is the poisson's ratio, δ_{ij} is the