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Research articles

Studies on laws of stress-magnetization based on magnetic memory testing technique

Shangkun Ren *, Xianzhi Ren

Key Laboratory of Nondestructive Testing of Ministry of Education, Nanchang Hangkong University, Nanchang 330063, China

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ABSTRACT

Metal magnetic memory (MMM) testing technique is a novel testing method which can early test stress concentration status of ferromagnetic components. Under the different maximum tensile stress, the relationship between the leakage magnetic field of at certain point of cold rolled steel specimen and the tensile stress was measured during the process of loading and unloading by repeated. It shows that when the maximum tensile stress is less than 610 MPa, the relationship between the magnetic induction intensity and the stress is linear; When the maximum tensile stress increase from 610 MPa to 653 MPa of yield point, the relationship between the magnetic induction intensity and the tensile becomes bending line. The location of the extreme point of the bending line will move rapidly from the position of smaller stress to the larger stress position, and the variation of magnetic induction intensity increases rapidly. When the maximum tensile stress is greater than the 653 MPa of yield point, the variation of the magnetic induction intensity remains large, and the position of the extreme point moves very little. In theoretical aspects, tensile stress is to be divided into ordered stress and disordered stress. In the stage of elastic stress, a microscopic model of the order stress magnetization is established, and the conclusions are in good agreement with the experimental data. In the plastic deformation stage, a microscopic model of disordered stress magnetization is established, and the conclusions are in good agreement with the experimental data, too. The research results can provide reference for the accurate quantitative detection and evaluation of metal magnetic memory testing technology.

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Ferromagnetic metal component, such as steel, is widely used in various industries, which have bored different forms of external loads, high temperature and high pressure for a long time, then the internal organizational structure will change, and then leading to the formation of stress concentration and microscopic damage. So efficient and reliable nondestructive testing (NDT) technology is vital for the early diagnosis of engineering equipment [1]. However, the normal NDT methods, such as ultrasonic method, permeation method and eddy currents method, are sensitive to macroscopic volume defects of ferromagnetic component instead of the stress concentration and early fatigue dmage. X-ray testing only can detect surface residual stress by inspecting material lattice distortion, and its equipment is very complex and expensive [2–3].

Metal magnetic memory (MMM), which was first presented at the 50th International Welding Conference in 1997 [4–5] and originally developed by Russian researchers [6–7], is a new, nondestructive testing (NDT) and diagnostic method for assessing ferromagnetic material stress concentrations [8–9] and fatigue damage. MMM is primarily based on the magnetic irreversible phenomenon that appears in stress concentrations and plastic deformation areas within ferromagnetic working pieces under load conditions.

The concept of metal magnetic memory (MMM) is that grain rotation and inverse magnetostrictive effect in the ferromagnetic interior will cause macroscopic magnetic properties of material under the action of both applied stress and geomagnetic field, the discontinuity of macroscopic magnetic properties given rise by stress concentration will be retained after removing stress [10–11]. MMM method is a novel nondestructive testing technology, which based on self-magnetic leakage field (SMLF) distributing in stress concentration zones of ferromagnetic material, determines the distribution of stresses [12–13]. Physical effect of MMM testing mainly include magneto-elastic effect, magneto-mechanical effect (such as magneto-strictive effect). The leakage magnetic field effect caused by inhomogeneity of structure and mechanical properties and magneto-plastic effect, which will lead to irreversible increase in magnetic induction under a weak

* Corresponding author.
E-mail address: renshangkun@yeah.net (S. Ren).

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magnetic field, a external stress in a certain direction applies to ferromagnetic component [14–15]. MMM signals are weak magnetic signal which is vulnerable to many factors, such as human factors (lift-off height, online or offline testing), chemical composition, the specimen shape, the notch shape, the heat-treating technology and the initial magnetization state of ferromagnetic materials, and environmental magnetic field, et al. [16–17]. Only by determining the influence of each factor on MMM signals and effectively eliminating the interference of each factor, can MMM signals be more accurately utilized to evaluate the damage extent of stress concentration zones, and to propose reliable criteria and evaluation parameters, which can comprehensive analyze stress state and deformation stage of ferromagnetic components so that early diagnosis can be achieved before the components being destroyed and existing potential danger [17–19]. Leng et al. [20] conducted a static load tensile test for demagnetizing and non-demagnetizing, obtaining the result that initial magnetization state exerted a tremendous influence on MMM signals. Zhang et al. [21] carried out magneto-mechanical coupling test on galvanized steel wire under the different magnetization state, getting the conclusion that magnetization state was a vital factor affecting magneto-mechanical coupling. Although many domestic and foreign authors have studied the influence of various factors on the MMM signals, the investigating on laws of stress-magnetization is still a few. This paper mainly study the laws of stress-magnetization by experimental and theoretical analysis methods, and conduct a static load tensile test on 45 steel specimens. The research results can provide reference for the accurate quantitative detection and evaluation of metal magnetic memory testing technology.

1. Experiment

1.1. Experimental method

Plain carbon structural steel 45 steel was selected as the test object in this paper due to its widely used in industrial production. The constant rate loading test is carried out on the 45 steel specimen under the condition of room temperature using the WDW-E100D electronic program-controlled testing machine. Among them, the maximum tensile load of the electronic tensile testing machine is 100 kN, the loading rate is 2 mm/min, and the load indication error is 0.5%–1.0%. The leakage magnetic field is measured by the weak magnetic field measuring instrument produced by LakeShore, whose measurement range is 0.001 Gs–300,000 Gs, measurement error is less than 0.2%, the resolution is 4%. The 45 cold rolled steel specimen structure diagram is shown in Fig. 1, and the specimen was subjected annealing to stress relief prior to testing. At a certain point in the specimen, the leakage magnetic field generated by the magnetization of the specimen is measured. The changing law of the leakage magnetic field can reflects the variation law of the magnetization intensity caused by the stress. This test is through the measurement of leakage magnetic field at a certain point on the specimen surface, to reflect the specimen magnetization state caused by stress. In theory, the magnetic properties of the ferromagnetic specimen will change during the stretching process. During the test, the specimen is placed vertically. The static tensile test was carried out at a tensile rate of 0.2 mm/min, and was loaded into different preset loads, and then unload the specimen to measure the magnetic memory signal at the fixed point for different loads. The upper measuring point M and the lower measuring point N are symmetrical about the center point of O, so the variation trend of magnetic properties at M point and N point are symmetric about O points, but was opposite in signal. It is analyzed by the measured results at measuring point M and N in this paper. Under different tensile stresses, the normal magnetic flux density B at the point of determination (upper measuring point M and lower measuring point N) of the specimen is measured on-line, where the law of B with the tensile stress can reflect the magnetic properties of the specimen with the stress changes. The distances of M point and N point to the center O are 40 mm, relative to the center O point symmetry.

2. Experimental results and discussion

2.1. Tensile curve of 45 cold rolled steel specimen

Fig. 2 shows the tensile curve of the 45 cold rolled steel specimen. As can be seen from Fig. 2, the yield strength of the specimen is 653 MPa, and the tensile strength is 774 MPa. 653 MPa is an important critical point, which is of great significance to the basic theory of force-magnetic effect and magnetic memory quantitative detection technology.

2.2. In the range of elastic stress, the basic law of ordered stress magnetization

Fig. 3 shows the relationship between the magnetic induction intensity of surface normal direction measured at the measurement point M and the tensile stress in the 45 cold rolled steel specimen. Fig. 3a shows the relationship curve between the magnetic flux density B measured at the measurement point M and the tensile stress after repeated loading – unloading twice, and the maximum tensile stress is 460 MPa. All measurements in this paper are the results of the measurements in the range of maximum stress after repeated loading-unloading 2 times. Through the repeated loading – unloading can eliminate the special effects of each specimen, not only can reflect the general law of the material, but also close to the real load-bearing components.

Fig. 3a shows the linear relationship between the magnetic induction intensity and the stress when the maximum tensile stress is 460 MPa. The variation law can be fitted as a straight line equation: $B = -2.357 + 0.0026\sigma$, and the maximum change in magnetic induction intensity is $\Delta B = 1.2 \times 10^{-4}$ T. The unit of tensile stress σ is MPa. Fig. 3b shows the relationship between the

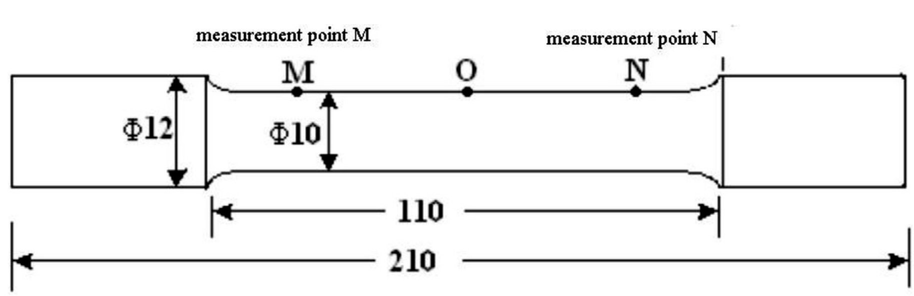

Fig. 1. The schematic diagram of the specimen (unit: mm).

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