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Effect of loading speed on the stress-induced magnetic behavior of ferromagnetic steel

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ABSTRACT

The primary goal of this research is to investigate the effect of loading speed on the stress-induced magnetic behavior of a ferromagnetic steel. Uniaxial tension tests on Q235 steel were carried out with various stress levels under different loading speeds. The variation of the magnetic signals surrounding the tested specimen was detected by a fluxgate magnetometer. The results indicated that the magnetic signal variations depended not only on the tensile load level but on the loading speed during the test. The magnetic field amplitude seemed to decrease gradually with the increase in loading speed at the same tensile load level. Furthermore, the evolution of the magnetic reversals is also related to the loading speed. Accordingly, the loading speed should be considered as one of the influencing variables in the Jies-Atherton model theory of the magnetomechanical effect.

1. Introduction

As is well known, the dimension and shape of ferromagnetic crystals can be altered during the process of magnetization and this phenomenon is called magnetostriction effect. Conversely, the intrinsic magnetization of a ferromagnetic material can also be changed, as mechanical actions are applied, which is usually named as piezomagnetic effect [1,2] and was first investigated by Villari in 1865. Ever since then, a lot of efforts have been made to study this effect both theoretically and experimentally. Brown [3] and Lliboutry [4] observed and described the reversal of magnetization and irreversible magnetization. Bozorth et al. [5,6] found out that the effect of unidirectional stress on magnetization depends on the magnetostriction of the material and the threshold of plastic flow also enhances the changes in magnetization. Craik and Wood [7] investigated the magnetization changes induced by uniaxial stress in a constant applied field and reported asymmetry properties of the piezomagnetic effect under tensile and compressive stresses. In 1984, Jiles and Atherton [8] explored the theory of the magnetization process in ferromagnets and its application to the magnetomechanical effect. Later, a model theory of the changes in magnetization that a ferromagnetic material undergoes when subjected to an applied uniaxial stress, called as 'Jies-Atherton model theory', was developed by Jiles et al. [9,10]. This theory was successively verified by Maylin [11] and Squire [12], and used in magnetomechanical effect analysis. Afterwards, the J–A model was improved constantly and applied widely [13–15].

In recent years, there has been a resurgence of interest in magnetomechanical effect because of its relevance to several technological problems, such as the use of magnetic materials in sensors and applications of magnetic method to non-destructive evaluation of stress in materials. For example, Wilson et al. [16] found that the stress in a sample could be measured using magnetic field sensing, which provided a portable solution for non-destructive evaluation. Huang et al. [17] confirmed the potential possibility of quantitative inspection of crack propagation by investigation of the spontaneous magnetic signal variations. Bormio-Nunes and Hubert [18] investigated the piezomagnetic behavior of Fe–Al–B alloys for the first time and proved the alloys as promising materials in magnetic sensors or actuators due to the high sensitivity of the magnetization with respect to the applied stress. Aydin et al. [19] analyzed the effect of multiaxial stress on the magnetic behavior of the iron sheets using a coupled magneto-mechanical model, and found that the simulation results were consistent with the experimental and modeling results from literature. However, the coupling relationship between the piezomagnetic signals and stress is very complex: many factors influence the variation of piezomagnetic signals, such as: loading type (tension, compression, cycle stress, etc.), the chemical compositions of ferromagnetic materials, the geometry and dimensions of the specimen, and the strain rate as well. Up to now, few studies have been carried out to investigate the effect of tensile loading speed on the magnetic behavior of steel. The previous research of the authors [20] has shown noticeable results with certain regularity: the differences between residual magnetic fields,

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Table 1
Chemical composition of Q235 steel.

Material	C	Si	Mn	P	S
Q235 (wt%)	0.14–0.22	≤0.35	≤1.4	≤0.045	≤0.05

Table 2
Mechanical properties of Q235 steel.

Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
Q235	203	250	375–460

caused by varying loading speeds, changed systematically as the applied load increases. In this paper, magnetic field variations with the loading speed varying from 0.5 mm/min to 6 mm/min are recorded in the whole loading and unloading processes of the tensile tests. By comparing the magnetic behaviors under different loading speeds, this research aims at developing a quantitative relationship between the piezomagnetic signals, applied tensile loads and the loading speeds.

2. Experiments

2.1. Specimen preparation

The tested material in this research is Q235 steel, a typical low-carbon structural steel widely used in engineering structures in China. Tables 1 and 2 present the chemical compositions and mechanical properties of Q235 steel, respectively. Specimens were machined into smooth plates with identical dimensions of a thickness of 4 mm and a cross-section of 100 mm^2 according to the Chinese standard GB/T 228-2002, as shown in Fig. 1..

2.2. Experimental procedure

The tensile tests were carried out at room temperature by a universal testing machine with a peak capacity of 200 kN. A standard 50 mm gauge length electronic extensometer was used to measure strain. A fluxgate magnetometer was employed to detect the piezomagnetic signals (B field). The selected measuring range of the magnetometer was ±1000 nT. The experimental setup of the test apparatus is shown in Fig. 2. The specimen made of Q235 steel was vertically mounted between the upper and lower grips. The magnetic probe was mounted onto the lower grip of the load unit with a rigid nonmagnetic support. Besides, it has been verified that there was no relative movement of significance between the probe and the specimen when tests were running. The distance between the tip of the magnetic sensor and the surface of a specimen was about 10 mm. The magnetic probe was shielded by a cylindrical Mu metal tube so that it could only record the magnetic field component parallel to the cylindrical axis of the probe..

Before the test was started, the specimens were initially demagnetized by a demagnetizer based on the alternating field demagnetization principle. In order to ensure that the initial magnetic fields of the specimens were close to each other, the average remaining remanence after demagnetization should be controlled under 5 A/m. During the test, each of the specimens experience five loading programmes with the same pre-set loads under different loading speeds. Specifically, in the first loading programme, specimen 1 was first loaded to an initial pre-set load P_i with a loading speed of 0.5 mm/min and then unloaded with an unloading speed of 6 mm/min. Then, the specimen was dismantled carefully from the loading grips, placed on a non-magnetic platform along the south-north direction and demagnetized again. In the next four programmes, specimen 1 was reloaded to the same pre-set load P_i with different loading speeds of 1 mm/min, 2 mm/min, 4 mm/min and 6 mm/min, respectively. However, the unloading speed in each loading programme was kept identical at 6 mm/min. At the same time, the magnetic field variations were monitored online by the magnetic probe at the same time during the whole process for further comparison. The above procedure was repeated with the next higher pre-set load until visible necking appeared.

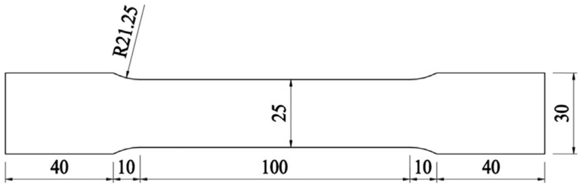

Fig. 1. Shape and dimensions of specimens (unit: mm).

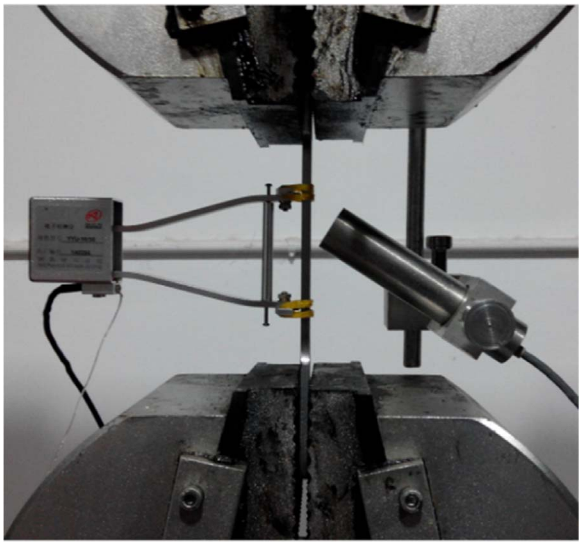

Fig. 2. Experimental setup of extensometer and fluxgate magnetometer.

3. Results and discussion

Fig. 3 displays the evolutions of the magnetic field under different loading speeds as the applied tensile loads increase from 10 kN to 25 kN in the elastic stage. It is obvious that the loading speed imposes strong impact on the magnetic field variations. Although the evolution trends of the magnetic field at the same load level remain similar, the shapes and positions of curves under different loading speeds vary conspicuously. The most visible feature here is that the magnetic field curve moves down and its amplitude decreases gradually with the loading speed increasing from 0.5 mm/min to 6 mm/min, even in different tensile load levels varying from 10 kN to 25 kN. In Fig. 3(a), the differences of the magnetic field variations caused by different loading speeds are relatively apparent: as the loading speed increases from 0.5 mm/min to 6 mm/min, the B Field at the maximum tensile load of 10 kN is reduced by about 18.6% from 86.2 nT to 70.2 nT. Furthermore, in the loading process from 0 kN to 10 kN, B field shows an almost linear increase. With the increase in loading speed, the magnetic traces tend to rotate clockwise and the initial slope of the B field curve decreases. In Fig. 3(b) and (c), the tensile load levels are 15 kN and 20 kN respectively. Although the magnetic traces curve down away from a straight line more significantly and the variation amplitudes increase, the evolution trends of the magnetic field under different loading speeds are consistent with that shown in Fig. 3(a): the magnetic field amplitudes decrease with the increasing loading speed and the magnetic field traces also rotate clockwise in these two load levels. In Fig. 3(d), at the applied tensile load level of 25 kN,