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Variation of stress-induced magnetic signals during tensile testing of ferromagnetic steels

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Abstract

Stress alone applied to ferromagnetic materials can induce the generation of weak magnetic signals on their surfaces, which can be potentially used to estimate the degree of damage of ferromagnetic components. In this paper, the normal component of stress-induced magnetic field, $H_p(y)$, was measured during tensile tests on the surfaces of sheet specimens of three ferromagnetic materials. It has been concluded that $H_p(y)$ depends on the applied stress and will present different characteristics on the elastic and plastic deformation stages, respectively. The phenomenon of sharp changes in magnetic signals occurring at the instant of fracture was also discussed from the view of the interaction energy in a ferromagnet.

Keywords: Applied stress; Normal component of stray field; Elastic deformation; Plastic deformation; Dislocation

1. Introduction

It is well known that the shape and dimension of ferromagnetic crystals can change during the magnetization process, which produces the so-called magnetostriction effect. Conversely, when external stress is applied to the ferromagnetic materials, their magnetic properties will be altered. This is called the piezomagnetic effect [1,2]. The piezomagnetic effect is gaining increased attention due to its relevance to magnetic measurements for the evaluation of stresses in materials. Recently, however, the great majority of research has been focused on the effects of stress on magnetic properties under the co-applied magnetic field, such as susceptibility, permeability, remanence, coercivity as well as the hysteresis loop [3–6], and those experiments have been performed under the existence of extra magnetic field. Little attention has been paid to the variations of spontaneous magnetic signals of ferromagnetic materials under stress without any other extra applied magnetic field (excluding the Earth's magnetic field). In 1977, Misra [7] reported the generation of a spontaneous magnetic field of the order of 0.1 T under uniaxial tensile stress. The specimens had been demagnetized before testing, but he found that the fractured pieces became magnetized just at the instant of fracture. His research group then presented a theoretical model in 1990 for this fracture-induced effect and concluded that the complex dislocation configuration during the necking and just prior to tensile fracture lead to the generation of transient magnetic field [8]. The research group also investigated the shape anisotropy of the magnetic field generation with different specimen cross sections including cylindrical, square, rectangular and thin-sheet. The results indicated that the magnetic field that was generated strongly depended on the degree of necking [9]. However, Misra's group only analyzed the stress-induced magnetic field generated just at the instant of tensile fracture, while the stray field of ferromagnetic specimen actually existed throughout the tensile process, whose variation can provide better reflection of stress state. In addition, at the beginning of the 1980s researchers in Russia also observed

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the stress-induced magnetic field on defective areas of boiler pipes in a power station, and developed some instruments for detecting the stress concentration zones in ferromagnetic components. This method was named Metal Magnetic Memory Testing [10–14]. However, there is still lack of systematic test data for their investigation on the coupling relationship between the stray field signals and stress. In fact, the coupling relationship is very complex. If the relationship can be clarified to some degree, it is possible to determine the damage degree of ferromagnetic component.

In this paper, static tensile tests of sheet specimens of low-carbon steel, medium-carbon steel and alloyed steel were performed. The normal components of the stress-induced stray field, $H_p(y)$, on the surface of specimens, were measured at predetermined stress levels throughout the tensile process. The relationship between applied stress and $H_p(y)$ was discussed and the microstructure influence on the stray field was analyzed as well.

2. Experiment

2.1. Specimen preparation

The tested materials were Q235 steel, 0.45%C steel and 45CrNiMoVA steel, respectively. Q235 steel and 0.45%C steel are carbon structural steels with different carbon contents; 45CrNiMoVA steel is a high-quality alloy steel containing many alloy elements. All of them are typical ferromagnetic materials widely used in bridges, welding structures and gear, main shaft, crankshaft, etc. Their chemical composition and mechanical properties are given in Table 1.

The shape of the flat specimen is shown in Fig. 1. Its surface roughness R_a was 1.6 μm; two parallel lines marked by numbers 1 and 2 with 10 mm of space vertically were drawn on the surface. There were 10 points with 10 mm intervals on every horizontal line chosen for $H_p(y)$ measurement. The length of each measured line was 90 mm.

2.2. Experimental arrangement

The tensile test was carried out with a servo hydraulic MTS810 testing machine with static error $\pm 0.5\%$. $H_p(y)$ value was measured by an EMS-2003 Metal Magnetic Memory instrument, the key part of which is a magnetic probe based on a Hall sensor. The magnetic probe with a sensitivity of 1 A/m is fixed on an electrical scanning platform made of non-magnetic materials and can be controlled to move automatically with a pace accuracy of 2.5 μm along the direction of measured lines vertically, collecting the normal component of the stray field from point 1 to point 10 exactly, avoiding interfering magnetic signals from surrounding objects and manual operation errors.

Table 1
Chemical composition (wt%) and mechanical properties of specimen materials

Type of steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Yield strength, σ_s (MPa)	Tensile strength, σ_b (MPa)
Q235	0.14–0.19	0.12–0.30	0.30–0.65	⩽0.045	⩽0.050	0.30	0.30	–	–	235	400
0.45%C	0.40–0.50	0.17–0.37	0.50–0.80	⩽0.040	⩽0.040	0.15	⩽0.25	–	–	386	679
45CrNiMoVA	0.42–0.49	0.17–0.37	0.50–0.80	⩽0.030	⩽0.030	0.80–1.10	1.30–1.80	0.20–0.30	0.10–0.20	800	1150