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Experiments on the magnetostriction properties of the China low activation martensitic steel

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HIGHLIGHTS

- Magnetostriction properties of the CLAM steel in several condition have been investigated.
- Along the direction of magnetic field, magnetostriction of the CLAM steel is compressive.
- Stress brings significant influence on the magnetostriction properties of the CLAM steel.
- The proposed model gives good agreement with experimental results.

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ABSTRACT

In this paper, the magnetostriction properties of China Low Activation Martensitic (CLAM) steel, a typical Reduced-activation Ferritic/Martensitic steel developed for fusion reactor application, have been experimentally investigated. With a magnetic field from 0 to 1 T and tensile stress from 0 to 130 MPa, the correlations of strain-magnetic field intensity in several experimental conditions have been measured. Stress was found giving significant influence on the magnetostriction properties of the CLAM steel. A constitutive model is proposed then for describing the magnetostriction property of the CLAM steel based on the experimental results. The proposed constitutive relation between the magnetic field and the magnetostriction strain gives good description of the observed phenomena and is in good agreement with the experimental results in the middle strength range of applied magnetic field. This work provides a basic constitutive relation for the magneto-mechanical coupling analysis of structures of the CLAM steel in Tokamak fusion reactors.

1. Introduction

China Low Activation Martensitic (CLAM) steel [1–4], a kind of Reduced-Activation Ferritic/Martensitic (RAFM) steel, is considered as a candidate structural material for the blankets and vacuum vessel in the Tokamak fusion reactor in China. To investigate the mechanical behaviors of the CLAM steel structures in giant magnetic field, the magnetostriction property of the CLAM steel material has to be clarified. In previous studies, researches on the magnetostriction property are mainly focused on the soft-magnetic material, giant magnetostrictive material and Galfenol alloy etc [5–8]. The magnetostriction property of the CLAM steel is considered faint compared to such materials, and its effect is often ignored in the analysis for the Tokamak structure design. There are few research results about this issue up to now. However, Tokamak fusion reactor works in a very strong magnetic field which may cause great influence on the structural mechanical behaviors [9,10]. In order to quantitatively evaluate the mechanical behaviors of Tokamak structures in a strong magnetic field, the magnetostriction property of the CLAM steel is necessary to be known. In this paper, measurements were performed to investigate the magnetostriction effect of the CLAM steel. Repeatable correlation between the deformation and applied magnetic field was obtained. Through the thermodynamic approach, a model for the magnetostriction constitutive relation was established at first time for the CLAM steel. By using the fitting coefficients obtained with the experimental results, it is found that the proposed constitutive model can give good description of the magnetostrictive effect of the CLAM steel

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Fig. 1. Experimental system: the multi-field coupling testing device.

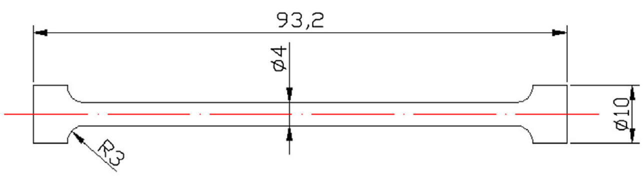

Fig. 2. Design and size of the specimen.

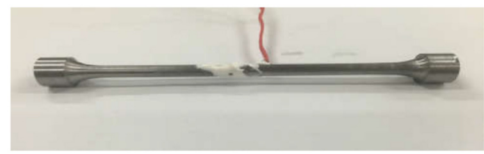

Fig. 3. Specimen with strain gauge.

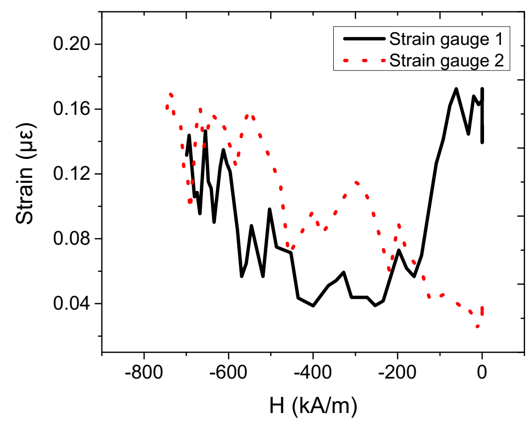

Fig. 4. Example of strain output due to external magnetic field.

especially in the middle strength range of the applied magnetic field.

2. Experiments

The experiments were performed with a multi-field coupling testing system, which can apply magnetic field and mechanical load to the specimen in the same time. The strength of magnetic field in the center of the electromagnet of the testing system can reach 1 T while a mechanical load is applied. The hydraulic devices of the testing system can provide a tensile load parallel to the direction of the applied magnetic field. The maximum mechanical load is up to 5000 N. The operating program of the multi-field coupling testing system provides an automatic control mode which can adjust the strength of the applied magnetic field in a steady speed. The mechanical loads are measured by a force sensor installed between the specimen and the hydraulic loading head, and are recorded and processed by the data processing unit together with the output signals of the strain gauges.

As depicted in Fig. 1, the experimental system contains three parts. First part is the electromagnet. The height of the cylindrical operating space between the two magnet poles is 180 mm. The magnetic field is along the vertical direction and almost uniform in the central region between the two magnet poles though the strength of magnetic field is a little larger at the edge region of the poles. In radial direction, the magnetic field is almost uniform in a region of 500 mm diameter. Outside this central cylindrical region, the magnetic field decreases rapidly in space. The second key part of the system is the force actuator which provides mechanical loads. A hydraulic device is installed on a retractable platform as the force actuator, which is made of stainless steel to reduce influence to the magnetic field. A fixture is consolidated in the top of the lifter of the hydraulic device, which provides a space to install the specimen and the sensor to measure load.

All specimens were fabricated with the CLAM steel. The CLAM steel was developed by the Fusion Design Study team of Chinese Academy of Sciences cooperated with several research institutes and universities. The performance of the CLAM steel has been reached the level of the other typical RAFM steels such as EUROFER97 and JLF-1. The chemical compositions of the CLAM steel used in this study are listed in Table 1. In order to be adapted to the fixture, the specimens were designed into a bone shape, as depicted in Fig. 2. The cylindrical specimen was 93.2 mm in total length, 10 mm radius in the end loading region and 4 mm radius in the measurement region. As shown in Fig. 3, a strain gauge was pasted on the middle of the specimen with its direction along the cylindrical axis. After the gauge consolidated to the specimen, a layer of silica gel was covered on the surface to protect the strain gauge. The 1/4 bridge method was adopted to connect the strain gauge, and a compensating piece was placed far away from the testing specimen to eliminate the influence of the temperature and magnetic field change.

In order to investigate the influence of magnetic field on the measurement precision of the strain gauge, a verification experiment was conducted. The strain gauge was located in a magnetic field without sticking to the specimen, and the direction of the gauge was set along the magnetic field. The output of the strain gauge for a magnetic field from 0 to 800 kA/m as illustrated in Fig. 4. A cyclic magnetic field from −800 to 800 kA/m was applied to the specimen. In Fig. 4, the negative magnetic field intensity is defined along the direction from the bottom to top of the electromagnet as shown in Fig. 1.

Without sticking to specimen, the output signal of the strain gauge reflects the influence of the magnetic field on the gauge. Such an influence can be divided into two parts. The first part is electromagnetic interference on the experimental instrument, and the second part is the influence of magnetic field on the strain gauge itself. In this work, several actions have been taken to reduce the influence of electromagnetic interference. Firstly, the hardware of