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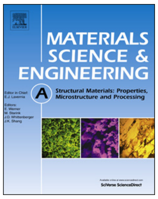

Effect of magnetic field on mechanical properties in Permendur

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ABSTRACT

Young modulus of magnetostrictive materials such as Permendur are changed by altering the external magnetic field. This phenomenon is called ΔE effect. In this paper, it has been experimentally shown that the shear modulus in Permendur is also changed in such a way that the ratio between Young modulus and shear modulus is not constant in different magnetic fields. Thus, Poisson ratio of it is also changed in different magnetic fields. Acoustic pulse–echo method is exploited to measure dependency of these properties to magnetic fields. In this method, longitudinal and shear sound wave velocities in Permendur are measured in different magnetic fields. Using these data, dependency of Young modulus, shear modulus and Poisson ratio on magnetic bias field in Permendur are calculated. Measurements are repeated 30 times in order to study test uncertainty. Changing in Poisson ratio can be interpreted as a result of changing in volume of magnetostrictive materials in different magnetic field (Nagaoka–Honda effect). The amount of this effect in ferromagnetic material is small. Hence, change in Poisson ratio in this material is predicted to be remarkably slight. For instance, based on presented results in Permendur, maximum changing in Poisson ratio is less than 0.014.

1. Introduction

Shape of ferromagnetic materials is changed under the influence of external magnetic field. This phenomenon is called Magnetostriction [1]. This effect is widely used to fabricate sensors, actuators and energy harvester devices [2,3]. In addition to changing shape in magnetostrictive materials, some mechanical properties of these materials are also depended on the external magnetic field. For instance, ΔE effect in magnetostrictive materials is the change in their Young modulus with magnetic field [4]. A lot of efforts have been done to determine ΔE effect in different magnetostrictive materials including giant magnetostrictive material such as Terfenol-D [5], and other magnetostrictive material such as Permendur [6]. Some efforts have been done to use this effect to fabricate sensors and actuators such as mechanical resonator [7]. There are some disagreements in reporting trend of ΔE effect in different papers. Because there are some factors (such as prestress and temperature) which can affect Young modulus of magnetostrictive materials; unpredicted behavior of these factors in different measurements set up was mentioned as a reason of these disagreements [8]. Results of Young modulus measurement in response to external magnetic fields from stress–strain curves show a decreasing trend at first and an increasing trend after minimum value [9].

It is a common interpretation to relate it to change in longitudinal sound wave velocity in Young modulus measurement [10] and also in study ΔE effect in magnetostrictive material [11,12]. Regarding to Eq. (1) [13], if Poisson's ratio remains constant in different magnetic fields, Young modulus and longitudinal sound velocity have the same trend with magnetic bias field.

$$C_b = C_0\sqrt{\frac{(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)}} \tag{1}$$

In Eq. (1), C_b is longitudinal sound wave velocity in finite sample, ϑ is Poisson ratio, C_0 is longitudinal sound wave velocity in infinite sample (1D specimen) and it is equal to $\sqrt{\frac{E}{\rho}}$, (E is Young modulus and ρ is density). Poisson ratio remains constant in different magnetic fields bias if the ratio between longitudinal and shear sound wave velocities remains constant. Longitudinal sound wave velocity (C_b) has an increasing trend with magnetic field. Presented measurement results for Permendur and previous reports about other magnetostrictive material (for instance: [11]) show this fact. Straight dependency between Young modulus and longitudinal sound wave velocity leads to an increasing trend for ΔE effect in spite of the expected result (i.e. results from

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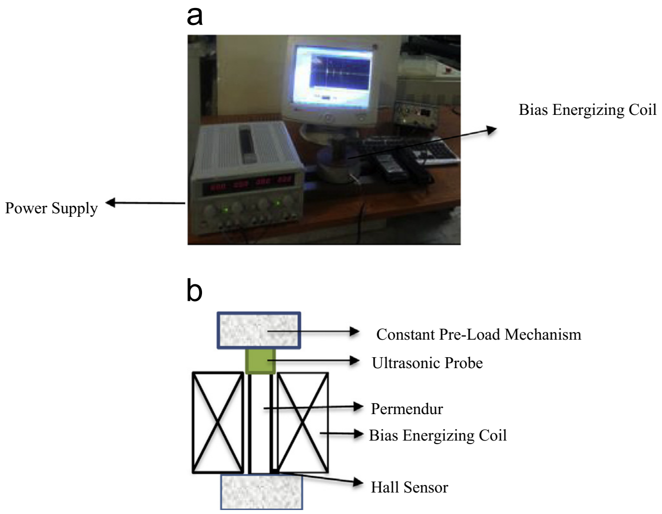

Fig. 1. (a) Picture and (b) schematic of experimental set-up

Table 1
Specification of probes.

Probe	Central frequency	Size (diameter)	Shape	Type
Longitudinal	10 MHz	12.7 mm	Circular	Contact
Shear	5 MHz	12.7 mm	Circular	Contact

Table 2
Specification of pulse-receiver.

Pulse/receiver, manufacturer: panametrics, model: 5072 PR
Setup *PRF=100* *Energy=4* *Damping=7* *Gain=28*

stress–strain curve).

In this paper, it has been experimentally shown that the trends of shear sound wave velocity and longitudinal wave velocity versus magnetic field in magnetostrictive material are not the same. Thus, Poisson ratio is not constant in different magnetic bias fields, and ΔE effect trend is not the same as longitudinal sound wave velocity trend. Changing Poisson ratio can be interpreted as a result of Nagaoka–Honda effect (changing volume due to magnetization).

Experimental study has been done on Permendur49. Permendur49 is an alloy of Iron, Cobalt and Vanadium [14]. Permendur49 is widely used to fabricate transducers [15], and actuators [16]. Acoustic method has been used for measuring mechanical properties of Permendur49 in different magnetic bias fields. To study uncertainty in measurements, each measurement is repeated 30 times. In each measurement, other influencing parameter such as preload has been kept constant.

In this paper, at first, a method and experimental set-up for measuring mechanical properties is described. Then, the results of the measurement consisting of longitudinal and shear wave velocity, Young modulus, shear modulus and Poisson ratio in different magnetic bias fields are presented.

2. Method

2.1. Acoustic method

In pulse–echo acoustic method, with measuring longitudinal (C_b) and shear (C_s) wave in materials, mechanical properties can be calculated with following equations [13].

$$E = \frac{\rho\, C_s(3C_b^2 - 4C_s^2)}{(C_b^2 - C_s^2)} \tag{2}$$

$$G = \rho\, C_s^2 \tag{3}$$

$$\vartheta = \frac{1 - 2\left(\frac{C_s}{C_b}\right)^2}{2\left(1 - \left(\frac{C_s}{C_b}\right)^2\right)} \tag{4}$$

In Eqs. (2)–(4), E is Young modulus, G is shear modulus, ϑ is Poisson ratio and ρ is density.

2.2. Experimental Set-up

For pulse–echo acoustic measurement, an experimental set-upshown in Fig. 1(a) has been designed and fabricated. In this setup, a coil with 1000 turns of 1.25 mm diameter enameled wire has been used to produce the magnetic bias field. Coil design has been made in such a way that Permendur is placed in the center of it. Therefore, the flux line in the Permendur is parallel. Magnetic field has been measured by Hall sensor. Contact between the ultrasonic probe and specimen with constant pre-load has been provided by pre-load mechanism. Thus, pre-stress in Permendur remains constant during the measurements. All the measurements have been done in room temperature. Demagnetization process has been done on Permendur sample before each test to avoid interference of hysteresis in measurement results.

The test procedure is accomplished according to ASTM E494 standard. NDT probes and A/D card with 100 mega sample per second data-acquisition for digitizing output signal have been used for these measurements. A/D card is fabricated by Gage Company and depth-post trigger has been adjusted to 7000. Specifications of probes (longitudinal and shear) and pulse-receiver are shown in Tables 1 and 2, respectively. Excitation voltage is tone burst shape with 250 V amplitude. Before the test, calibration with V1 block (made in SONATEST) has been done.

Fig. 2 shows output signals. By measuring the time of flight (time between peaks) and the thickness of Permendur specimen, sound wave velocity can be calculated by Eq. (5) [17].

$$C = \frac{(A_k n_1 t_1 C_k)}{(A_1 n_k t_k)} \tag{5}$$

In Eq. (5),

A_k = distance from first to Nth back echo on the known material (calibration V-block), measured along the base-line of the A-scan display,
n_1 = number of round trips in Permendur,
t_1 = thickness of Permendur,
A_1 = distance from first to Nth back echo on the Permendur, measured along the base-line of the A-scan display,
n_1 = number of round trips in the known material (calibration V-block),
t_k = thickness of the known material (calibration V-block) and
C_k = velocity in the known material (calibration V-block)

By using this procedure, shear sound wave velocity in Permendur is measured from the output shear signal, and longitudinal sound wave velocity is measured from the longitudinal signal.

Permendur density is 8150 kg/m^3 according to the