韓國精密工學會 2002年度 春季學術大會論文集 pp.275~278 KSPE 02S107

Temperature Dependence of Magnetostriction in Terfenol-D

Young-Woo Park(Mecha. Eng. Dept., CNU), Ki-Kyung Kum(Graduate School, CNU),
Seung-Hyun Han(Mecha. Eng. Dept., CNU)

Terfenol-D의 온도에 따른 자기변형 특성

박영우(충남대 메카트로닉스공학과), 금기경(충남대 대학원),
한승현(충남대학교 메카트로닉스공학과)

ABSTRACT

The performance of Terfenol-D, the commercially available magnetostrictive material, is highly dependent on the prestress, magnetic field intensity and temperature. This paper presents an experimental investigation of the temperature effect on the magnetostriction in Terfenol-D. The effects of both prestress and magnetic field on the magnetostriction are also presented. Experimental results show that both the prestress and magnetic field on the magnetostriction are significant. It is also observed that the displacement decreases slightly to around 40℃, then increases to 80℃. It indicates that the displacement decreases due to the reduced magnetization, and increases due to the thermal expansion, as the temperature increases. It means that the reduced magnetization affects more in the displacement change up to 40℃, and the thermal expansion affects more in the displacement change beyond 40℃

Key Words : Terfenol-D, magnetostriction, magnetic field, magnetization, thermal expansion

1. Introduction

Magnetostriction is a transduction process in which an electrical energy is converted into a mechanical energy [1]. It is related to the change in the geometrical dimensions of a body subjected to a magnetic field. The magnetostriction effect was first discovered in nickels by James Joule in 1842, and has been well-known for cobalt, iron and alloys of these materials. However, their magnitudes still limited to 50 ppm. Recent development of alloys of rare earth elements with iron has given us the new horizon of the new application of the magnetostriction effect. This rare earth magnetostrictive material, Terfenol-D, exhibits giant magnetostriction of about 2000 ppm [Butler, 1988].

There exist several factors which influence the performance of a magnetostrictive material. Those are temperature, magnetic field and mechanical prestress [2]. Moffet et al. investigated the effect of prestress on Terfenol-D material properties [3]. They concluded that proper mechanical prestress and magnetic bias conditions are critical to successful use of Terfenol-D in transducers and actuators. Clark and Crowder studied the temperature dependence of magnetostriction and compared it with theory [4]. They concluded that the temperature effect is significant on the magnetostriction.

There are, however, few papers dealing with temperature effect on the magnetostriction in Terfenol-D. Thus, this paper aims to study the effect of temperature on the magnetostriction in Terfenol-D and to analyze the interactive effect between prestress, magnetic field and temperature on the magnetostriction in Terfenol-D.

2. Theory

Magnetostriction is a transduction process in which an electrical energy is converted into a mechanical energy. It is related to the change in the geometrical dimensions of a body subjected to a magnetic field. Fig. 1 shows the magnetostriction phenomenon.

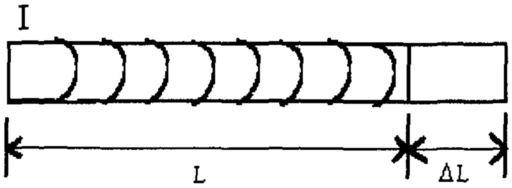

Fig. 1 Magnetostriction phenomenon

Magnetic field intensity, H, can be expressed as

$$H = NI/L \qquad (1)$$

where, N = number of coil turns, L = rod length, I = current

Magnetostiction can be expressed as

$$\lambda = c\sigma + Hd \qquad (2)$$

where, c=compliance, σ=prestress, and d=piezomagnetic constant.

If $\sigma = 0$, Eq. (2) can be rewritten as

$$\lambda = H d \qquad (3)$$

Also, magnetostriction can be expressed as

$$\lambda = \Delta L/L \qquad (4)$$

where, ΔL = elongated length.

From Eqs. (3) and (4), we obtain

$$\Delta L = H*d*L \qquad (5)$$

The generated force can be calculated by using

$$F = E*A*\Delta L/L \qquad (6)$$

where, E=Young's modulus of Terfenol-D, A=cross sectional area of the rod.

3. Experimental Procedure

The test rig consists of a drive rod, a coil-wound bobbin, a force sensor, a displacement sensor, a thermocouple foil, a current transducer, a prestress bolt, and a frame. The drive rod is a Terfenol-D rod that is 10 mm in diameter by 45 mm in length. The bobbin is made of a solid aluminum, and wound with approximately 1240 turns of 0.4-mm copper wire. Terfenol-D rod is placed inside the bobbin. A D.C. power supply is used to provide current for generating necessary magnetic fields. The force sensor used is a PCB piezoelectric load cell with a sensitivity of 11.241 mV/N. The displacement sensor used is an Electro EMD 4960 with a sensitivity of 7.874 mV/mm on the steel target. The K-type thermocouple foil by Omega is used and can measure up to 260°C. The current transducer used is HY50-P by LEM for converting the induced current into the voltage. It is known that the Terfenol-D performs better under the prestress [1]. This knowledge is incorporated into the design of the test rig using the prestress bolt on one end of the Terfenol-D rod. The frame is machined from a solid block of 8 cm-thick aluminum, which has an integral flexure. Current, force, and displacement data are fed into the data acquisition program through National Instruments DAQ I/O connector and National Instruments A/D card, and temperature data through RS-232 and National Instruments A/D card. Fig. 1 shows a schematic diagram of the experimental setup.

Several sets of experiments are conducted to accomplish investigation into the performance of Terfenol-D. First, the effect of prestress from 1.27 MPa to 10.16 MPa without a magnetic bias is investigated. Second, the magnetic field is vared from 15 kA/m to 60 kA/m for a given prestress to show the effect of magnetic field on the magnetostriction. Third, the temperature is increased to 80 ℃ with various prestress for a given magnetic field intensity. Finally, the interactive effect is investigated.

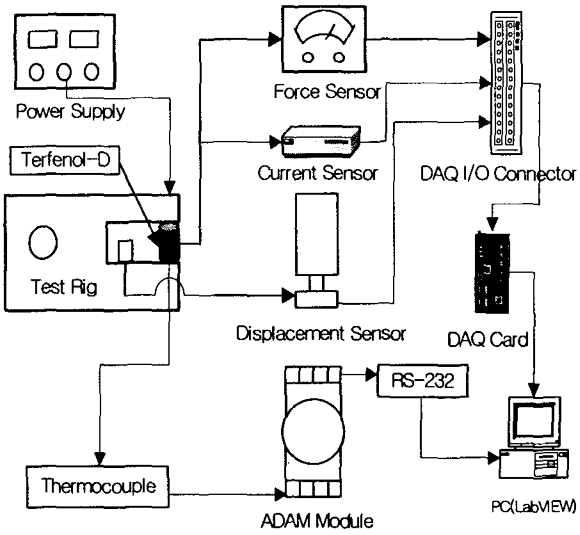

Fig. 1 Schematic diagram for the experiment

4. Results and Discussion

4.1 The effect of prestress on magnetostriction

Figs. 2 and 3 show the effect of the prestress and magnetic field (H) on the displacement and force generated. It is found that both the displacement and force increase up to 7.64 MPa, then decrease. It is also found that both the displacement and force increase as the magnetic field magnitude increases. The generated displacement and force at H = 15 kA/m are relatively small and mot easy to identify. The peak displacement (25 μm) and force (194 N) occur at H = 60 kA/m and $\sigma = 7.64$ MPa. Magnetostriction (λ or ΔL/L)) is the fractional increase in length, obtained by the application of a magnetic field H, and can be expressed as

$$\lambda = c\sigma + Hd \qquad (3)$$

where, c = compliance, σ = prestress, and d = piezomagnetic constant.

According to Eq. (3), λ increases as the prestress and magnetic field increase. Experimental observations agree well with the theory and data found in the literature [3, 5]. The generated force is a function of λ, so the increase of λ results in the force increase.

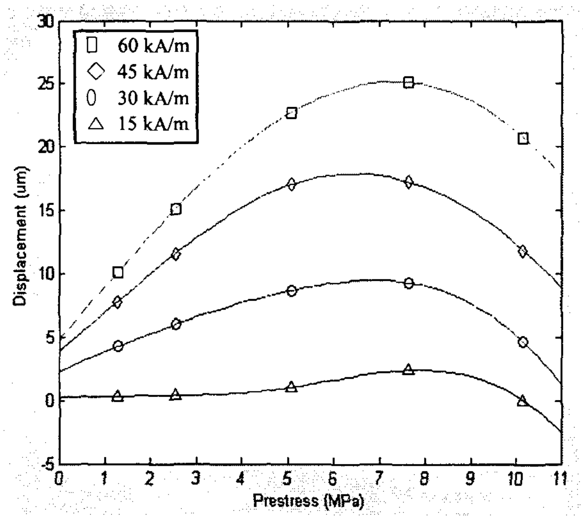

Fig. 2 Prestress vs. displacement with various magnetic field

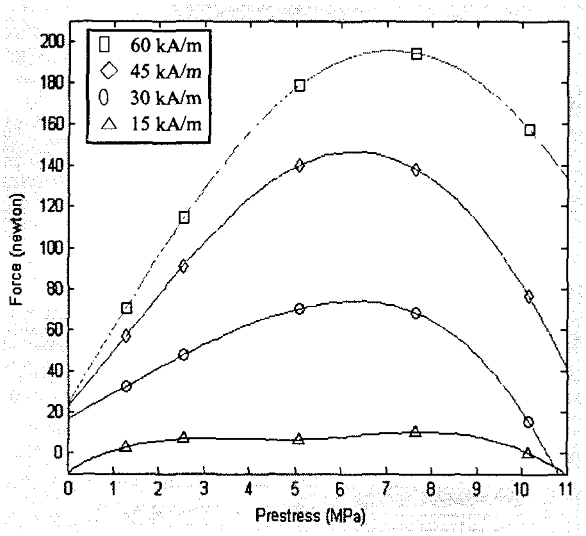

Fig. 3 Prestress vs. force with various magnetic field

4.2 The effect of temperature on magnetostriction

Fig. 4 shows the variation of the displacement in accordance with the temperature increase. Prestress is varied from 1.27 MPa to 10.16 MPa under the constant H (60 kA/m). It is observed that the displacement decreases slightly to around 40℃, then increases to 80℃. As the temperature increases, the displacement continuously decreases due to the reduced magnetization. Beyond 40℃, the displacement increases due to the thermal expansion. It means that the reduced magnetization affects more in the displacement change up to 40℃, and the thermal expansion affects more in the displacement change beyond 40℃. Table 1 summarizes the change in the displacement from the room temperature to 80℃with the variation of the prestress. It indicates that the higher the pretstress the larger the displacement change. It is also observed that the current magnitude decrease by 0.34 A~0.37 A. It is a natural phenomenon with the increase of temperature. Thermal expansion coefficient of Terfenol-D is 12 ppm/℃. Thus, the displacement change due to the temperature change can be calculated.

$$\Delta L = 42\text{x}10^3 \text{ x } \Delta T \text{ x } 12\text{x}10^{-6} = 0.50\Delta T$$

If ΔT= 56℃, ΔL becomes 28 μm. It is obvious that the calculated value is much larger than the measured value. It means that the reduced magnetization affects more in the displacement change up to 40℃, and the thermal expansion affects more in the displacement change beyond 40℃. The measured value is combined effect between the increase due to temperature minus the decrease due to the reduced magnetization. It is also observed that the prestress affects the magnetostriction with the temperature. The dispalcement with higher prestress tends to keep the initial value up to 40℃.

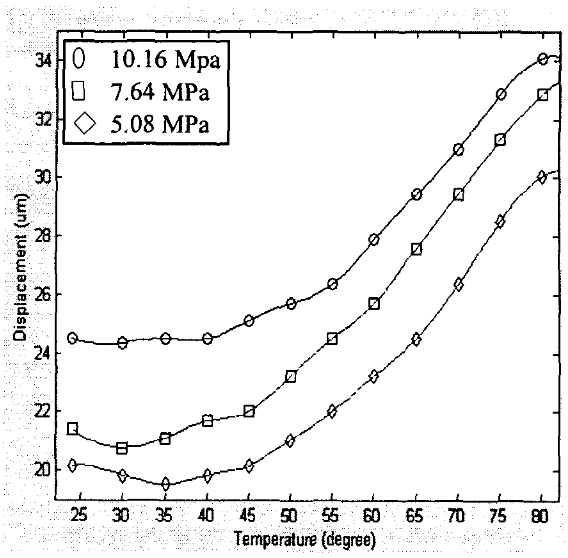

Fig. 4 Temperature vs. displacement with various prestress

Table 1 ΔL and ΔI with the different prestress

Prestress, MPa	ΔL, μm	ΔI, A
5.08	7	0.35
7.64	10	0.37
10.16	13	0.34

5. Conclusion

Investigation is conducted to study the temperature dependence in Terfenol-D. To this end, the temperature is increased to 80℃with various prestress for a given magnetic field. Also, the effect of prestress (1.27 MPa ~ 10.16 MPa) and magnetic field (15 kA/m ~ 60 kA/m) is investigated. The major conclusions of the present study are as follows:

1. The magnetostriction in Terfenol-D is dependent on the temperature. The reduced magnetization and thermal expansion seems to have a crossed effect on the magnetostriction. The prestress plays a role in the performance of Terfenol-D with the temperature change.
2. The prestress influences the performance in Terfenol-D. The optimal prestress, however, exists. It is 7.64 MPa within the scope of this study.
3. The magnetic field affects the magnetostriction in Terfenol-D. The higher magnetic field, the higher magnetostriction. The magnetic field, however, increases the temperature in Terfenol-D.

Reference

1. Butler, J. E., Application Manual for the Design of ETREMA Terfenol-D Magnetostrictive Transducer, Edge Technologies, Inc., Ames, IA, 1988.
2. Etienne du Tremolet de Lacheisserie, Magnetostriction Theory and Applications of Magnetoelasticity, CRC Press, Inc., Boca Raton, 1993.
3. Moffet, M., Clark, A. E., Wun-Fogle, M., Linberg, J., Teter, J., McLaughlin, E., "Characterization of Terfenol-D for Magnetostrictive Transducers", Journal of Acoustic Society of America, 89(3), pp.1448-1455, 1991.
4. Callen, E. and Callen, H. B. Phys. Rev. A139 455, 1965.
5. Greeough, R., Jenner, A., Schulze, M., Wilkinson, A., "The Properties and Applications of Magnetostrictive Rare-earth Compounds", Journal of Magneticsand Magnetic Materials, 101, pp.75-80, 1991.