An initial investigation into the change in magnetomechanical properties of terfenol-d rod due to prestress and temperature

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Összfoglalás

Az előterhelés és a hőmérséklet hatásának vizsgálata a terfenol-d rúdanyag magnetomechanikai tulajdonságaira. Szerzők az intelligens mágneses anyagok (SMM) csoportjába tartozó, erős magnetostrikciót mutató anyagok (GMM) egyikének, a terfenol-d terbium-diszprózium-vas ötvözet magnetostrikciós tulajdonságainak (λ fajlagos hosszváltozás, ΔW A/m csillapodás) változását vizsgálták a σ_0 előterhelés és a T hőmérséklet függvényében. A szakítógépre telepített mérési rendszert a *3. ábra* szemlélteti. A terfenol-d anyagból készített próbatest méretei: Ø 10 x 50 mm. A vizsgálat eredményeit a *4. – 9. ábrák* szemléltetik. Ezek alapján a következőket állapították meg:

1. A σ_0 előterhelés szignifikáns hatással van a magnetostrikciós tulajdonságok változásra és a GMM anyagban elnyelt energia mennyiségére. A magnetostriktív karakterisztika széles tartományban lineáris.
2. A magnetostrikció szempontjából az előterhelés optimális tartománya: σ_0 = 10 – 13 MPa. A vizsgált anyagból készülő működtető (pl. *2. ábra*) konstruálásnál a csillapítást is figyelembe véve a σ_0 = 10 MPa az optimális.
3. A 10 < T < 20°C hőmérséklet-tartományban a hőmérséklet hatása elhanyagolható.
4. A vizsgálati módszerrel nyerhető eredmények felhasználhatók a magnetostrikció elvén működő szerkezetek konstruálásához.

Introduction

Magnetostriction is a physical phenomenon that can be described as the deformation of a body in response to a change in its magnetisation (for examined materials due to a change of external magnetic field). From the other papers [1, 2, 3] it is well known that deformation λ depends on such parameters as temperature T, applied external stress σ_0 (prestress), external magnetic field intensity H, mechanical and magnetic load spectrum. In conventional materials, as iron, nickel or cobalt, λ amount is ca. 0,005%. The reciprocal phenomenon consists in a changing of magnetization due to applying a stress to the material. It is known as reverse magnetostriction or Villary effect. This phenomenon is commonly used in magnetostrictive sensors.

In 1965 in Naval Ordnance Lab and Ames Laboratory it was discovered [4], that some rare earth elements and alloys, e.g. Tb (terbium), Dy (dysprosium) and Sm (samarium), exhibit much higher magnetostriction in cryogenic temperatures than nickel – ca. 0,2%. Few years later an alloy of rare earth elements and iron was developed which exhibits giant magnetostriction in room temperature. This group of materials is called Giant Magnetostrictive Materials (GMM). GMM belong to the group of Smart Magnetic Materials (SMM). Nowadays the most widely known is intermetallic alloy $Tb_xDy_{1-x}Fe_y$ where $x = 0{,}27 \div 0{,}30$ and $y = 1{,}92 \div 2{,}00$ [5] – called Terfenol-D. It is manufactured in the form close to uniform crystal or as powders by Bridgman or Czochralski method and as thin films by magnetron sputtering.

GMM allow interchange of mechanical and magnetic energies (*Fig. 1*) and have been used for many years in magnetostrictive transducers. They have been used due to simple construction, e.g. in magnetostrictive ultrasonic generators generating low frequency ultrasonic waves ($2 \cdot 10^5$ Hz) or in magnetostrictive sensors sensing mechanical ultrasonic waves [6]. These transducers based on conventional materials, for example ferromagnetic rod of ferrites or nickel. The discovery of giant magnetostrictive phenomenon allowed for construction new generation of magnetostrictive transducer, with much better parameters. It significantly increased the area of their possible application.

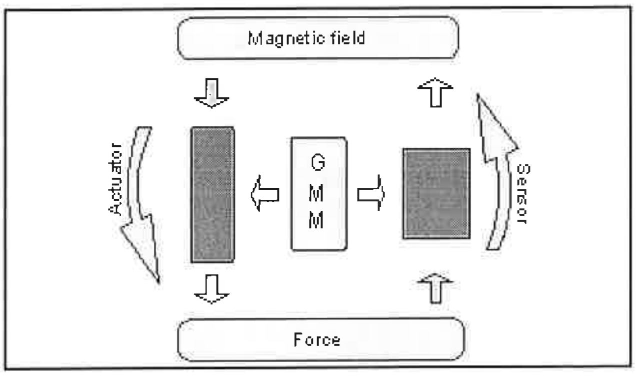

Fig. 1 A schematic diagram of energy transformation in magnetostrictive materials [7]

1. ábra. A magnetostriktív anyagokban végbemenő energiaátalakulás vázlata [7]

The magnetomechanical phenomenon of the magnetostrictive materials can be described by the linear equations given below:

$$\varepsilon = \varepsilon(\sigma, H), \tag{1}$$

$$B = B(\sigma, H), \tag{2}$$

with mechanical strain ε, mechanical stress σ, magnetic field strength H, magnetic flux density B within the magnetostrictive material.

The authors applied an advanced giant magnetostrictive material (GMM) [7, 8] to a magnetostrictive actuator construction (*Fig. 2*). Important role in construction of actuator play applied stress (prestress)

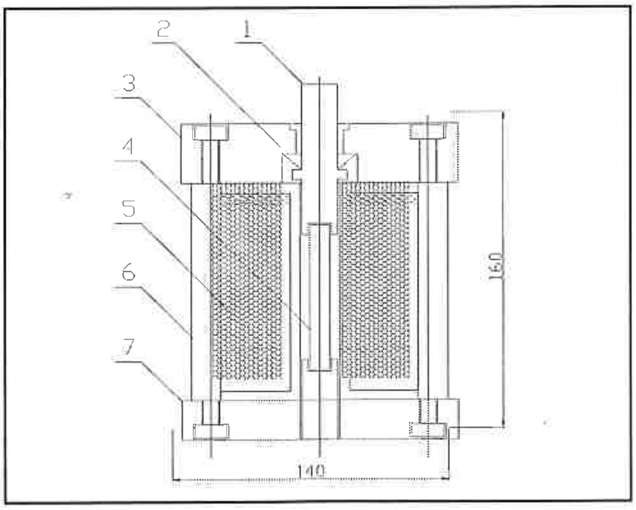

Fig. 2 A schematic diagram of the magnetostrictive actuator; 1 – drive rod, 2 – spring, 3 – upper cover, 4 – magnetostrictive material, 5 – coil, 6 –housing rods, 7 – bottom cover

2. ábra. A magnetoinduktív készülék vázlata; 1 – a mozgató rúd, 2 – rugó, 3 – felső fedél, 4 – a magnetostriktív anyag, 5 – tekercs, 6 – a burkolat rudazata, 7 – alsó fedél

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and magnetic field (bias magnets). According to theory [9, 10] the influence of prestress σ_0 is justified – associated with crystal lattice deformation what causes a change in a direction of magnetization vector and magnetic anisotropy. The device enables a smooth change of prestress s_0 and bias magnetic field. Fundamental task was to find an appropriate prestress value for the specific GMM – optimum for such reasons as a linearity of H-λ curves and efficiency of magnetomechanical coupling.

Experimental investigation

Description of investigated object and examination proposal

GMM rods [7, 8] the size of ϕ10 mm x 50 mm were examined. The tests were aimed at measuring magnetostriction λ along the rod-axis due to change magnetic field intensity H, for different prestress value σ_0 (constant temperature T and quasistatic field changing). Additionally an influence of temperature was planned to measure.

Measurement set-up

The set-up, shown in *figure 3*, enabled a control of σ_0, H, T and a measurement of the end of the GMM rod displacement Δl, while the other end was fixed. λ was calculated dividing Δl by the length of the rod l.

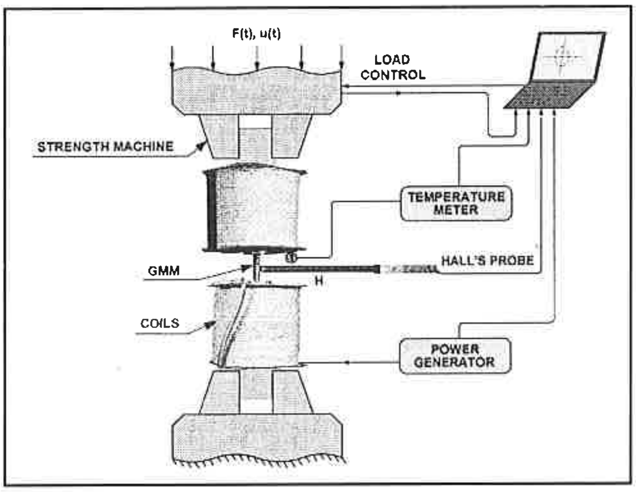

Fig. 3 A schematic diagram of the measurement set-up [11]
3. ábra. A mérési rendszer vázlata

A strength test machine realized the control of an applied prestress σ_0 in the form of force loads. The machine enabled Δl measurements too. The external magnetic filed was generated by the system of two coils [7, 8] in the range of ±130 kA/m. The magnetic field intensity measurement was realized by Hall sensor. The temperature was control by a cooling system. The data was collected by PC workstation equipped with a 16-bit measuring card.

The measurements were performed in two steps:

I – measurement of magnetostriction λ for different prestresses σ_0 = {1; 4; 10; 13} MPa and temperatures T = {10; 15; 20} ^{0}C;

II – for σ_0 = {1; 4; 7; 10; 13; 16; 19; 22; 25; 28; 31; 34; 37; 40} MPa with T = 20^{0}C.

Results and discussion

The data was processed with use of HPVee 5.0 software. In *figure 4* is shown the chosen results of H-λ curves for the prestress σ_0 = {4; 10; 13; 19} MPa at T = 20^{0}C.

In *figure 5* is shown influence of temperature on magnetostriction for temperatures 10, 15, 20 ^{0}C and prestress value σ_0 = 10 MPa. The presented results and the others for σ_0 = {1; 4; 13} MPa allow to say that the influence of temperature in few degrees range can be neglected.

In *figure 6* is shown magnetic field intensity H vs. the magnetostriction λ for different prestress values σ_0 = {1; 4; 10; 16; 19; 25; 40} MPa at T = 20^{0}C. Differences between λ-maximum and hysteresis losses in H-λ origin are evident. These results are shown in *figure 7*. λ maximum changed from $3 \cdot 10^{-4}$ (at H = 20 kA/m) to $1{,}2 \cdot 10^{-3}$ (at H = 120 kA/m). The curvilinear character of λ(H) signals saturated (reached maximum) for prestress range $\sigma_0 = 5 \div 13$ MPa.

Following, the influence of prestress σ_0 on damping value was ana-

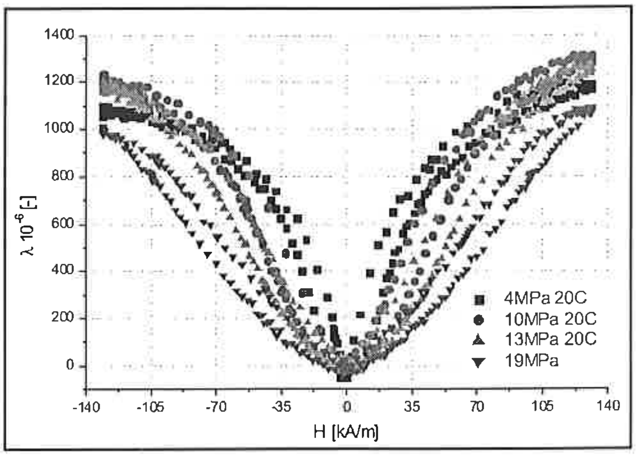

Fig. 4 Influence of prestress on magnetostriction [12]
4. ábra. A σ_0 előterhelés hatása a λ magnetostrikció – H térerő függvény menetére T = 20 °C-on

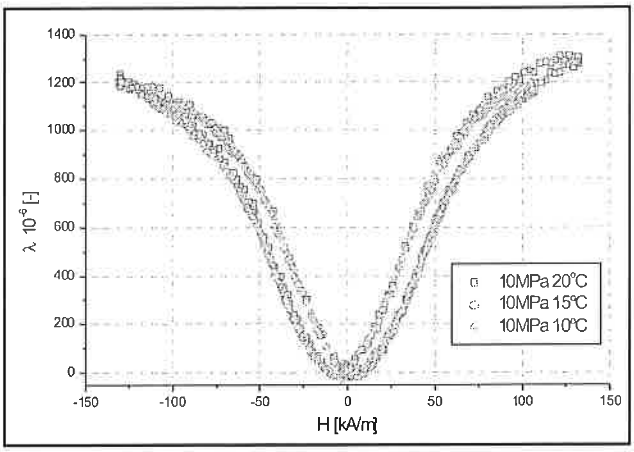

Fig. 5 Influence of temperature on magnetostriction (for σ_0 = 10 MPa)
5. ábra. A T hőmérséklet hatása a λ magnetostrikció – H térerő függvény menetére, σ_0 = 10 MPa

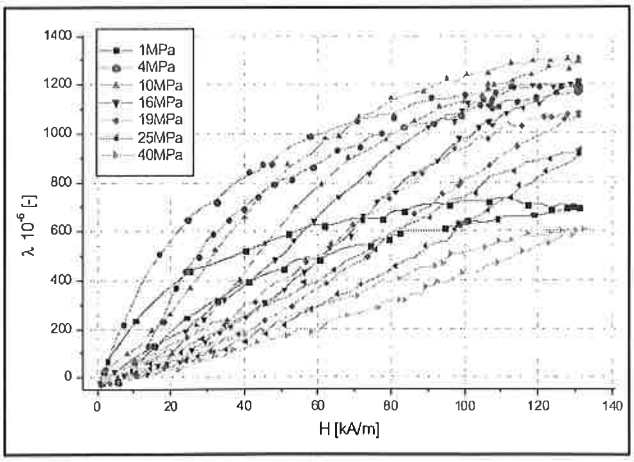

Fig. 6 Influence of prestress on magnetostriction (T = 20°C) [12]
6. ábra. A σ_0 előterhelés hatása a λ(H) függvény menetére, (T = 20°C) [12]

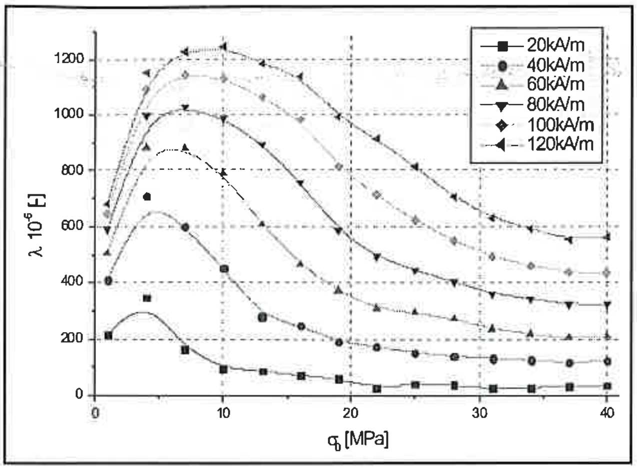

Fig. 7 Magnetostriction vs. prestress at different magnetic field intensity [12]
7. ábra. A H térerő hatása a $\lambda(\sigma_0)$ függvény menetére [12]

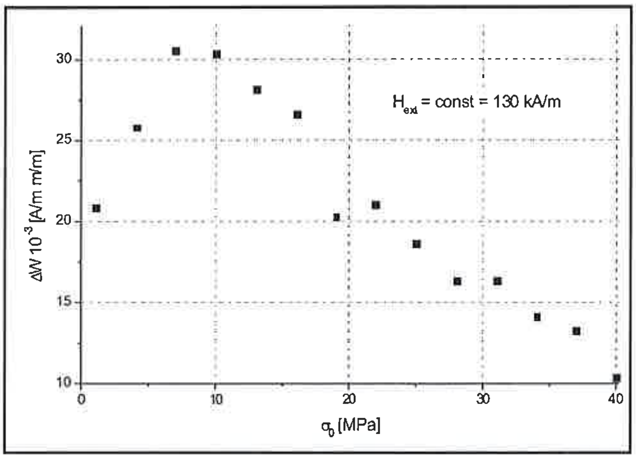

Fig. 8 Magnetomechanical damping vs. prestress (H = 130 kA/m)
8. ábra. A magnetomechanikai csillapítás – előterhelés függvény (H = 130 kA/m)

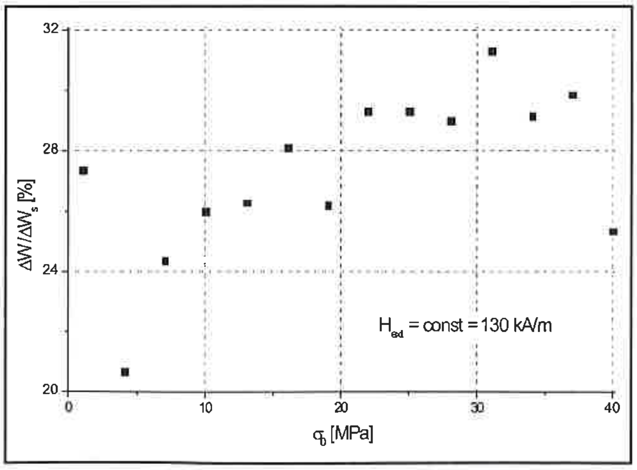

Fig. 9 Magnetomechanical damping vs. prestress (H = 130 kA/m)
9. ábra. A magnetomechanikai csillapítás – előterhelés függvény (H = 130 kA/m)

lysed and is shown in *figure 8*. The damping quantity ΔW was defined as the hysteresis loops area in H-λ origin (only for positive values of H). The mentioned damping dimension is [A/m · m/m]. The presented results show the case for H = 130 kA/m. The damping value ΔW increases as long as σ_0 = 10 MPa and next decreases nearly linearly until ΔW = 10 A/m m/m.

A setting-up ΔW values divided by whole magnetomechanical coupling energy ΔW_s (the area under magnetostrictive curves in H–λ origin) is significant (*Fig. 9*). It was noticed that this value is relatively small (25 ÷ 26%), it means the efficiency of magnetomechanical coupling is quite high, for prestress range $\sigma_0 \approx 10 \div 13$ MPa. Similar results were presented in [1].

Conclusions

1. The investigations showed the significant influence of prestress σ_0 on the shape of magnetostrictive curves and quantity of dissipated energy in GMM. The wide range of linear magnetostrictive characteristics was presented.
2. The tests enabled to find the optimum range of prestress, both for characteristic shape linearity and maximum magnetostriction, as $\sigma_0 = 10 \div 13$ MPa. Finally, taking into account the damping values, for a magnetostrictive actuator application the value σ_0 = 10 MPa was proposed.
3. It was shown the change of temperature in a range of few degrees at room temperature for tested material has not significant influence on magnetostriction.
4. The achieved results make building a control system for the constructed actuator possible.

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