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The Magnetoelastic Properties of Co-Based Amorphous Alloy Under Torque Operation

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The paper presents the results of the investigation of the magnetoelastic properties of selected Co-based amorphous alloy subjected to the shear stress resulting from applied torque. The toroidal core, wound from an amorphous ribbon of the investigated material, is subjected to torque operation generated by the mechanical equipment. Magnetoelastic characteristics obtained for varying magnetizing field amplitude indicate that for high magnetizing fields, the magnetoelastic torque sensitivity is comparable with that of as-quenched Fe-based amorphous alloys and is relatively low. However, for lower fields, the sensitivity reaches significant values, which creates the possibility of utilization of the investigated Co-based alloy in torque sensing applications.

topics: magnetoelastic effect, torque sensing, Co-based amorphous alloy, magnetoelastic sensitivity

1. Introduction

Torque measurement is crucial in many aspects of modern mechanical engineering, such as rotational movement transmission systems or evaluation of structural elements exposed to torsion. Among many solutions known in this field, magnetoelastic sensors are particularly interesting. Their operation is based on the magnetoelastic effect, which involves a change in the magnetic state of ferromagnetic or ferrimagnetic material under the influence of shear stress resulting from applied torque.

One of the known solutions is the utilization of a toroidal magnetic core twisted along its axis [1–3]. In such construction, the magnetic core is both a measurement transducer and torque transmitting element at the same time, which simplifies the construction of the sensor. This eliminates the necessity of any rigid connections between magnetic and non-magnetic elements, which may introduce undesired initial stress. The toroidal core provides a closed magnetic circuit, so the demagnetization field does not affect the sensitivity of the sensor and allows for obtaining a uniform distribution of the shear stress along the entire magnetic circuit. So far, mostly Fe- or Fe–Ni-based amorphous and nanocrystalline alloys have been taken into account as materials for this type of torque sensor. Due to the high saturation magnetostriction, they exhibit significant stress sensitivity, however, it is obtainable only after additional thermal processing of the material [1, 4, 5] due to the high internal stress resulting from the rapid quenching manufacturing process. Nevertheless, as it has been proven previously, Co-based amorphous alloys, despite vanishing magnetostriction, can also exhibit significant magnetoelastic sensitivity under the influence of axial stress [6]. Therefore, it is an interesting issue to study the magnetic behavior of Co-based amorphous alloys under torque operation with regard to potential sensor application.

The paper deals with the magnetoelastic characteristics of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ soft magnetic amorphous alloy subjected to the shear stress resulting from applied torque. The toroidal core, wound from an amorphous ribbon of the investigated material, is subjected to torque operation generated by the mechanical equipment. The magnetoelastic characteristics were investigated for varying magnetizing field amplitude to determine the influence of this parameter on obtained torque sensitivity.

2. Magnetoelastic effect under torque

The classical magnetoelastic effect (Villari effect) involves a change in the magnetic state of the material, expressed, for example, as a change in magnetic flux density B in set magnetizing field H, under the applied uniaxial stress σ [7]. It can be considered on the basis of the total free energy density of the magnetic material [8, 9]. For amorphous alloy, with no magnetocrystalline anisotropy [10, 11], formed into toroidal core reducing demagnetization energy, the total free energy density w can be expressed simply as the sum of magnetizing field energy density (Zeeman energy density) w_H and magnetoelastic anisotropy energy density w_σ [7], i.e.,

$$w = w_H + w_\sigma = -\mu_0 H M_s \cos(\psi - \varphi) + \frac{3}{2}\lambda_s \sigma \sin^2(\varphi), \quad (1)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is magnetic permeability of free space, M_s is spontaneous magnetization, λ_s is saturation magnetostriction, ψ is the angle between magnetizing field H and magnetic anisotropy axis, and φ is the angle between magnetization M_s and anisotropy axis.

When the toroidal magnetic core is considered, magnetized along its perimeter and twisted along its axis, the introduced shear stress can be decomposed into tensile and compressive stress, creating a single common anisotropy axis at the $\pi/4$ angle against the magnetizing filed H direction [3, 12]. Therefore, (1) takes the form [13]

$$w = -\mu_0\, H\, M_s \cos\left(\frac{\pi}{4} - \varphi\right) - \frac{3}{2}\lambda_s \sigma \cos(2\varphi). \quad (2)$$

Zeeman energy density w_H forces the magnetization M_s vector to direction $\pi/4 - \varphi = 0$ against the anisotropy axis, for which the w_H component reaches its minimum. On the other hand, the magnetoelastic anisotropy w_σ tends to orient the magnetization M_s along the direction $2\varphi = 0$, so the preferred M_s vector orientation is either parallel ($\varphi = 0$) or antiparallel ($\varphi = \pi$) to the anisotropy axis. This indicates that torsion alone cannot magnetize the material, as both directions are equally probable, and total magnetization of the material remains close to 0. However, in the presence of magnetizing field H, the applied torque affects the total magnetization of the material. Therefore, the magnetic state of the twisted core results from the interaction between Zeeman energy density w_H and magnetoelastic anisotropy energy density w_σ. Yet due to the non-parallel directions corresponding to both energy density minima, both energies are competing, and the application of torque always decreases the total magnetization (and magnetic flux density). This behavior differs from the classical case of axial stress, where magnetization can be either increased or decreased, depending on the sign of product $\lambda_s\,\sigma$ [14, 15].

As the magnetic state of the material is defined by the competition between Zeeman energy density w_H and magnetoelastic anisotropy energy density w_σ, their ratio is crucial for the torque the sensitivity of the material. Thus, for the set range of applied torque, it can be expected that reducing the amplitude of magnetizing field H can positively affect the sensitivity of the core. Similar behavior has been observed previously in the case of axial stress applied to ferrite [15] and constructional steel [16]. Therefore, the investigation of the torque on the magnetic state of the Co-based amorphous alloy was performed for the wide range of magnetizing field amplitudes, which, scaled by the coercive field H_c measured in magnetic saturation, was from $0.2H_c$ to $5.0H_c$. Such an approach allowed us to determine the optimal magnetization conditions for torque sensing.

TABLE I

Magnetic properties of investigated $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy measured at magnetizing field of 220 A/m (magnetic saturation).

Parameter	Unit	Value
saturation magn. flux density B_m	mT	737
magnetic remanence B_r	mT	471
coercive field H_c	A/m	3.3
maximum magn. permeability μ_{max}	–	110 000

TABLE II

Geometrical parameters of the investigated toroidal core.

Dimension	Unit	Value
outer diameter D	mm	32.4
inner diameter d	mm	24.0
thickness h	mm	8.0
magnetic flux effective path l_e	mm	88.59
effective cross-sectional area S_e	mm^2	29.84

3. Investigated material

The investigated material was a Co-based amorphous alloy $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ formed into a toroidal magnetic core. The material was investigated in an as-quenched state, with no thermal processing performed. Basic magnetic properties of the material, measured in a saturation field 220 A/m before the experiment, are presented in Table I. Co-based amorphous alloys exhibit relatively low maximum magnetic flux density B_m (below 1 T), however, they are known for high maximum relative magnetic permeability μ_{max}. The coercive field H_c is low, which leads to low power loss in the magnetization cycle. Co-based amorphous alloys with the addition of about 4% Fe exhibit vanquishing magnetostriction (below 0.5 μm/m in the case of the investigated alloy). Yet, due to the high magnetic permeability, their magnetoelastic sensitivity can be significant, as it was previously proven for axial stress in [6].

The investigated alloy was manufactured in the form of a ribbon, 22 μm thick and 8 mm wide. The ribbon was wound into the toroidal core, providing a closed magnetic circuit and uniform distribution of the shear stress along the magnetic flux path. The geometrical dimensions of the core and parameters of the magnetic circuit are presented in Table II.

4. Measurement methodology

The application of torque was performed utilizing the methodology previously described in [1–5] for Fe- and Fe–Ni-based amorphous and nanocrystalline alloys. Epoxy resin molds were made on the base planes of the prepared toroidal core. Radial groves on the outer planes of the molds allowed us to provide coils necessary for magnetic measurements and transmit the applied torque to the core. Two coils were made: a magnetizing coil composed of 5 turns and a sensing coil composed of 50 turns. The device for torque application is discussed in [3]. The applied torque was measured with a ZEPWN CL 22 strain gauge torque sensor with a measurement range of up to 10 Nm. The torque applied to the core was limited to about 4.2 Nm to ensure that the material was working in the elastic region.

Measurements of the magnetic characteristics were performed with the automatic hysteresisgraph system described in [17]. The device was originally developed for the investigation of soft magnetic ferrites, however, its capabilities allow it to be used in measurements of soft amorphous alloys. The investigated core was magnetized with a linearly changing magnetizing field (triangle waveform) of frequency 1 Hz. The amplitude of the magnetizing field was scaled with respect to the value of saturation coercive field H_c provided in Table I. There were 8 measurement points selected, with magnetizing field amplitude values being: $0.2H_c$, $0.5H_c$, $0.8H_c$, $1.0H_c$, $1.5H_c$, $2.0H_c$, $3.0H_c$, and $5.0H_c$. The measurements at these 8 points were repeated for subsequent values of the applied torque. Before each measurement, the material was demagnetized.

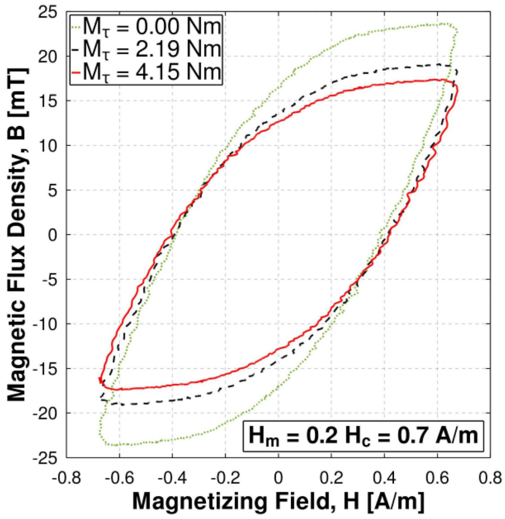

Fig. 1. Influence of applied torque M_τ on hysteresis loop of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy for magnetizing field amplitude of 0.7 A/m.

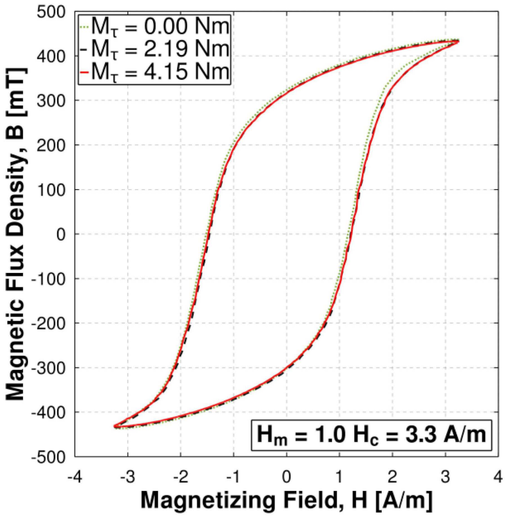

Fig. 2. Influence of applied torque M_τ on hysteresis loop of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy for magnetizing field amplitude of 3.3 A/m.

5. Results and discussion

As a result of performed measurements, magnetoelastic characteristics of the investigated Co-based amorphous alloy were determined under the operation of torque. Figures 1 and 2 present the influence of applied torque on the hysteresis loop of the material for selected values of magnetizing field amplitude H_m of 0.7 A/m ($0.2H_c$) and 3.3 A/m ($1.0H_c$), respectively. The loops are presented for the unloaded sample (0.00 Nm), middle-range torque (2.19 Nm), and maximum torque (4.15 Nm). For the lowest applied magnetizing field (Fig. 1), the application of torque introduces significant changes in the hysteresis loop of the material. Both maximum magnetic flux density B_m and magnetic remanence B_r are decreasing. At the same time, the coercive field H_c remains relatively constant. The observed change in B_m is not linear — the more significant decrease occurs in the first half of the torque range. For the higher magnetizing field amplitude (Fig. 2), the influence of applied torque on the magnetic state of the material is negligible — all three loops are identical. Similar behavior was observed for higher H_m values. For amplitudes between $0.2H_c$ and $1.0H_c$, the influence of torque was observable, but the changes were lower than those presented in Fig. 1.

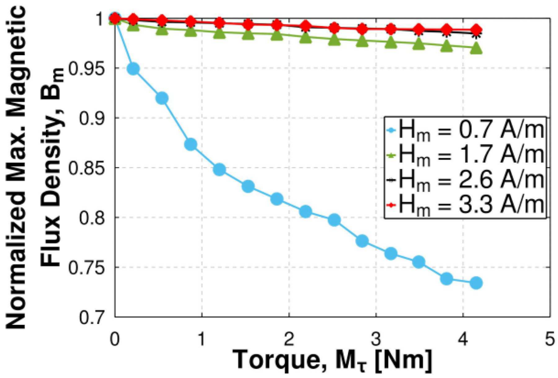

Fig. 3. Magnetoelastic characteristics $B_m(M_\tau)$ of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy for lower amplitudes of magnetizing field.

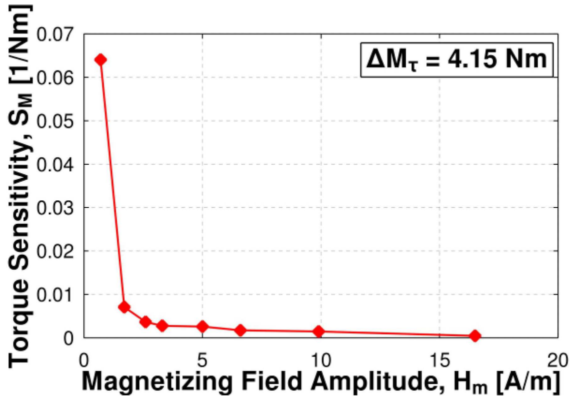

Fig. 5. Dependence of the torque sensitivity of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy on the amplitude of magnetizing field.

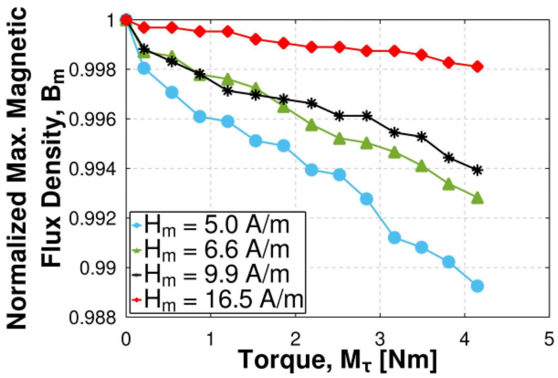

Fig. 4. Magnetoelastic characteristics $B_m(M_\tau)$ of $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy for higher amplitudes of magnetizing field.

TABLE III

Signal change and magnetoelastic torque sensitivity S_m of the investigated $Co_{69}Fe_4Ni_1Mo_2Si_{12}B_{12}$ amorphous alloy for applied torque change ΔM_τ = 4.15 Nm.

H_m [A/m]	ΔB_m [mT]	δB_m [%]	S_M [Nm^{-1}]
0.7 (0.2H_c)	6.3	26.58	0.0641
1.7 (0.5H_c)	8.2	2.94	0.0071
2.6 (0.8H_c)	5.9	1.52	0.0037
3.3 (1.0H_c)	5.0	1.15	0.0028
5.2 (1.5H_c)	5.5	1.07	0.0026
6.5 (2.0H_c)	3.9	0.72	0.0017
9.8 (3.0H_c)	3.6	0.61	0.0015
16.3 (5.0H_c)	1.2	0.19	0.0005

Figures 3 and 4 present the magnetoelastic $B_m(M_\tau)$ characteristics of the investigated material. For better representation, maximum magnetic flux density B_m is normalized with value for unloaded core $B_m(M_\tau = 0)$. It can be seen that the largest change in B_m within the investigated torque range occurs for the lowest magnetizing filed amplitude $H_m = 0.7$ A/m (0.2H_c). For $H_m = 1.7$ A/m (0.5H_c), the influence of torque is still observable, albeit much lower. At a magnetizing field of amplitude close to H_c, the applied torque does not influence B_m significantly. Similar behavior occurs for H_m values above the coercive field, as presented in Fig. 4, where the vertical scale had to be changed to better present the obtained results. Therefore, it seems that for higher magnetizing field amplitudes, the applied torque does not affect the magnetic state of the material significantly.

On the basis of investigated characteristics, the change in maximum magnetic flux density was calculated as

$$\Delta B_m = B_m\,(M_\tau{=}0\,\mathrm{Nm}) - B_m\,(M_\tau{=}4.15\,\mathrm{Nm})\,, \tag{3}$$

and the relative change as

$$\delta B_m = \frac{\Delta B_m}{B_m\,(M_\tau{=}0\ \mathrm{Nm})}. \tag{4}$$

The magnetoelastic torque sensitivity S_M expressed in Nm^{-1} was calculated according to

$$S_M = \frac{\delta B_m}{\Delta M_\tau}, \tag{5}$$

where ΔM_τ is the change in applied torque equal to 4.15 N m. The results of the calculations are presented in Table III. The dependence of calculated sensitivity S_m on the magnetizing field amplitude H_m is also presented in Fig. 5.

On the basis of data presented in Table III, it can be seen that an increase in the magnetizing field amplitude H_m leads to a decrease in both absolute ΔB_m and relative δB_m change in maximum magnetic flux density. This leads to the significant decrease in magnetoelastic torque sensitivity S_M observed in Fig. 5. The reason for such behavior is the competition between Zeeman energy density and magnetoelastic anisotropy energy density, discussed in Sect. 2. Only for the lowest amplitudes of the magnetizing field, the energy provided with the shear stress resulting from applied torque is high enough to significantly influence the magnetic state of the material. For higher fields, Zeeman energy density strongly dominates over magnetoelastic anisotropy, and thus, the change in magnetic flux density is negligible.

Magnetoelastic sensitivity obtained for the lowest magnetizing field amplitude $H_m = 0.7$ A/m is 0.0641 N m^{-1}, and the corresponding relative change δB_m is 26.58%. Such a result is comparable with the values reported for as-quenched Fe-based amorphous alloys (35.3% for $\Delta M_\tau = 6.6$ N m in [4]), although higher than reported for as-quenched Fe–Ni-based alloys (0.36% for $\Delta M_\tau = 4.0$ N m in [1]). However, it has to be noted that the cited values were obtained at higher magnetizing fields, above the material H_c value. At low magnetizing fields, the sensitivity of the considered materials might be significantly higher.

6. Conclusions

The obtained measurement results seem to confirm the theoretical description based on the competition between Zeeman energy density and magnetoelastic anisotropy energy density in shaping the magnetic state of the material subjected to torque. The highest torque sensitivity was achieved for the lowest value of magnetizing field amplitude, where Zeeman energy density is also the lowest.

Only for the lowest magnetizing field amplitude the influence of torque on the magnetic properties of the investigated Co-based amorphous alloy was significant. The sensitivity obtained at these conditions is comparable with that of as-quenched Fe-based amorphous alloys measured in higher fields. There are no reports on the behavior of Fe-based alloys in low magnetizing fields, therefore, a direct comparison of both types of alloys in corresponding fields is impossible.

In a more magnetomechanically complicated case of shear stress resulting from torque (anisotropy axis oriented at $\pi/4$ against the magnetizing field), the assumption of favorable influence of high magnetic permeability on the magnetoelastic is not confirmed. Obtaining significant torque sensitivity requires a drastic reduction of the magnetizing field. In such fields, the application of the investigated material in torque sensing seems to be possible. However, it has to be taken into account that in low magnetizing fields, the magnetic flux density is also low, and the measurement signal is susceptible to interference.

References

[1] J. Salach, A. Bieńkowski, R. Szewczyk, *J. Magn. Magn. Mater.* **316**, 607 (2007).

[2] J. Salach, in: *Recent Advances in Mechatronics*, Eds. R. Jabłoński, M. Turkowski, R. Szewczyk, Springer, Berlin 2007, p. 606.

[3] J. Salach, A. Bieńkowski, R. Szewczyk, in: *Mechatronics*, Eds. R. Jabłoński, T. Březina, Springer, Berlin 2011, p. 131.

[4] J. Salach, A. Bieńkowski, R. Szewczyk, in: *Sensors 2004*, IEEE, Vienna 2004, p. 505.

[5] J. Salach, A. Bieńkowski, R. Szewczyk, *Acta Phys. Pol. A* **113**, 115 (2008).

[6] A. Bieńkowski, R. Szewczyk, *Sens. Actuators A Phys.* **113**, 270 (2004).

[7] B.D. Cullity, C.D. Graham, *Introduction to Magnetic Materials*, 2nd ed., John Wiley & Sons, Hoboken (NJ) 2009.

[8] S. Lesz, R. Szewczyk, D. Szewiaczek, A. Bieńkowski, *J. Mater. Process. Technol.* **157–158**, 743 (2004).

[9] R. Andreescu, B. Spellman, E.P. Furlani, *J. Magn. Magn. Mater.* **320**, 1827 (2008).

[10] F. Luborsky, J. Becker, R. McCary, *IEEE Tran. Magn.* **11**, 1644 (1975).

[11] R.C. O'Handley, *Modern Magnetic Materials: Principles and Applications*, 1st ed., John Wiley & Sons, New York 1999.

[12] A. Hernando, V. Madurga, M. Vázquez, *J. Phys. D Appl. Phys.* **11**, 2401 (1978).

[13] I.J. Garshelis, W.S. Fiegel, *J. Appl. Phys.* **57**, 3502 (1985).

[14] P. Švec, R. Szewczyk, J. Salach, D. Jackiewicz, P. Švec, A. Bieńkowski, J. Hoško, *J. Elect. Eng.* **65**, 259 (2014).

[15] M. Kachniarz, J. Salach, *Measurement* **168**, 108301 (2021).

[16] D. Jackiewicz, M. Kachniarz, A. Bieńkowski, R. Szewczyk, in: *Recent Advances in Systems, Control and Information Technology*, Eds. R. Szewczyk, M. Kaliczyńska, Springer, Berlin 2016, p. 689.

[17] T. Charubin, P. Nowak, M. Nowicki, R. Szewczyk, M. Urbański, *Acta Phys. Pol. A* **133**, 1049 (2018).