*Proceedings of the 21st International Conference on Global Research and Education (Inter-Academia 2024)*

# Comparison of the Influence of Torsional Stresses on the Magnetic Properties of Amorphous and Ceramic Materials — Ferrites

J. Salach*

*Faculty of Mechatronics, Institute of Metrology and Biomedical Engineering, Warsaw University of Technology, św. A. Boboli 8, 02-525 Warsaw, Poland*

Doi: 10.12693/APhysPolA.146.615 *e-mail: jacek.salach@pw.edu.pl

The paper presents the results of the comparison of magnetoelastic properties of selected amorphous and ceramic materials under the influence of shear stress resulting from the applied torque. The objects of the research were toroidal cores made of magnetically soft materials, such as ferrite and amorphous iron-based alloy. The ferrite core was made by pressing and sintering powdered material. The amorphous core was wound from amorphous material in the form of a ribbon. The comparison shows similarities and differences between both materials.

topics: magnetoelastic effect, torque sensing, magnetoelastic sensitivity

## 1. Introduction

The influence of stress, both from compressive forces and from torsional moments, on the magnetic properties of magnetic materials is significant. This is important not only because of the possibility of using these materials as sensors [1], but also because of the stabilizing magnetic properties of transformer cores and other electronic components containing cores made of soft magnetic materials [2]. Incorrect assembly can lead to a change in the parameters of a given element, and consequently to destabilization of the entire system. For this reason, these studies are important for the entire electronics industry.

The influence of compressive and tensile stress on magnetic materials with a crystalline structure, e.g., ceramic ferrites and amorphous structure [3, 4], is already well known and documented in many publications [5]. However, the influence of stress from an applied torque on such materials is not sufficiently known. There are a few publications documenting such experiments [6]. The effect of torque on the investigated element combines compressive and tensile stress. Therefore, the analysis of the impact of the acting stress on the magnetic properties is more complicated than in the case of the classical Villari effect.

## 2. Measurement methodology

In order to select the simplest possible system for analysis, where compressive and tensile stresses with a strictly defined distribution will occur, toroidal samples were selected. For the amorphous material, this is a thin ring wound from an amorphous ribbon. The dimensions of the ring are

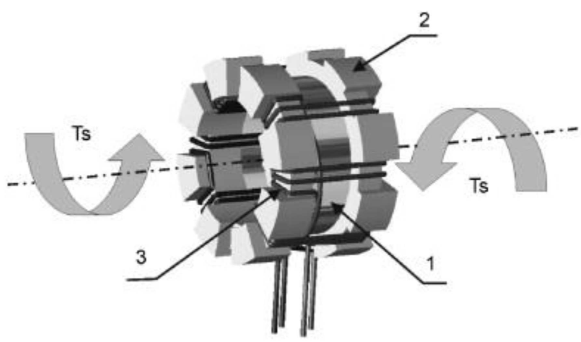


Fig. 1. Mechanical system for applying the uniform torsional, axial shearing stress to the ring-shaped core: 1 — ring-shaped core under investigation, 2 — magnetizing and sensing windings, 3 — nonmagnetic backings with grooves.

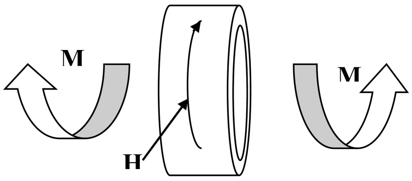


Fig. 2. Research methodology; $M_s$ — torque, $H$ — magnetic field.

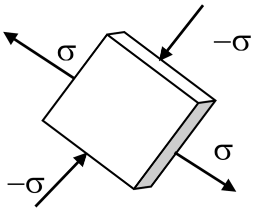


Fig. 3. Stresses distribution on the elementary fragment of material under the influence of torque.

an inner diameter of 25 mm, an outer diameter of 30 mmm and a height of 10 mm. For the ferrite material, there is a ring with the dimensions: inner diameter of 16 mm, outer diameter of 26 mm, and height of 15 mm.

The research methodology was as follows. The mechanical system is shown in Fig. 1. The torque $M_s$ is applied to the ring along the axis, generating defined stresses.

The toroidal cores were also chosen for reasons related to the measurement of magnetic properties, as they provide a closed magnetic path for the magnetizing field strength $H$ generated in the core. A closed magnetic circuit allows the demagnetization field in the core to be minimized, which facilitates the analysis of measurement results. The methodology is presented in Fig. 2.

The shear stress introduced by the applied torque can be considered as a simultaneous action of compressive $-\sigma$ and tensile stress $\sigma$ on an elementary [7] fragment of the investigated core presented in Fig. 3.

The average stress can be determined from

$$\sigma = \frac{M_s}{2\pi r_{av}\delta}, \tag{1}$$

where $\sigma$ and $-\sigma$ are tensile and compressive stress [MPa], respectively; $\delta$ — ring wall thickness [m], $r_{av}$ — average ring radius.

## 3. Results of investigation

The study focuses on comparing the results of the effect of stress from torque acting on rings of amorphous iron-based alloy and nickel–zinc ferrite. The amorphous alloy was investigated in two states,

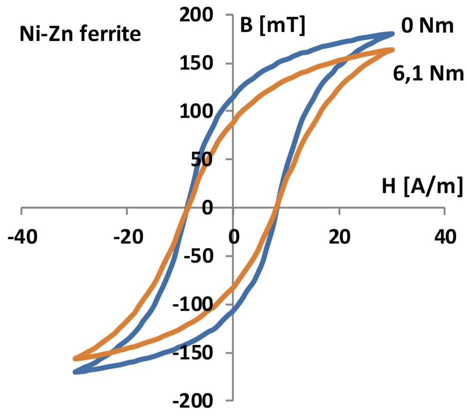


Fig. 4. Characteristic $B(H)$ under the influence of torque on a ring-shaped core made of Ni–Zn ferrite.

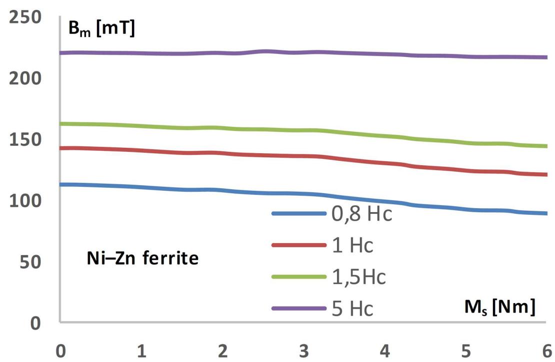


Fig. 5. Magnetoelastic characteristics $B_m(M_s)$ for a ring core made of Ni–Zn ferrite.

i.e., as-cast and after thermal relaxation at 365°C for 1 h. All samples were ring-shaped and the torque was applied along their axis.

The following methodology was used to compare the results. The tested cores were magnetized with a magnetizing field strength that was a multiple of the coercive field $H_c$ for each material. The comparison was carried out in the same range of stress.

The change in the shape of the hysteresis loop $B(H)$ for the Ni–Zn ferrite under the influence of torque is presented in Fig. 4.

The influence of torque on the maximum magnetic flux density $B_m$ for a core made of nickel–zinc ferrite is shown in Fig. 5. The results are for the values of $0.8H_c$, $1H_c$, $1.5H_c$ and $5H_c$, which correspond to the magnetizing field values of 16, 20, 30, and 100 A/m, respectively.

The change in the shape of the hysteresis loop $B(H)$ for an iron-based amorphous alloy in an as-cast state under the influence of torque is shown in Fig. 6.

The influence of torque on the maximum magnetic flux density $B_m$ for a core made of an iron-based amorphous alloy in an as-cast state is shown in Fig. 7. The results are for the values

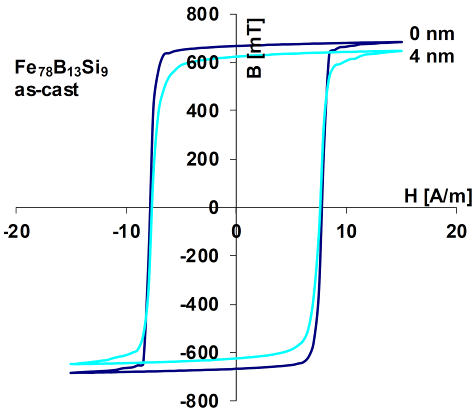


Fig. 6. Characteristic of $B(H)$ under the influence of torque on a ring-shaped core made of iron-based amorphous alloy in an as-cast state.

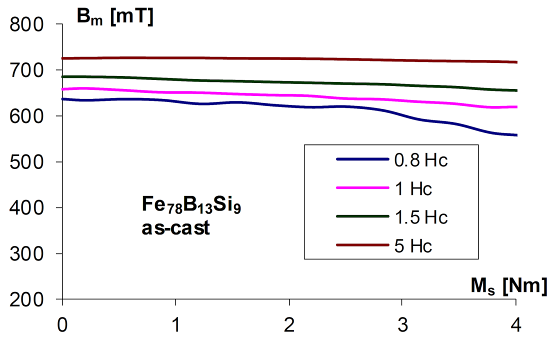


Fig. 7. Magnetoelastic characteristics $B_m(M_s)$ for a ring core made of iron-based amorphous alloy in an as-cast state.

of $0.8H_c$, $1H_c$, 1.5 $H_c$, and $5H_c$, which correspond to the magnetizing field values of 6.5, 8, 12, and 40 A/m, respectively.

The torque influence on the shape of the hysteresis loop $B(H)$ for an iron-based amorphous alloy after thermal relaxation at 365°C for 1 h is presented in Fig. 8.

The influence of torque on maximum magnetic flux density $B_m$ for a core made of an iron-based amorphous alloy after thermal relaxation at 365°C for one hour is presented in Fig. 9. The results are for the values of $0.8H_c$, $1H_c$, $1.5H_c$ and $5H_c$, which correspond to the magnetizing field values of 3.2, 4, 6, and 20 A/m, respectively.

The obtained results indicate that all tested materials exhibit magnetoelastic sensitivity in the range of acting torsional moments.

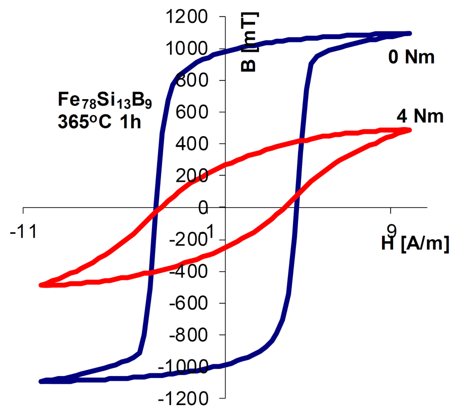


Fig. 8. Characteristic of $B(H)$ under the influence of torque on a ring-shaped core made of iron-based amorphous alloy after thermal relaxation at 365°C for 1 h.

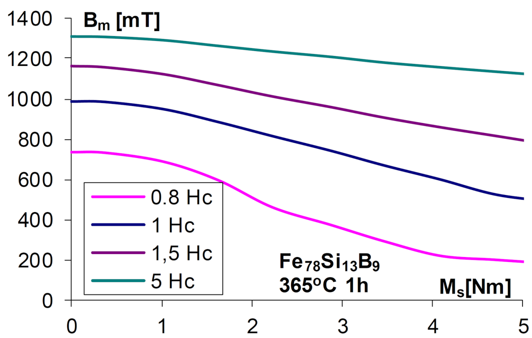


Fig. 9. Magnetoelastic characteristics $B_m(M_s)$ for a ring core made of iron-based amorphous alloy after thermal relaxation at 365°C for 1 h.

## 4. Discussion

The study of the effect of torque on the magnetic properties of selected soft magnetic materials shows that their magnetoelastic sensitivity is diversified. This sensitivity depends on the state of the material, whether it is in the raw state — as-cast or after thermal relaxation, as well as on the material itself, whether it is a ceramic ferrite material or an amorphous alloy. It can also be seen that soft magnetic materials, previously not considered in torque sensing applications like ferrites, also exhibit significant magnetoelastic sensitivity under the operation of torque.

For cores made of amorphous alloy, in the as-cast state and after thermal relaxation, the values of the applied torque ranged from 0 to 4 Nm. However, for the core made of Ni–Zn ferrite, the applied torque value was within the range of 0 to 6 Nm. This difference results from the fact that the ferrite core had different dimensions, and the same torque generated different stresses within the material. Therefore, the ranges of the applied torque were selected in a way that allowed for the obtaining of similar changes in generated shear stresses for each investigated core. The magnetoelastic torque sensitivities of the materials investigated in such conditions are compared in Table I.

TABLE I

Magnetoelastic torque sensitivity of investigated soft magnetic materials.

| Core material | The value of the maximum magnetizing field with respect to coercive field $H_c$ | | | |
|---|---|---|---|---|
| | $0.8H_c$ | $1H_c$ | $1.5H_c$ | $5H_c$ |
| Ni–Zn ferrite | 27% | 18% | 13% | 1.5% |
| $Fe_{78}B_{13}Si_9$ as-cast | 11% | 5% | 4% | 0.9% |
| $Fe_{78}Si_{13}B_9$ at 365°C for 1 h | 72% | 47% | 30% | 13% |

The analysis shows that all materials exhibit significantly higher relative sensitivity for low magnetizing field strength, while the sensitivity decreases with increasing magnetizing field strength values. The highest magnetoelastic sensitivity is shown by the amorphous material after thermal relaxation, $Fe_{78}Si_{13}B_9$ at 365°C for 1 h. This sensitivity changes by 72% when the core is magnetized with a magnetizing field strength of $0.8H_c$. On the other hand, the lowest sensitivity is shown by the same material in the raw state, $Fe_{78}B_{13}Si_9$ as-cast, which is 11% for an analogous magnetizing field strength value at similar stress. A core made of ferrite material based on nickel and zinc showed a sensitivity of 27% for comparable stresses.

## 5. Conclusions

The results presented in the paper indicate that soft magnetic materials exhibit significant magnetoelastic sensitivity under shear stress resulting from the applied torque. For the first time, the torque sensing application involves the Ni–Zn ferrite. The material exhibits relatively high sensitivity, significantly exceeding the iron-based amorphous alloy in an as-quenched state. However, thermal relaxation favors amorphous alloy over ferrite, as its sensitivity drastically increases as the effect of relieving internal stress. On the other hand, additional thermal processing may increase the cost of the potential torque sensor, so ferrite exhibiting significant sensitivity without any additional processing seems to be a promising material as well.

The relation between all the sensitivity of all three cores is consistent in all considered magnetizing fields. The sensitivity of ferrites always exceeds that of as-cast amorphous alloy, yet it is lower than the sensitivity of amorphous material after thermal relaxation. However, it should be noted that for each material obtained, the sensitivity was highest in the lowest value of the magnetizing field. This allows us to assume that further lowering of the magnetizing field could positively affect the magnetoelastic sensitivity of soft magnetic materials under torque operation. Therefore, the magnetoelastic properties of soft magnetic materials in low magnetizing fields should be the subject of further research.

## References


[1] A. Bienkowski, R. Szewczyk, J. Salach, *Acta Phys. Pol. A* **118**, 1008 (2010).

[2] A. Wozniak, M. Kretkowski, R. Jablonski, *Metrol. Meas. Syst.* **14**, 351 (2007).

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

[4] A. Bienkowski, R. Szewczyk, J. Salach, R. Kolano, *Solid State Phenom.* **154**, 23 (2009).

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

[6] J. Salach, in: *Advanced Mechatronics Solutions*, 1st ed., Eds. R. Jabłoński, T. Březina, Springer, Cham 2016, p. 515.

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