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Analysis and Computer Modeling of Magnetoelastic Characteristics of FeNi-based Amorphous Ring-shaped Core under Uniform Compressive and Tensile Stresses

JACEK SALACH[a], ROMAN SZEWCZYK[b], ADAM BIEŃKOWSKI[a], DOROTA JACKIEWICZ[a]

[a] Institute of Metrology and Biomedical Engineering
Warsaw University of Technology, Warsaw, Poland
{j.salach,a.bienkowski,d.jackiewicz}@mchtr.pw.edu.pl
[b] Industrial Research Institute for Automation and Measurements, Warsaw, Poland
szewczyk@mchtr.pw.edu.pl

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Abstract: Paper presents methodology of generation of the uniform, compressive or tensile stresses in ring-shaped amorphous alloys core. In this study we use the set of special nonmagnetic, cylindrical backings. These backings enabled the core to be wound as well as create the possibility of generation of uniform compressive and tensile stresses. Using presented methodology the magnetoelastic characteristics were experimentally determined for $Fe_{40}Ni_{38}Mo_4B_{18}$ Metglas 2826 MB amorphous alloy. Knowledge about these properties is important for users of inductive components with amorphous alloys cores due to the fact, that changes of flux density due to magnetoelastic effect exceed 40%.

Keywords: magnetoelastic effect, amorphous alloys

1. Introduction

Magnetoelastic Villari effect is connected with the changes of flux density B achieved in the magnetic core, for given magnetizing field Hm, when it is subjected to mechanical stresses σ generated by external forces [1]. Magnetoelastic properties of the magnetic materials may be described by $B(H)_\sigma$ characteristics, which represent the influence of both tensile and compressive stresses on magnetic hysteresis loops of the material. This effect is described theoretically, however it seems not to be verified experimentally for compressive and tensile stresses in ring-shaped samples made of soft amorphous alloys. Lack of this knowledge is especially important due to the fact, that magnetoelastic effect has significant technical aspects connected both with development of magnetoelastic stress and force sensors, as well as changes of properties of cores of inductive components subjected to accidental mechanical stresses.

Magnetoelastic force sensors exhibit about 100 times higher stress sensitivity that commonly used strain-gauges [2]. Moreover such sensors have very high stress strength together with rust resistance [3]. In addition magnetoelastic sensing elements may be flat, what is especially important where space for sensor montage is limited. On the other hand magnetoelastic sensors have higher uncertainty of indications than strain-gauges. However, they are successfully used in specialized applications, where extremely high robustness is required. One of such application is monitoring the combustion process in large diesel engines e.g. in diesel locomotives [4].

Inductive cores of electronic components often require high permeability. High initial permeability is caused by small magnetic and magnetocrystalline anisotropy [5]. As a result participation of magnetoelastic energy in total free energy of high-permeability inductive core is dominant. As a result such cores are very sensitive to stresses caused by external forces [6]. Such forces can be applied to the material in assembly process of inductive component with amorphous core, or by thermal expansion of the material during the operation of the component [7]. These stresses may be particularly large in case of miniature components, where even small forces may cause significant stresses. As a result the magnetoelastic effect may have significant impact on the efficiency and other functional properties of the inductive component and cause malfunction or even damage of electronic device – such as switching mode power supply [8].

For indicated above reasons, the magnetoelastic characteristics should be carefully studied from the point of view of practical applications. Presented paper tries to fill the gap in the state of the art, connected with method of testing of magnetoelastic characteristics in full range of compressive and tensile stresses. Moreover it gives guidelines enabling simple prediction of soft magnetic material's response on stresses from external forces. As a result in may be useful for both producers and users of soft magnetic materials.

2. Method of investigation

The main barrier in testing of magnetoelastic properties of soft magnetic materials (such as amorphous alloys) is lack of methodology enabling application of both compressive and tensile stresses in required way. Such methodology has to:

- enable application of uniform compressive and tensile stresses to the core. When distribution of stresses is non-uniform, such as in the case of ring-shaped magnetoelastic sensors developed by Mohri [9], results of investigation are difficult for interpretation from physical point of view. Moreover range of possible stresses is limited to the stress strength of the most stressed area of the core,
- enable use of cores with closed magnetic circuit, such as ring-shaped cores. When core's magnetic circuit is open, demagnetization occurs. In such a case interpretation of results of investigation requires analysis of demagnetization, which is non-linear and difficult to determine with sufficient accuracy [10], especially in the case of high permeability materials,
- use shapes of magnetic materials cores used in industrial purposes, to reduce its costs.

The idea of the method of applying both compressive and tensile stresses to the ring-shaped core made of soft magnetic material is presented in figure 1. In this method compressive or tensile force is applied perpendicularly to the base of ring-shaped core. As a result uniform distribution of compressive or tensile stresses is achieved in the tested core. However, it should be noted, that direction of stresses is perpendicular to the direction of magnetizing field, what should be considered in interpretation of experimental results.

Technical solution of mechanical system enabling application of both compressive and tensile stresses to the ring-shaped core is presented in figure 2. In the case of tensile stresses [11], special nonmagnetic backings are glued to the investigated ring-shaped core (1) as it is presented in figure 2a. Due to holes in these backings, core can be wound by magnetizing and sensing winding. Moreover, nonmagnetic shaft may be mounted to these backings. Then tensile force is generated by (5) and set of the springs (4) enable force stabilization. Value of tensile force is measured by reference, strain-gauge force transducer (2), together with electronic signal processing unit (3).

In the case of compressive stresses, method which was presented previously [12, 13], uses the special set of nonmagnetic, cylindrical backings was used, in order to obtain the uniform compressive stresses in the tested ring-shaped core and enable it to be wound, as it is presented in figure 2b. Between the nonmagnetic backings (2) and the ring core (3), a special elastic spacer is placed, to guarantee the uniform distribution of the stresses in the tested core (3). Magnetizing and measuring windings are placed in special grooved races (2a) in backings. Compressive force (F) is applied to device by hydraulic press, via the base backings (1). The ball joint is used to avoid bending of the sample, which could lead to a non-uniform stress distribution in the sample.

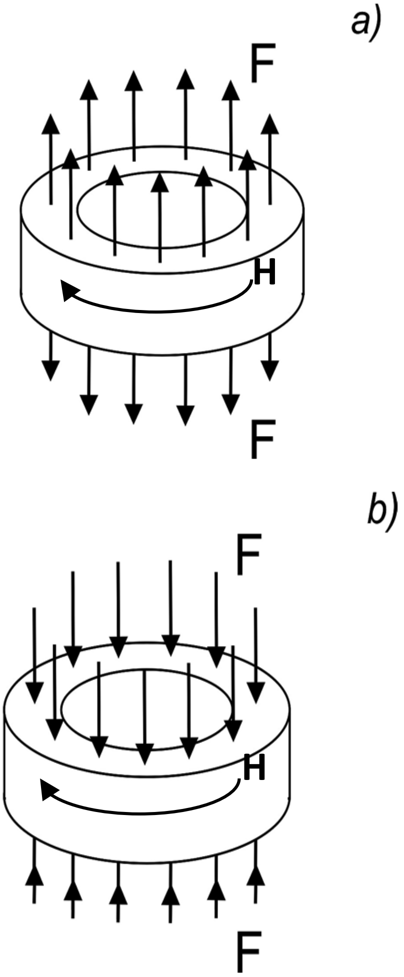

Fig. 1. Idea of the method of application uniform stresses from external force F to ring-shaped core where H is the magnetizing field: a) tensile stresses, b) compressive stresses

Force F applied to the core, generating both compressive and tensile stresses was measured using strain gauge-based sensor. As a result, taking into account force F measurements uncertainty as well as uncertainty of calculation of sample cross section S, uncertainty of stresses σ measurements in the investigated core was estimated at the level of 3%. Taking into account accuracy of integration module in digitally controlled flux meter, the uncertainty of flux density B measurements in ring-shaped sample was assessed at the level of 5%.

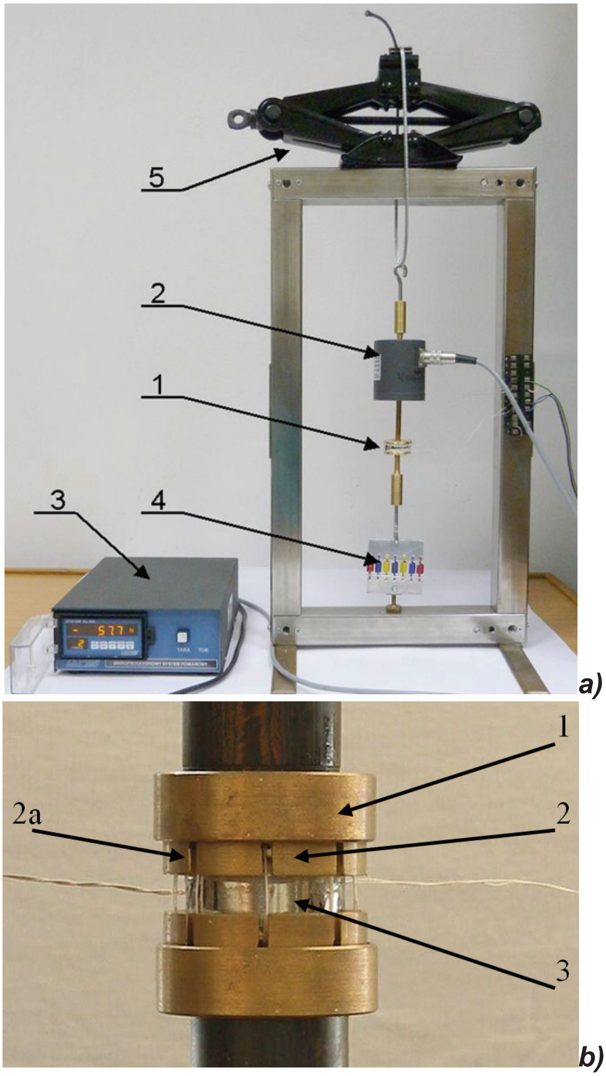

Fig. 2. Mechanical system for application of the uniform stresses to ring-shaped core [11, 12]: a) tensile stresses: 1 – core under investigation, 2 – reference, strain-gauge force transducer, 3 – electronic signal processing unit, 4 – set of the springs, 5 – tensile forces generator, b) compressive stresses: 1 – base backings, 2 – cylindrical, non-magnetic backings, 2a – grooves for the windings, 3 – core under investigation

For investigation focused on both compressive and tensile stresses ring-shaped sample made of $Fe_{40}Ni_{38}Mo_4B_{18}$ Metglas 2826 MB amorphous alloy was used. Core was annealed in temperature 360°C for one hour. The outside diameter of the core was 32 mm, inside diameter was 25 mm and core's height was 8 mm. Magnetic hysteresis loops were measured by digitally controlled hysteresis graph HB-PL3.0. Magnetizing field frequency was 0.5 Hz what enables quasi-static measurements.

3. Results of investigation

The influence of both tensile and compressive stresses σ on the shape of hysteresis $B(H)$ loop of $Fe_{40}Ni_{38}Mo_4B_{18}$ Metglas 2826 MB amorphous alloy is presented in figure 3.

Accordingly to common convention, the tensile stresses are marked as positive, whereas compressive stresses are marked as negative. It was observed for amplitude of magnetizing field H_m equal 5 A/m (figure 3a), that for compressive stresses σ up to 10 MPa value of maximal flux density B in the core increases from 264 mT to 297 mT. Moreover, for tensile stresses σ up to 3 MPa value of maximal flux density B in the core decreases to 140 mT. The same tendencies were observed for higher values of magnetizing field H_m equal to 12 A/m (figure 3b). In this case maximal flux density B in the core increases from 374 mT to 408 mT for compressive stresses up to 10 MPa and decreases for tensile stresses σ up to 3 MPa to 208 mT.

Figure 4 presents the magnetoelastic characteristics $B(\sigma)_{Hm}$ of investigated core for both compressive and tensile stresses. It can be generalized, that for compressive stresses σ, maximal value of flux density B increases, whereas for tensile stresses σ maximal value of flux density B decreases for given amplitude of magnetizing field Hm. Moreover, percentage changes of maximal value of flux density B is higher for lower values of amplitude of magnetizing field H_m, for both tensile and compressive stresses σ.

4. Discussion of experimental results

In presented methodology direction of applied stresses σ (both compressive and tensile) is perpendicular to the direction of magnetizing field H. In such a case value of effective mechanical stresses s_{eff} causing magnetoelastic effect may be calculated from following equation [14, 15]:

$$\sigma_{eff} = \sigma \cdot (\cos\varphi - \nu \sin\varphi) \tag{1}$$

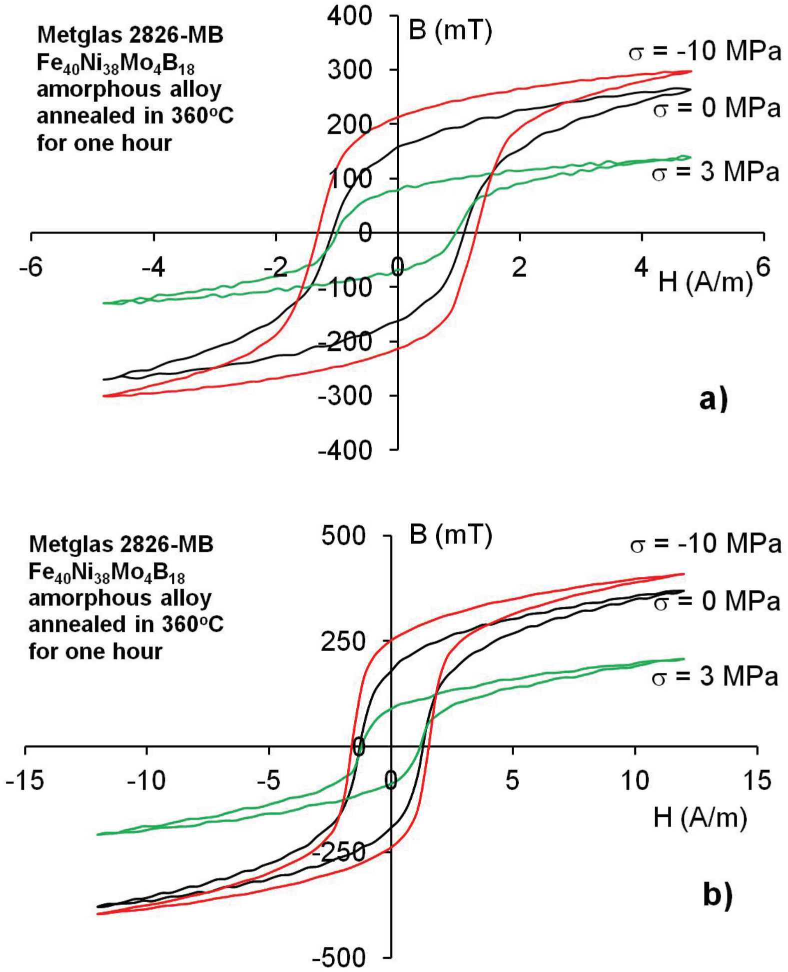

Fig. 3. Influence of both compressive stresses *σ* (marked as negative) and tensile stresses *σ* (marked as positive) on the shape of magnetic hysteresis loop *B(H)* of $Fe_{40}Ni_{38}Mo_4B_{18}$ amorphous alloy for different values of amplitude of magnetizing field H_m:
a) H_m = 5 A/m, b) H_m = 12 A/m

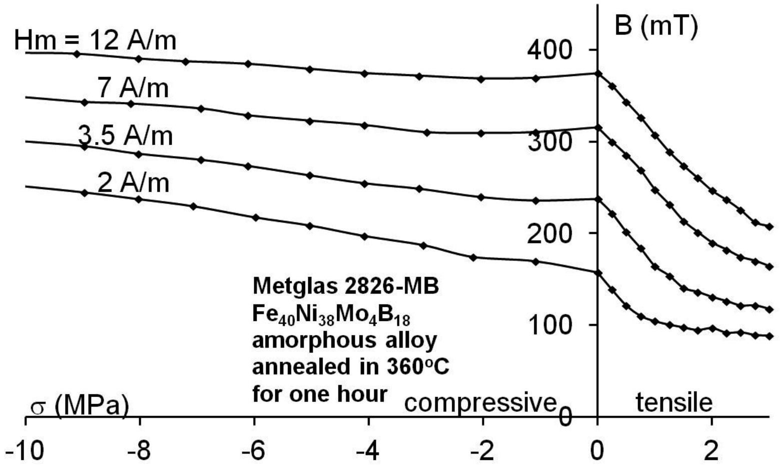

Fig. 4. Influence of both compressive and tensile stresses σ on maximal value of flux density B achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Fe_{40}Ni_{38}Mo_4B_{18}$ amorphous alloy

where φ is the angle between mechanical stresses σ direction and magnetizing field H direction, whereas v is the Poisson's ratio for soft amorphous alloy $Fe_{40}Ni_{38}Mo_4B_{18}$.

In presented method of applying the stresses σ to the ring-shaped sample, stresses are perpendicular to the magnetizing field H direction. As a result, due to the fact, that $\varphi = 90^{o}$, equation (1) can be simplified [16]:

$$\sigma_{eff} = -v \cdot \sigma \tag{2}$$

Due to the fact, that Poisson's ratio is positive [17], from the point of view of magnetoelastic effect, the equation (2) can be interpreted as follows: compressive stresses perpendicular to the magnetizing field direction act as tensile stresses and respectively in such a case the tensile stresses act as compressive.

In thermodynamic equilibrium, the way in which material reacts on the stresses σ in the direction of magnetizing field H should be connected with Le Chatelier's principle [18]:

$$\left(\frac{d\lambda}{dH}\right)_{\sigma} = \left(\frac{dB}{d\sigma}\right)_{H} \tag{3}$$

where λ is the value of magnetostriction of magnetic material. However, the presence of hysteresis may disturb this dependence.

It should be indicated, that for $Fe_{40}Ni_{38}Mo_4B_{18}$ Metglas 2826 MB amorphous alloy, positive value of magnetostriction up to 8 mm/m is observed [19]. In such a case, for stresses σ parallel to the magnetizing field H direction, increase of flux density B under tensile stresses should be observed. However, under compressive stresses σ, value of flux density B should decrease for given value of magnetizing field H. Taking into account effective value of stresses s_{eff} (given by equation 2) responsible for magnetoelastic effect, the results presented in figure 4 are in perfect agreement with the Le Chatelier's principle.

As it is presented in figure 4 the stress sensitivity of $Fe_{40}Ni_{38}Mo_4B_{18}$ Metglas 2826 MB amorphous alloy increases with decreasing of amplitude of magnetizing field H_m, what is observed as percentage increase of changes of maximal value of flux density B for given stresses σ. We suppose, that this phenomenon is connected with increasing of participation of magnetoelastic energy in the total free energy of the sample, due to decreasing of magnetostatic energy, for lower values of the magnetizing field H_m. Moreover asymmetry of $B(\sigma)_H$ dependences is caused by both presence of magnetoelastic Villari point [13] as well as significant presence of randomly oriented residual stresses in magnetic materials, generated during the production process.

Presented results may be the base for further quantitative modeling of magnetoelastic properties of soft amorphous alloys. Such models may be elaborated on the base of Jiles-Atherton-Sablik model [20, 21], Preisach model [22] or other models describing the stress dependence of the shape of B(H) hysteresis loop.

5. Conclusion

Presented new method of testing of the magnetoelastic properties of soft amorphous alloys under both compressive and tensile stresses enable achievement of uniform stresses distribution as well as used ring-shaped cores with closed magnetic circuits. As a result presented method may fill the gap connected with possibility of testing the magnetoelastic properties of soft amorphous alloys for electronic applications. Knowledge about these properties is important for users of inductive components with amorphous alloys cores due to the fact, that changes of magnetic properties due to magnetoelastic effect exceed 40% [23].

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Analiza i modelowanie magnetosprężystych charakterystyk rdzenia pierścieniowego stopu amorficznego na bazie żelaza i niklu poddanego działaniu naprężeń ściskających i rozciągających

Streszczenie

W artykule przedstawiono metodykę zadawania jednorodnych naprężeń ściskających i rozciągających do rdzenia pierścieniowego wykonanego ze amorficznego stopu magnetycznie miękkiego. Do badań wykorzystano zestaw specjalnych, cylindrycznych nakładek wykonanych z materiału niemagnetycznego. Z wykorzystaniem tych nakładek powstała możliwość zarówno wykonania uzwojenia magnesującego i pomiarowego, jak również obciążenia rdzenia w zakresie naprężeń rozciągających i ściskających. Z wykorzystaniem przedstawionej metodyki zbadano charakterystyki magnetosprężyste stopu amorficznego o składzie $Fe_{40}Ni_{38}Mo_4B_{18}$ (Metglas

2826 MB). Wiedza w zakresie tych charakterystyk jest ważna z punktu widzenia dla użytkowników elementów indukcyjnych z rdzeniami ze stopów amorficznych. Należy podkreślić, że pod wpływem naprężeń mechanicznych, wartość maksymalnej indukcji magnetycznej B w rdzeniu może zmieniać się nawet o 40%.