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STRESSES INFLUENCE ON MAGNETIC CHARACTERISTICS OF AMORPHOUS RING CORES FOR CURRENT TRANSDUCERS

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This paper presents results of investigation of stress influence on magnetic characteristics of amorphous ring cores for current transducers. Ring-shaped cores were made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy in as-quenched state, and after annealing. Thermal treatment was performed to improve the magnetic properties of amorphous core, *ie* to obtain a narrower hysteresis loop and a higher maximum flux density. Investigation of influence of compressive and tensile stresses on magnetic parameters of ring shaped cores was conducted to select a core least susceptible to the influence of stresses, and thus most suitable for industrial current transducer applications.

Keywords: current transducers, magnetoelastic effect, amorphous alloys

1 INTRODUCTION

Current transducers using ring cores from amorphous materials are a new type of current transducers. Cores of this type are characterized by high permeability and low coercivity force. For this reason, they can be used both to measure currents of high density and very low density of about μA [1]. The core magnetic parameters have major impact on the results of measurement with the Current Transducers. The temperature have a low impact on these parameters. The more significant effect is from thermal treatment, like thermal annealing or thermomagnetic treatment. But the most important influence on parameters of amorphous ring cores is from stresses from external forces, both compressive and tensile. Such stresses may arise as a result of deliberate and intentional actions, which is used in compressive and tensile force sensors [2,3], as well as unintentional *eg* as a result of errors in the assembly or design. Such errors result in various types of stress occurrence in the core. These stresses can completely change the magnetic parameters of the core by up to several tens of percent.

The paper presents the measurement results of the influence of the thermal annealing carried out in order to obtain better parameters of the amorphous cores. The influence of external stresses on the magnetic properties of the amorphous core for current transformers is also investigated. The cores of this type can be used in conventional current transducers, as well as in DC current transducers containing in their structure the Hall effect sensor. This sensor can be either based on classical semiconductor or on the newest class of graphene Hall effect sensors [4,5].

2 METODOLOGY OF INVESTIGATION

The construction of the current transducer can be divided for three distinct element groups. These are the magnetic core, most often ring-shaped, with mechanical elements, Hall efect sensor mounted in the gapped core, and electronic processing circuit providing power and Hall-effect sensor output signal conditioning to commonly recognized standards. Power supply systems and signal conditioning components are generally commercially available, and do not constitute research topics. The Hall effect sensor for which the magnetic core is developed was described in [6,7]. The main aim of the research was to develop a ring-shaped core capable of obtaining the best performance characteristics of the current transformer. The most important factor influencing these parameters is stress.

The main objectives which should be fulfilled by the test stand for this type of cores are:

- enable application of uniform compressive and ensile stresses to the core. When distribution of stresses is non-uniform, such as in the case of ring-shaped magnetoelastic sensors developed by Mohri [8,9] 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 utilization 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,
- utilize magnetic materials cores of shapes used in industrial purposes, to reduce their 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, which should be considered in interpretation of experimental results.

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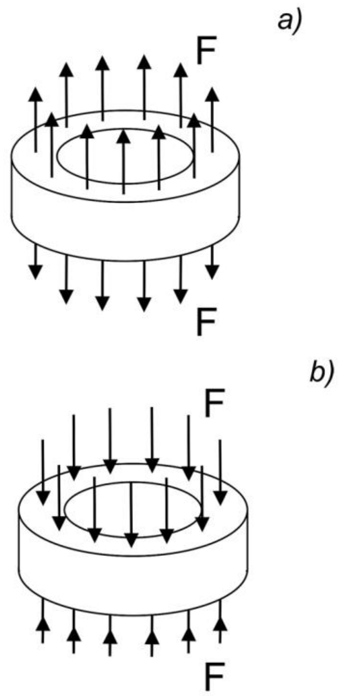
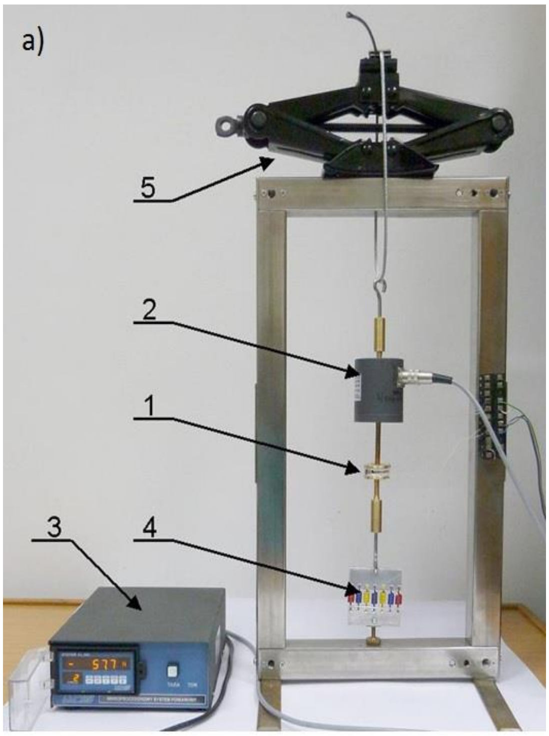


Fig. 1. Idea of the method of application uniforms stresses from external force F to ring-shaped core: a) tensile stresses, b) compressive stresses

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 the holes in these backings, core can be wound by magnetizing and sensing winding. Moreover, nonmagnetic shaft may be mounted to these backings. Than 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 [9] a 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.

For investigation focused on both compressive and tensile stresses ring-shaped sample made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy in as-quenched state and after annealing was used.



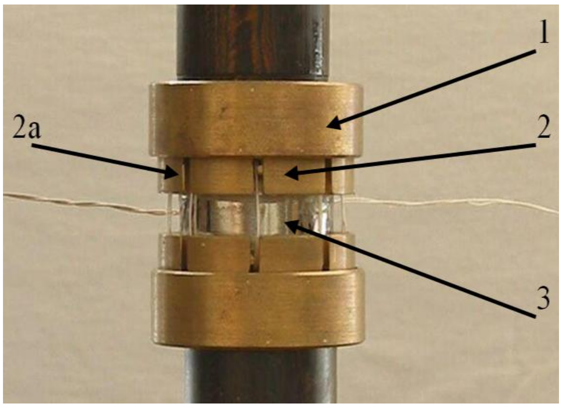


Fig. 2. Mechanical system for application of the uniform stresses to ring-shaped core [11, 12]: a) tensile stresses: 1 – core under investigation, 2 – reference, strain-gauge force transducer, 3 – electronic signal processing unit, 4 – set of the springs, 5 – tensile forces generator, b) compressive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

This alloy has high permeability more than 60,000 and a nearly zero magnetostriction. The outside diameter of the core was 32 mm, inside diameter was 25 mm and core's height was 10 mm. Magnetic hysteresis loops were measured by digitally controlled hysteresis graph HB-PL3.0. Magnetizing field frequency was 0.5 Hz which enables quasi-static measurements. HBPL hysteresis graph consists of precise function generator, voltage-to-current converter as well as an ultrastable integrator. Before each measurement the drift compensation of the integrator as well as sample demagnetization were performed.

3 RESULTS OF INVESTIGATION

Results of research show the effect of compressive and tensile stresses on the magnetic properties of amorphous cores. This investigation were showed on Fig. 3. – Fig. 9. The tested cores were heat treated in order to get rid of stresses generated in the amorphous ribbon during manufacture. One core to which no heat treatment was applied was taken for comparison. The cores were heated for one hour in argon protective atmosphere at 350°C, 355°C, 360°C, 365°C and 370°C.

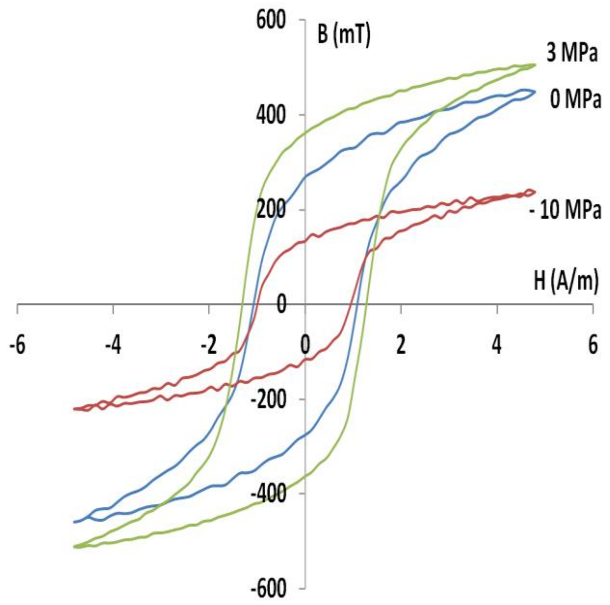


Fig. 3. Influence of both compressive and tensile stresses σ on hysteresis loop $B(H)\sigma$ ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy in as-quenched state. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 8 A/m.

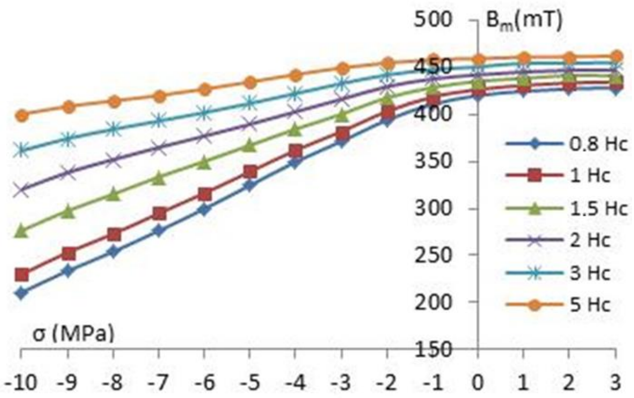


Fig. 4. Influence of both compressive and tensile stresses σ on maximal value of flux density B achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy in as-quenched state. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 8 A/m.

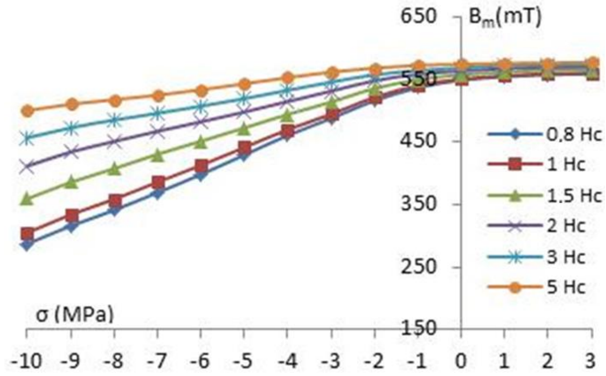


Fig. 5. Influence of both compressive and tensile stresses σ on maximal value of flux density B achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy after thermal treatment in 350 °C. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 2.4 A/m.

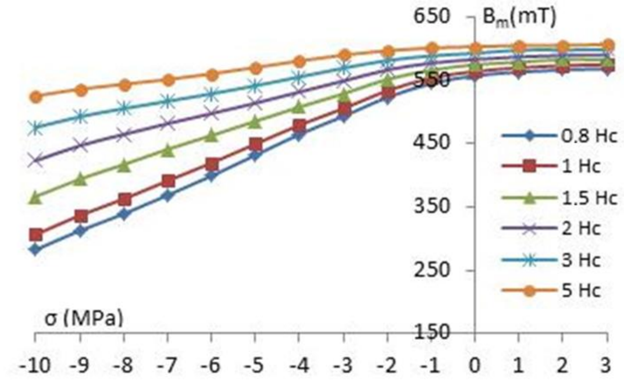


Fig. 6. Influence of both compressive and tensile stresses σ on maximal value of flux density B achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy after thermal treatment in 355 °C. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 1.9 A/m.

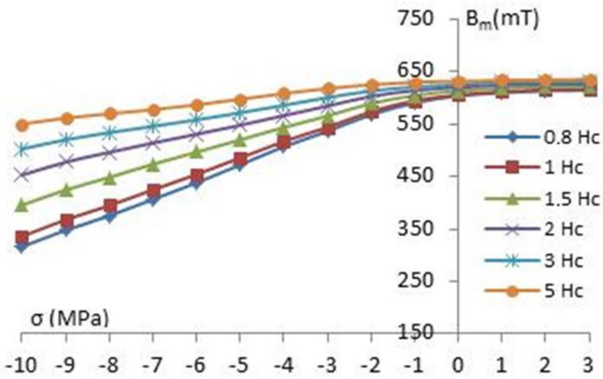


Fig. 7. Influence of both compressive and tensile stresses σ on maximal value of flux density B achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy after thermal treatment in 360 °C. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 1.5 A/m.

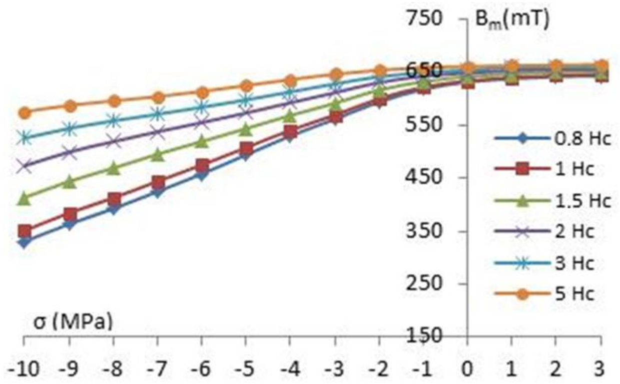


Fig. 8. Influence of both compressive and tensile stresses σ on maximal value of flux density *B* achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy after thermal treatment in 365 °C. Amplitude of magnetizing field H_m is a multiple of coercive field H_c= 1.2 A/m.

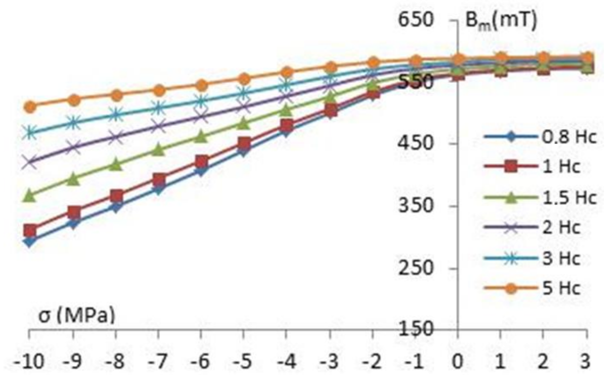


Fig. 9. Influence of both compressive and tensile stresses σ on maximal value of flux density *B* achieved for different values of amplitude of magnetizing field H_m in ring-shaped core made of $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ amorphous alloy after thermal treatment in 370°C. Amplitude of magnetizing field H_m is a multiple of coercive field H_c = 2.6 A/m.

Due to the fact, that investigated amorphous alloy exhibit nearly-zero magnetostriction, value of flux density is the highest for not stressed material. However, sample is more sensitive for compressive stresses, what may be explained by small, remaining negative saturation magnetostriction of sample.

The highest flux density B_m and smallest coercive force H_c, were obtained for the core annealed in 365°C. This mean, that such temperature of annealing is optimal from the point of view of magnetic properties of the $Co_{66}Fe_4Ni_1Si_{15}B_{14}$ alloy. Moreover, there was also the highest influence of stresses observed for sample annealed in this temperature, what is very important information for development process of current transducers.

4 CONCLUSIONS

The study showed that the effect of stress on the magnetic properties of ring cores is significant. This effect is also dependent on the heat treatment temperature which was subjected to the tested core.

The compressive stresses have a much greater influence on the magnetic properties of the core than the tensile stresses.

The results show that the best magnetic properties were observed for the core after the thermal relaxation in 365°C. The significant impact of stresses however, indicate that for the current transducers the cores in as-quenched state are best suited.

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