Stress Monitoring of Composites with Fe-based Amorphous Microwires by Non-contact Magnetic Method

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***Abstract* - The deformation of amorphous materials causes a change in their magnetic properties. If it occurs within the elastic region, such changes are reversible and can be used to control stresses. This applies both to the amorphous alloys themselves and to composites with embedded amorphous microwires. New experimental results on monitoring of the applied tensile stresses in Fe-based amorphous microwires after different regimes of treatment are presented. We investigated the amplitude of the Electro-Motive Force (EMF) signal due to the Barkhausen effect, the saturation magnetostriction and the coercivity. We used a non-contact method for stress monitoring of ferromagnetic microwires. It was found that the dependence of the EMF signal on the axial tensile stress of microwire exhibits a maximum. We observed a significant increase in the maximum of the EMF signal for microwires after annealing and its shift to higher tensile stresses. Using the obtained data, we evaluated the possibility of stress monitoring in a composite material containing such microwires.**

Keywords-amorphous microwires; magnetic properties; stress sensitivity; non-contact method.

I. INTRODUCTION

Amorphous Fe-based microwires are attractive first of all due to their magnetic bistability and Giant MagnetoImpedance (GMI) effect, which is used as a contact method of stress control in various magnetoelastic sensors [1]-[3]. Additionally, their low dimensionality and excellent mechanical properties are appropriate for the development of composites with embedded microwires. In this case, the microwires can be regarded as embedded sensors: their impedance is sensitive to the wire magnetic structure and is responsible for the appearance of a controlled microwave dielectric response [4][5]. The stress-sensitive magnetic properties of the amorphous ferromagnetic microwire have also been used for stress control. This is due to the stress dependence of the switching field that is determined to a great extent by the value of the magnetostriction coefficient of microwires [1]. During the magnetization reversal of the ferromagnetic microwire, jumps in its magnetization (large Barkhausen jumps) occur. They can be registered as the electromotive force peaks depending on the magnetic field [3]. The peak amplitude and the peak position are affected by stress. Consequently, the stress state of the composite material containing such microwires can be controlled by a non-contact method.

The rest of the paper is structured as follows. In Section II, we present the experimental details. Section III contains the results and discussion, and we conclude the work in Section IV.

II. EXPERIMENTAL DETAILS

In this work, we investigated the change in amplitude of the electromotive force signal under tensile stress of Fe-based amorphous microwires with different composition.

Under the influence of the external Alternating Current (AC) magnetic field, generated by the magnetizing coil, the EMF induction is produced in the pick-up coil. Pulses associated with the motion of domain walls appear on the main sinusoidal signal. For given amplitude and frequency of magnetic field, the value of register signal depends on the magnitude of the mechanical stresses in the sample (microwire or the composite). The value of magnetostriction coefficient for as-prepared microwire was measured by a small angle magnetization rotation method.

The tensile stress in the microwire was carried out using a universal Zwick/Roell tensile machine with a high-precision force transducer according to uniaxial stretching. During the experiment, the pick-up coil was placed in the vicinity of the testing sample.

For the stress monitoring of the composite material, a ferromagnetic microwire was introduced into it. The composite samples were made of carbon fiber impregnated with resin and the ferromagnetic microwire was implemented between the layers of prepregs. Afterwards, the composite was compressed and cured under the pressure of 170 MPa at 115°C for 120 min. The composite samples for

 ISBN: 978-1-61208-745-0

the tensile tests had an in-plane size of 2x15 cm and a thickness of 1-2 mm.

III. RESULTS AND DISCUSSION

In the first step, the amplitude of the EMF signal of the ferromagnetic amorphous microwires with a different composition and geometry was measured. We observed sharp EMF peaks associated with the domain wall propagation under an action of the AC magnetic field on the screen. The amplitude of the EMF signal at a given frequency and amplitude of the external magnetic field was proportional to the magnetic flux of the microwire. For the as-prepared microwire, we measured the value of the magnetostriction coefficient, λs, and found that the amplitude of the EMF signal grows with increasing the magnetostriction coefficient of the investigated microwires: there is a correlation between the amplitude of EMF signal and the magnetostriction coefficient of the investigated microwires. This allowed us to choose the most suitable microwire compositions.

In the second step, we measured the dependence of the EMF voltage of the microwires on the tensile stress. For all investigated microwires, the dependence of the EMF signal on external stress presents a maximum at 60-120 MPa. This peak may be associated with a change of the hysteresis loop of the amorphous microwires under the stress, which must be attributed to the influence of the applied stresses on the velocity of the Domain Wall (DW) propagation and the magnetostriction coefficient. The magnetization of a ferromagnetic material due to strain is known to be proportional to the magnetostriction coefficient and the initial magnetic permeability. The magnetostriction coefficient of ferromagnetic amorphous microwires changes with stresses exhibiting a maximum and their initial magnetic permeability decreases because the domain wall mobility decreases with the applied stresses. Thus, it can be suggested that the observed dependence, which exhibits a maximum, is most likely related to the stress dependences of magnetization and magnetostriction.

After removing the glass coating, i.e., by reducing the internal stresses, there is an increase in the magnitude of the peak by 2 times. We also observed a shift of the EMF peak toward higher values of tensile stresses. For the microwire with removed glass coating, this maximum was observed up to 300 MPa, whereas for the glass-coated microwire - only up to 100 MPa.

In the case of the partially crystalline sample, the internal stresses are smaller due to partial stress relaxation associated with recrystallization of nanocrystalline materials. This sample presents larger stress sensitivity of the EMF signal due to a higher magnetic permeability of this sample. In addition, the maximum EMF amplitude versus stress from partially crystalline microwire is observed at higher stress values. This can be explained by lower values of magnetostriction in a partially crystalline microwire, which leads to higher stress sensitivity for the partially crystalline microwire as compared to the amorphous sample.

Annealing of the Fe-rich microwires leads to improvement of magnetic softness, DW velocity and mobility, and internal stresses relaxation. Owing to this, we observed a significant increase in the maximum of the EMF amplitude for microwires after annealing and its shift to higher tensile stresses.

After the introduction of a microwire in the carbon composite, the overall appearance of the dependence of EMF on stress is maintained. The detected signal from a microwire in the composite is proportional to its deformation. The elastic modulus of the amorphous Fe-based alloy is about 120 GPa [6]. The measured value of elastic modulus for the studied carbon composite is 54 GPa. This means that, for the same strain, the microwire in the composite is exposed to twice higher stress value than the composite matrix. This, at first, reduces the range of possible stresses measured from microwire embedded in the composite, and, secondly, leads to the appearance of strong stresses at the interface between the microwire and the composite matrix. The main cause of the breakdown of the connection between the microwire and the composite is the destruction of the glass coating. Low limit of glass coating deformation becomes, therefore, an obstacle to expanding the measuring range of mechanical stresses in the composite.

IV. CONCLUSION

The magnetic properties of a ferromagnetic microwire, embedded in the composite matrix, depend on its stress-strain state. This allows stress monitoring in composites by non-contact induction method. Using a microwire without glass coating as a stress-sensitive element, we can expand the range of stress control in the composite material by this method.

ACKNOWLEDGMENT

The authors acknowledge the Russian Foundation for Basic Research (Grant 16-53-48012) and the Ministry of Education and Science of the Russian Federation in the framework of Increase Competitiveness Program of NUST «MISIS» (К2-2014-013 and К2-2017-089).

REFERENCES

[1] P. Aragoneses et al., “The Stress dependence of the switching field in glass-coated amorphous microwires,” J. Phys. D: Applied Phys. V.31, pp. 3040-3045,1998.

[2] A. F. Cobeño, A. Zhukov, J. M. Blanco, V. Larin, and J. Gonzalez, “Magnetoelastic sensor based on GMI of amorphous microwire,” Sensors and Actuators A, v.91, pp.95-98, 2001.

[3] J. Olivera et al., “An Embedded Stress Sensor for Concrete SHM Based on Amorphous Ferromagnetic Microwires,” Sensors, v.14, pp. 19963-19978, 2014.

[4] M. Ipatov, V. Zhukova, A. Zhukov, and L.V. Panina, “Microwave Metamaterials Containing Magnetically Soft Microwires,” Advances in Science and Technology, v.75, pp. 224-229, 2010.

[5] F.X. Qin et al., “Effects of wire properties on the field-tunable behaviour of continuous-microwire composites,” Sensors and Actuators A, v. 178, pp.118– 125, 2012.

[6] H. Chiriac, T.A. Ovari, and Gh. Pop, “Internal stress distribution in glass-covered amorphous magnetic wires,” Phys. Rev. B., v.42, 101- 105, 1995.