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Cast Amorphous Magnetic Microwires for Medical Applications

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Mini Review

Magnetic microwires demonstrate large variety of magnetic behaviours which is important for sensing applications. Depending on the chemical composition of the metallic core, for Co-, Fe- and Ni- based composition as well as on the cooling rate, the microwires properties are very different. The geometrical characteristics of the microwire depend on the physical properties of a metallic alloy and of glass, on the diameter of the glass tube, and the parameters of the heating inductor.

The diameter of metallic core in these microwires can range from 0.1µm to 70µm, and their thickness of the glass can vary from 1µm to 20µm. Moreover, the length of the cast microwire can reach up to 104 m. Technological aspects of Taylor–Ulitovsky method for fabrication of glass-coated microwire with different structure are analyzed. Magnetic properties of cast amorphous and nanocrystalline microwires have been reviewed considering their potential application.

This work evaluates the feasibility for implanting short segments of Barkhausen microwires in treatment volumes of patients requiring radiation therapy. Such locating of deep-seated sites prior to each treatment is not done routinely or is usually achieved through imaging with ionizing radiations. Present therapeutic procedures can result in substantial heterogeneities in the dose distributions or significant doses to surrounding normal tissues, resulting in poorer control of the tumors and/or increased complications. The microwire implants make it possible to accurately locate the microwire by way of re-entrant magnetic flux measurements, and hence, pinpoint the treatment volume prior to and during treatment.

A correlation between the frequency of natural ferromagnetic resonance (NFR) (1-12GHz) determined from the dispersion of permeability and alloy composition (or magnetostriction between 1 and 40ppm) of glass-coated microwires has been systematically confirmed. Absorption of composite (microwire pieces embedded in a polymer matrix) screens has been experimentally investigated. Parallel theoretical studies suggest that a significant fraction of the absorption can be ascribed to a geometrical resonant effect, while a concentration effect is expected for the thinnest microwires.

The importance of the medical application relates to the fact that internal organs requiring radiation therapy are subject to movement within the body over time. Therefore, location of a tumor determined by an x-ray computerized tomography scan or magnetic resonance imaging prior to the onset of the radiation treatment becomes inaccurate once organs readjust position due to eating, walking, or other bodily motions. As a result, radiation extending periodically over days or weeks can miss the intended target with collateral damage to neighboring tissue. By sensing the position of a small implanted magnetically tag it becomes possible to pinpoint a tumor's location just prior to or during treatment. It is known the cast glass-coated amorphous micro- and nanowires (CGCMNWs) with positive magnetostriction possesses a rectangular hysteresis loop and its magnetization is reversed by a large Barkhausen jump (LBJ)[1], the coercive force of which can be regulated by both the residual and by both the external mechanical stresses.

Various wires (including micro- and nanowires) feature properties of magnetization reversal with the use of LBJ, and their magnetic structure can differ from the magnetic structure of the cast glass-coated amorphous micro- and nanowires (CGCMNWs). In this case, the possibility of their long-term existence in certain (one of two) magnetized states and the stepwise transition from one magnetized state to another is called the magnetic bistability effect (by analogy with similar effects in other sections of physics). However, as was already noted in [2,3], the particular domain structure of these micro- and nanowires can differ from one another. Therefore, a wider theoretical study of the bistability phenomenon in magnetic materials that will not depend on the particular magnetic structure makes some sense.

Bistable ferromagnet (BF) technology is usually reduced to its formation in material with a strongly pronounced gradient of the magnetic potential profile, which is possible, e.g., in cast glass-coated amorphous micro- and nanowires (CGCMNWs), in the presence of quasi-mono-axial magnetic anisotropy. Then, both bistable states can be abstractedly represented as energy levels of the system spaced by the energy barrier. BFs were earlier obtained by thermal and mechanical treatment. Thus, in particular, the well-known Wiegand vicalloy wire was obtained [1]. In contrast to the Wiegand wire, since the production moment, the cast glass-coated amorphous micro- and nanowires (CGCMNWs) with a positive magnetostriction is a BF.

In addition to the cast glass-coated amorphous micro- and nanowires (CGCMNWs) manufacturing technology, there is the Unitika technology (Unitika Ltd.). The wires manufactured by the Unitika technology (this technology is also called in rotating water quenching) possess another magnetic structure and different (from the cast glass-coated amorphous micro- and nanowires (CGCMNWs)) magnetic characteristics, although they are also referred to BF. The properties of cast glass-coated amorphous micro- and nanowires (CGCMNWs) are basically discussed in this work, but our many results can be referred to any BF. We will start to discuss the magnetization reversal mechanisms, which were opened, in particular, in studies of the magnetization reversal of materials out of the Wieg and vicalloy wire and earlier in studies of multiple jump materials and theoretically studied in detail in [2,3]. In our opinion, it is necessary to theoretically analyze the experimental results obtained in [2,3] from this position.

The study of two Barkhausen jump forms as two independent magnetization reversal mechanisms was started in works [3]. When multiple jump magnetization reversal domains, it is very difficult to analyze single jumps (the experimental problems are discussed in [3]). It followed from the results of [3] that, along with the simple 180° - movement of the domain boundaries, which are retarded by defects, there are the magnetization reversal forms due to the interaction of these boundaries leading to an abnormal magnetization jump but physically to the stepwise domain reorganization. Just this magnetization reversal was later called relaxational [3].

The relaxational mechanism is characterized by a pulse with a steep leading edge and a gentle falling edge. The accelerative mechanism is characterized by a smooth increase and a sharp fall of the second leading edge of the pulse (Figure 1). The analysis of the studies shows that the operating characteristics of the BF in which these mechanisms show themselves are ambiguous. Therefore, it is necessary to study in detail the usefulness of the first or second type of pulses (or even their combinations).

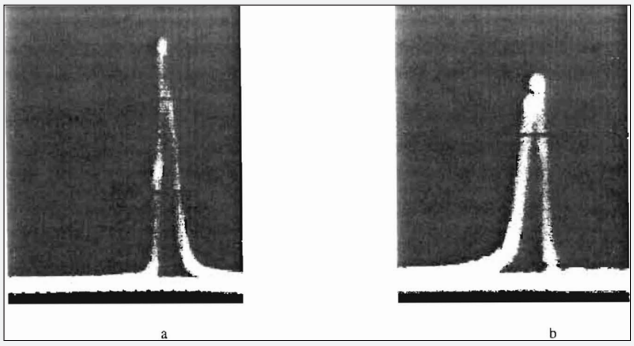

Figure 1: (a) Relaxational and (b) accelerative pulse forms in CGCMNWs [3].

Work [3] was one of the first studies in which attention was paid to the need for the similar analysis of two Barkhausen jump (BJ). In addition, it was noted that, in a deformed Wiegand wire (namely, it was studied earlier) the accelerative form of the magnetization reversal pulse was more stable (the fluctuation of the parameters did not exceed 10%). Moreover, the accelerative movement form was also characterized by sufficiently high pulse duration (~50μs) and a relatively small starting field (as compared with the relaxation movement's form).

The relaxational form of the magnetization reversal pulse was more stable in CGCMNWs (according to [3], the fluctuation of the parameters did not exceed 1%). It was established in the cast glass-coated amorphous micro- and nanowires (CGCMNWs) that a more stable magnetization reversal form is related exactly to the relaxational form (in contrast to a Wiegand wire). At the same time, the magnetization reversal mechanism was carried out in a certain sequence. The magnetization reversal started inside the microwire, where the magnetic anisotropy is lower, and the domain wall formed there probably propagated in an accelerative way. This process corresponded to the nucleation of the magnetization reversal, and, in certain magnetization reversal conditions, it could fail to show itself (e.g., due to a small starting field and a small relative volume of the switched material). Then, the relaxation jump of the magnetization reversal pulse occurs through the potential barrier, which also ends with the possible accelerative movement of the domain wall.

Then, the relaxation movement form played the main part in the magnetization reversal process, which is more stable in the cast glass-coated amorphous micro- and nanowires (CGCMNWs) case. One can make a competent assumption that the relaxation magnetization reversal form will play an even more important part when the sizes of the microwire's diameter are decreased (in its moving to a nanowire).

Since we assume that the relaxation magnetization reversal movement's form can be actually independent of the movement of the domain wall, which is always accompanied by the presence

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of eddy currents, it is possible to more simply describe the magnetization reversal process of the dipole of the micro- and nanowires, which we will consider further.

Theoretical and experimental results

Let us show magnetic dipole with the scheme of measuring of coil (Figure 2). Components of the magnetic field intensity are written as [3]:

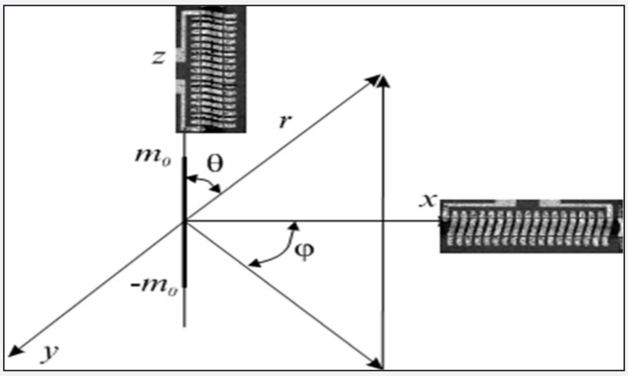

Figure 2: Experimental arrangement of measure for dipole [3].

$$\left.\begin{aligned} H_r &= 2[M_d(\omega)]\left[\frac{2\pi i}{\lambda}\frac{1}{r^2}+\frac{1}{r^3}\right]\cos\theta\, e^{i\frac{\omega r}{c}} \\ H_\theta &= [M_d(\omega)]\left[-\frac{(2\pi)^2}{\lambda^2}\frac{1}{r}+\frac{2\pi i}{\lambda}\cdot\frac{1}{r^2}+\frac{1}{r^3}\right]\sin\theta\, e^{i\frac{\omega r}{c}} \\ H_\phi &= 0 \\ [M_d(\omega)] &= \frac{[m_0]G(\omega)}{4\pi\mu_0} \end{aligned}\right\} \quad ,(1)$$

Where ω/c = 2π/λ, and λ is the radiation wavelength, m_0 is dipole moment, G is propagation function

$$\mu_0 = 4\pi\cdot 10^{-7} \text{ H/m}.$$

Let us consider the extreme case when r/λ< 1. This case corresponds to low frequencies [3]:

$$\left.\begin{aligned} H_r &\sim 2[M_d]\frac{1}{r^3}\cos\theta \\ H_\theta &\sim [M_d]\frac{1}{r^3}\sin\theta \\ H_\phi &= 0 \\ [M_d] &\approx \frac{[m_0]}{4\pi\mu_0} \end{aligned}\right\} . \quad (2)$$

Equations (1), (2) enable to theoretically estimate the BJ . We note the special features of measuring the magnetic pulse data [3]:

1. The signal of the scheme measuring of coil - X (Figure 2), which is twice larger than the signal of the scheme measuring of coil - Z (Figure 2) makes it preferable, and this is used in experiment.

2. For the cast glass-coated amorphous micro- and nanowires (CGCMNWs) dipole with the saturation induction value BS ≈1 T (for an Fe-based microwire) and with the microwire volume V ≤10^{-11} m^3 (for a microwire with a core diameter of ~40μm and a length of ~10^{-2}m), the equipment fixing this dipole radiation field should be sensitive to magnetic fields of 10^{-7} A/m near the dipole (r<1m). The smallness of this value (below the magnetic noise level) is determined by the smallness of the dipole volume.

The possibility of measuring the LBJ in the near-field zone of the signal by an induction measuring coil was checked in [3] (Figure. 2). The signal of the magnetic flow variation owing to the component *Hr* was recorded. The end wall of the measuring coil was directed at a right angle to the vector *r* and perpendicular to the dipole's center. The external magnetic field, which initiated the magnetization reversal of the dipole, did not create an induction EMF (induced electromotive force) in the measuring coil.

Therefore, in this scheme (the scheme measuring of coil -X in Figure 2), a compensating coil is not needed. In this case, the radio-field component is absent, and the measuring coil receives the near field of the microwire dipole (with a length of 3cm and a core diameter of ~50μm). As was noted, only the signal corresponding to the near - field zone was observed in [3]. Therefore, the induced electromotive force (EMF) of the received radiation signal varied in accordance with $1/r^3$ law (Figure 2 & 3). It follows from the results of [3] that the application of magnetic labels out of microwires is strongly limited due to the small distances of the signal's reception. However, this does not prevent one from using similar microwire labels for medicine, as was proposed in [3].

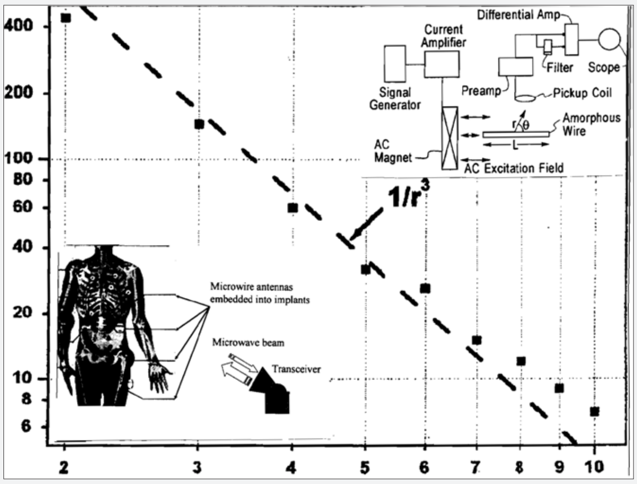

Figure 3 : Dependence of the EMF (plotted in the Y-direction (in mV)) from the distance between the center of the dipole and the end wall of the measuring X- coil (plotted in the X-direction (in cm)) [2,3].

(Inset: principal electronic schema is presented).

The critical length of the cast glass-coated amorphous micro- and nanowires (CGCMNWs) sections at which the BF effect with the LBJ is preserved is about a millimeter, being

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as least ten (or more) times smaller than bistable tapes and wires. The magnetization reversal rate of the cast glass-coated amorphous micro- and nanowires (CGCMNWs) is higher than those of its analogs. One can hope that, for nanowires, which can be obtained from cast glass-coated amorphous micro- and nanowires (CGCMNWs) by constriction these parameters will be better.

At present, micro- and nanowires can be used for applications in code labels for goods, car parts, valuables documents, securities, and money (Figure 3 & 4). They also find application in medicine for distinguishing affected organs or observations of transport process of medicinal preparations (with magnetic labels) in organisms. Note that this transport process could be controlled by an external magnetic field .

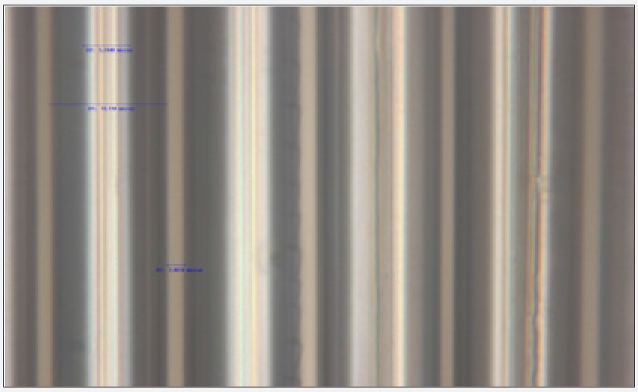

Figure 4 : Micrograph (100 time enlarged) of the parallel array (grid) of microwires. The distance between wires is 2μm. the inner diameter is 5μm and the thickness of the glass shell is 4μm. Film dimensions (4mmx5mmx4μm).

The obtained experimental and theoretical results testify that labels made out of magnetic micro- and nanowires can be used only at small distances from the recording units (at distances of ~ (0.1-1)m) depending on the micro- and nanowires' diameter. In this aspect, they are not competitive for the known radio-frequency identification (RFID) systems. However, if the location of the label (as, e.g., in [2,3]) and the use of the label in environments absorbing radio waves are necessary or the priority of using the label is not the reading distance but, e.g., confidentiality, the use of the magnetic label out of micro- and nanowires can become preferable. In addition to the Barkhausen effect, the cast glass-coated amorphous micro- and nanowires (CGCMNWs) labels also possess natural ferromagnetic resonance (NFR see below), which can be also used as an additional property for identification.

At present, need to working on finding will be made the algorithm to solve this problem using multiple sets of interrogation coils. To date we are encouraged that even very short wires (~3cm, 50μm in diameter) have the potential of being used as tags to accurately locate hidden portions of the human body requiring medical treatment.

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