Cast Amorphous Magnetic Microwires for Medical Locator Applications

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***Abstract* — This article 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 implants make it possible to accurately locate the microwire by way of re-entrant flux measurements, and hence, pinpoint the treatment volume prior to and during treatment.**

***Index Terms* — Barkhausen jump, bistable microwires, identification systems.**

1. INTRODUCTION

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 tag magnetically it becomes possible to pinpoint a tumor's location just prior to or during treatment.

It is known that a cast amorphous microwire in glass encapsulation (CAMGE) with positive magnetostriction possesses a rectangular hysteresis loop and its magnetization is reversed by a large Barkhausen jump (LBJ), the coercive force of which can be regulated by both the residual and external mechanical stresses (see, fig. 1 and [1]).

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 CAMGE. 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], 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 CAMGE, 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 [2]. In contrast to the Wiegand wire, since the production moment, the CAMGE with a positive magnetostriction is a BF.

In addition to the CAMGE 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 CAMGE) magnetic characteristics, although they are also referred to BF.

The properties of CAMGE 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 Wiegand vicalloy wire and earlier in studies of multiple jump materials and theoretically studied in detail in [2]. In our opinion, it is necessary to theoretically analyze the experimental results obtained in [3] from this position.

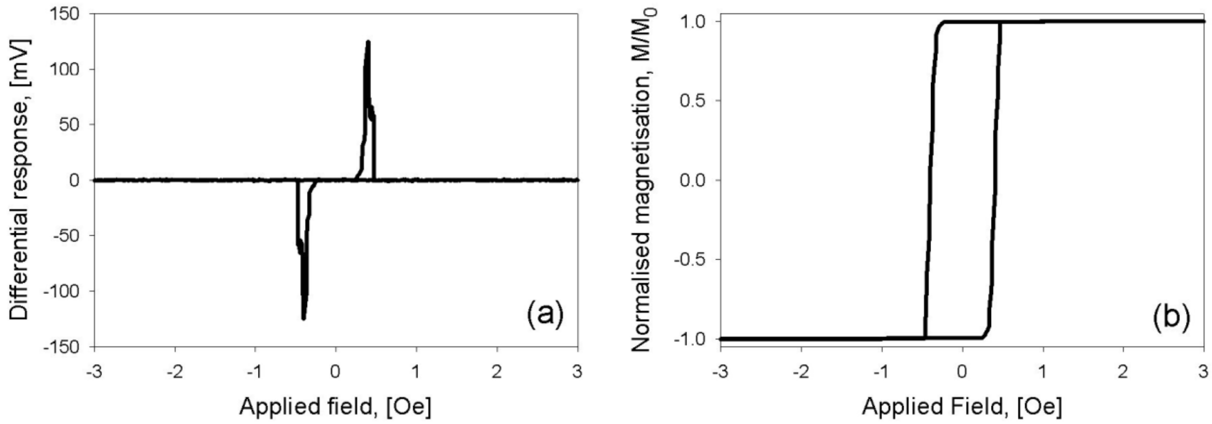

Fig 1 Differential (a) and integral (b) hysteresis loop by large Barkhausen jump.

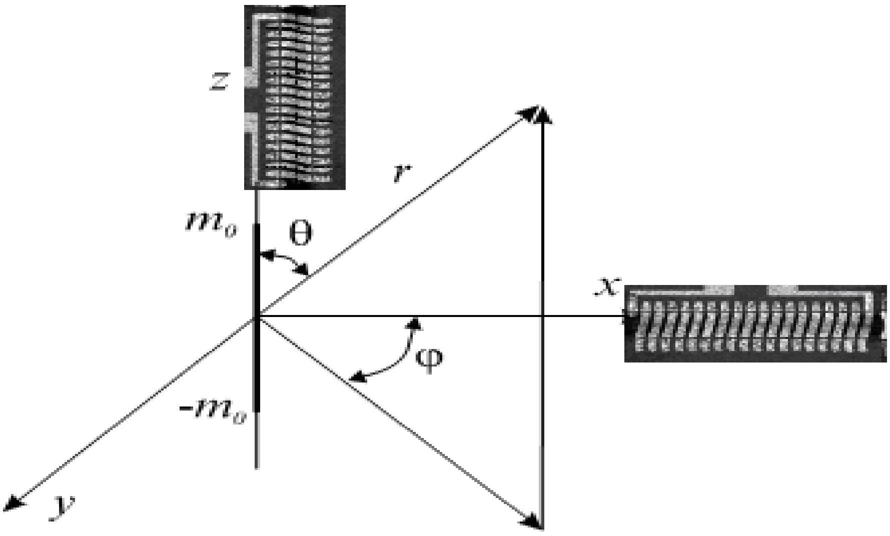

Fig. 2. The experimental arrangement of measure for dipole

2. THEORETICAL and EXPERIMENTAL RESULTS

Let us show magnetic dipole with the scheme of measuring of coil (see fig. 2).

Components of the magnetic intensity are written as:

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

where $\omega/c = 2\pi/\lambda$, and λ is the radiation wavelength, m_0 is dipole moment, G is propagation function ($\mu_0 = 4\pi\cdot 10^{-7}$ H/m).

(The absolute values of the vector projections are given without taking the signs into account.)

Let us consider the extreme case when $r/\lambda < 1$. This case corresponds to low frequencies by which the LBJ is characterized, and the contribution of the member that is proportional to $1/r^3$ is important for them. It is known that the electric and magnetic fields of these members are shifted in phase by $\pi/2$; hence, the averaged energy flow of the near field is equal to zero.

Below, we will be interested only in the dependence of the magnetic field intensity on the distance to the dipole. Formulas (1) reflect the dynamic and quasi-static processes. The propagation function $G(\omega)$ should reflect the actual movement of the domain wall. The simplest form of the delta shaped pulse will be used. That does not actually reflect the magnetization reversal process and can be only used in the estimates.

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

Equations (2) enable to theoretically estimate the BJ recording range.

Could be noted the special features of recording the magnetic pulse data:

1. The signal of the scheme measuring of coil - X (see fig. 2), which is twice larger than the signal of the scheme measuring of coil - Z (see fig. 2) makes it preferable, and this is used in experiment (see below). There is no radio signal in this configuration, but it exists, e.g., in the measurements in accordance with scheme measuring of coil - Z.

2. For the CAMGE dipole with the saturation induction value $B_S \approx 1$ T (for an Fe-based microwire) and with the microwire volume $V \leq 10^{-11}$ m^3 (for a microwire with a core diameter of ~ 40 μm 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 < 1 m). The smallness of this value (below the magnetic noise level) is determined by the smallness of the dipole volume.

The possibility of recording the LBJ in the near-field zone of the signal by an induction measuring coil was checked in [3] (see on the scheme of measuring of coil –X fig. 2 and on high – inset fig. 3).

The signal of the magnetic flow variation owing to the component H_r 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 in the measuring coil.

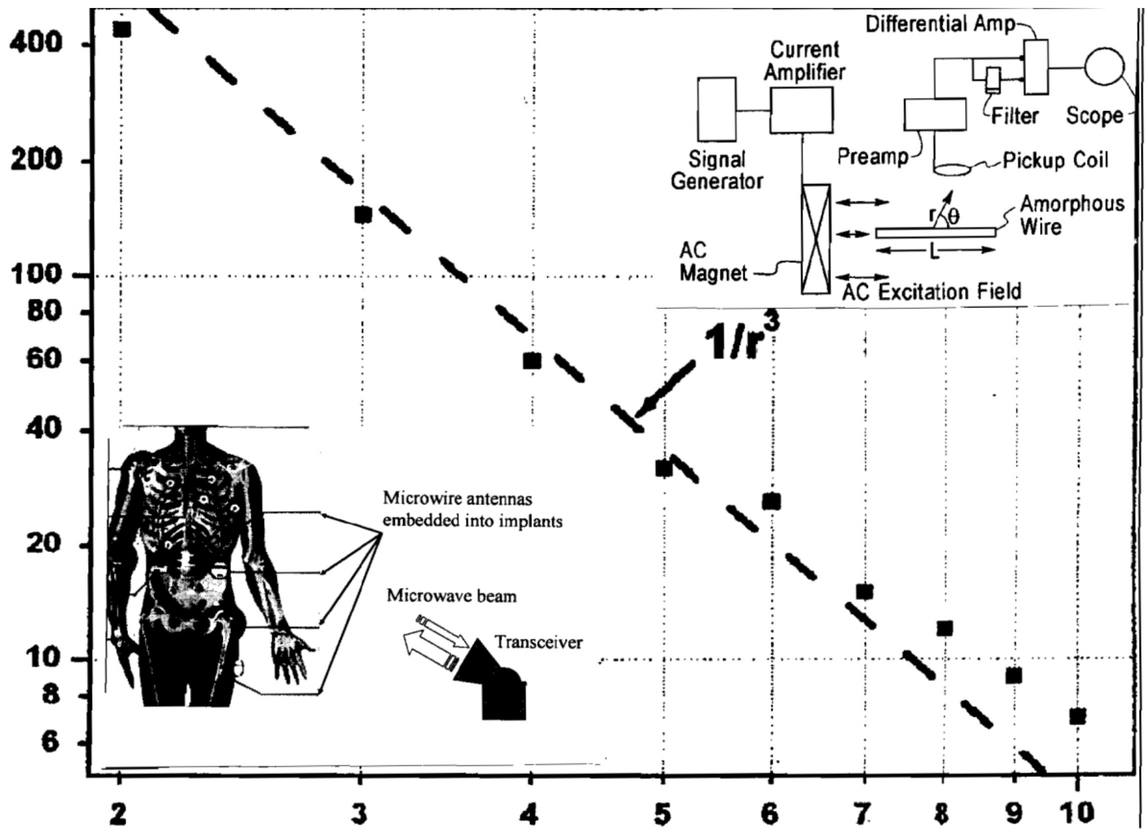

Fig. 3. Dependence of the EMF at the measuring coil plotted in the Y-direction (in mV) on the distance between the center of the dipole and the end wall of the measuring coil in the X-direction (in cm) [3]. The vector r (the distance from the dipole to the coil) is perpendicular to the center of the dipole and the end wall of the measuring pickup coil. (Insets: schema magnetic location and principal electronic schema measure are presented).

Therefore, in this scheme (the scheme measuring of coil -X in fig. 2, and on high – inset fig. 3), 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 3 cm and a core diameter of ~50 μm [3]).

The studies were performed using Fe - and Co - based CAMGE [4] where the measuring coil was placed along the dipole's axis (with the end wall at a right angle to the dipole) at some distance from it. In this case, a compensating coil is needed. (It is corresponding to scheme Z presented on fig. 2).

The maximum distance for the signal receipt from the Fe - based CAMGE reached ~20 cm (according to [4], when the core diameter is ~20 μm and the dipole length is ~3 cm), but, in this geometry, one can expect a significant increase in the signal reception distance at large switching rates, when the radio signal from the dipole can be significant.

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 (Fig. 3). The angular dependence obtained in [3] also corresponds to formulas (2). The results obtained in [4] differ from those of [3] since the $1/r^3$ law is not true for them, probably, because not only the near - field zone radiation was measured (at least we have no other explanations).

It follows from the results of [3, 4] 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].

It is known that the average energy flow from the radiating dipole is proportional to the radiation frequency to the fourth power [5]. The increase in the radiation frequency is intended to substantially raise the radio signal's power (see the possible technical solution in [6, 7]).

As is known, the electromagnetic wave actually carries the electromagnetic energy, which decreases, as that of any point electromagnetic energy source, according to the $1/r^2$ law (spherical wave). In addition, the indexation of the electric field component by the measuring unit can be more preferable in this case.

Note that there are conditions in which the radio waves are strongly absorbed. However, in these conditions, the radiation of the near- field zone can be revealed, thus making just the near - field signal urgent.

3. CONCLUSIONS

The critical length of the CAMGE sections at which the BF effect with the LBJ is preserved is about a millimeter, being as least ten (or more) times smaller than bistable tapes and wires obtained by other methods. The magnetization reversal rate of the CAMGE is higher than those of its analogs. One can hope that, for nanowires, which can be obtained from CAMGE by constriction with thinning, these parameters will be better.

At present, bistable micro- and nanowires can be used for applications in code labels for goods, car parts, valuables, documents, securities, and money; the creation of informational files; for the remote control of actuating mechanisms; and the creation of sensitive elements (sensors) in measuring equipment. 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.

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 [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 CAMGE labels also possess natural ferromagnetic resonance (NFMR), which can be also used as an additional property for identification.

The present measurements in [3] of re-entrant flux reversal as a function of position confirm that short sections of implanted wire will be useful in locating visibly inaccessible living tissue, and hence, have the desired medical applications. Initial conditions have so far required that the wire be straight and its length known. A more difficult task remains, namely, that of locating the magnetic dipole for an arbitrary unknown initial position which corresponds more realistically to a medical implant.

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 (~3 cm, 50 μm 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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