MICROWIRES FOR MEDICAL APPLICATIONS

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Abstract

Results of a study for the medical applications of micro- and nanowires are described. The magnetic characteristics of glass-coated Fe-based cast amorphous microwires (with a positive magnetostriction constant) are proposed. The residual stress distributions in this type of microwires determine the domain structures and the switching field behavior. These wires are characterized by a rectangular hysteresis loop and can be used in measuring and identification engineering. A model that describes the process of the reversal magnetization of an amorphous microwire with the help of a large Barkhausen jump is proposed. The model is estimated with regard to the optimization of the signal-to-noise ratio. The results obtained do not contradict the existing physical concepts concerning a domain wall motion and are more general and realistic than the previous models.

1. Introduction

The importance of the medical application is associated with the fact that internal organs requiring radiation therapy are prone to moving within the body over time. Therefore, the location of a tumor determined by X-ray computed tomography scanning or magnetic resonance imaging prior to the onset of the radiation treatment becomes inaccurate once organs readjust their 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 a collateral damage to the neighboring tissue. Magnetic sensing of the position of a small implanted tag makes it possible to pinpoint the tumor's location just prior to or during treatment.

It is known that a cast amorphous microwire (CAM) with positive magnetostriction exhibits a rectangular hysteresis loop and the magnetization of it is reversed by a large Barkhausen jump (LBJ), the coercive force of which can be regulated by both residual and external mechanical stresses (see, e.g., [1–12]).

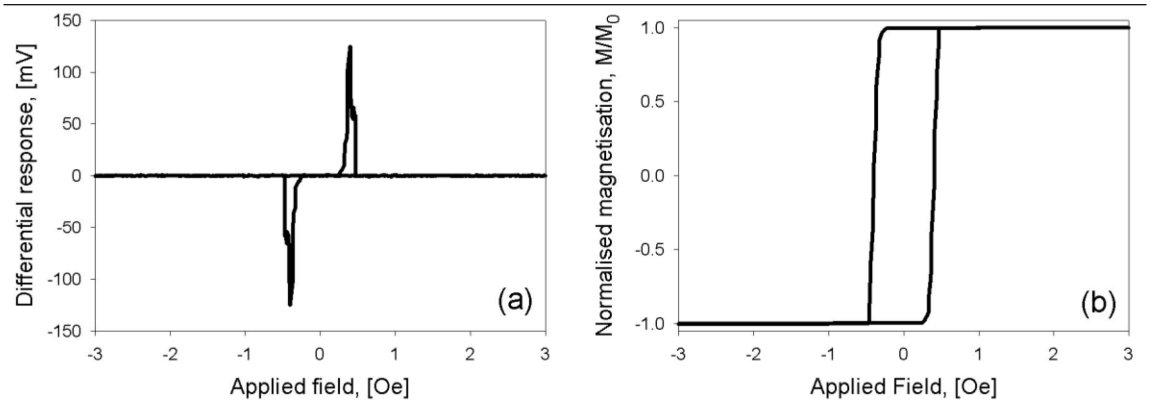

Fig. 1. (a) Differential and (b) integral hysteresis loop by an LBJ.

Various wires (including micro- and nanowires) have feature properties of magnetization reversal with the use of an LBJ; their magnetic structure can differ from the magnetic structure of a CAM. In this case, the possibility of their long-term existence in certain (one of two) magnetized states and a stepwise transition from one magnetized state to another is referred to as the magnetic bistability effect (by analogy with similar effects in other branches of physics). Typically, the bistable ferromagnet (BF) technology consist in the formation of a BF in a material with a strongly pronounced gradient of the magnetic potential profile (e.g., in CAMs) in the presence of quasi-mono-axial magnetic anisotropy. In this case, both bistable states can be abstractedly represented as energy levels of a system spaced by an energy barrier. Bistable ferromagnets were previously obtained by thermal and mechanical treatments. Thus, in particular, the well-known Wiegand Vicalloy wire was prepared [1]. Unlike the Wiegand wire, since the production moment, a CAM with a positive magnetostriction is a BF. In addition to the CAM manufacturing technology, there exists the Unitika technology (Unitika Ltd.). Wires manufactured by the Unitika technology, which is also referred to as in-rotating water quenching, have a magnetic structure and magnetic characteristics that differ from those of CAMs, although they are also attributed to a BF.

2. Theoretical Remarks

Figure 2 shows a magnetic dipole wire and pickup coils.

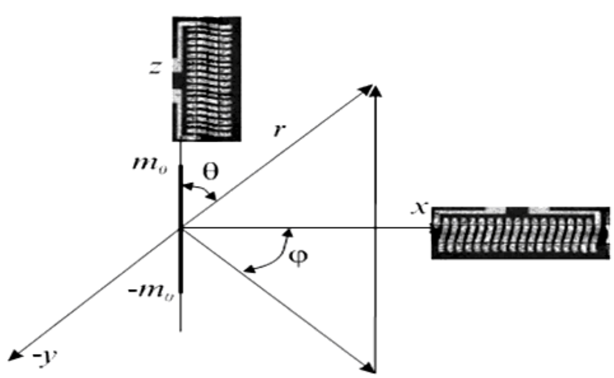

Fig. 2. Experimental arrangement of a dipole wire.

Hertz vector $\vec{\Pi}_m$ for dipole is represented as follows [4–7]:

$$\vec{\Pi}_m(t,r) = m_0 \frac{e^{j\omega\left(t - r/c\right)}}{4\pi\mu_0 r}, \tag{1}$$

where $\omega = 2\pi f$ (ω/c = 2π/λ, and λ is the radiation wavelength), f is the frequency , c is the velocity of light, ($\mu_0 = 4\pi \cdot 10^{-7}$ H/m, $i = \sqrt{-1}$), m_0 is the dipole moment ($\vec{m}_0 = \vec{B}_S V$, $\vec{B}_S$ is the saturation induction of the CAM, V is the dipole volume), and r is the distance from a point of supervision of a field (see Fig. 2).

The function of change of the magnetic moment ($0 \le t \le \infty$) has the form

$$f(t) = Sign(t) - 2e^{-\alpha t} \cdot \theta(t), \tag{2}$$

$$Sign(t) = \begin{cases} 1 & , \ t \ge 0, \\ -1 & , \ -\infty < t < 0, \end{cases}$$

where α is the dipole switching speed.

The transformation of vector function $\vec{\Pi}_m(t,r)$ is as follows:

$$\vec{\Pi}_m(\omega) = \frac{m_0}{4\pi\mu_0 r}\left(\frac{2i}{\omega} - \frac{2}{i\omega + \alpha}\right) e^{-i\omega\frac{r}{c}}. \tag{3}$$

Vector $\vec{\Pi}_m(\omega)$ is written as follows (in Cartesian coordinates):

$$\vec{\Pi}_m(\omega) = \left(0, 0, \Pi_z(\omega)\right)$$

The components of function $\vec{\Pi}_m(\omega)$ are written as follows (see Fig. 2, in spherical coordinates):

$$\left.\begin{aligned} \Pi_r(\omega) &= \Pi_z(\omega)\cos\theta \\ \Pi_\theta(\omega) &= \Pi_z(\omega)\sin\theta \\ \Pi_\varphi &= 0 \end{aligned}\right\}. \tag{4}$$

The magnetic field intensity is obtained as follows:

$$\vec{H}(\omega) = rotrot\vec{\Pi}_m(\omega).$$

The components of the magnetic intensity are written as follows:

$$\left.\begin{aligned} &H_r = 2[M_d(\omega)]\left(\frac{2\pi i}{\lambda}\frac{1}{r^2}+\frac{1}{r^3}\right)\cos\theta\, e^{i\frac{\omega r}{c}} \\ &H_\theta = [M_d(\omega)]\left[-\left(\frac{2\pi}{\lambda}\right)^2\frac{1}{r}+\frac{2\pi i}{\lambda}\cdot\frac{1}{r^2}+\frac{1}{r^3}\right]\sin\theta\, e^{i\frac{\omega r}{c}} \\ &H_\phi = 0 \\ &[M_d(\omega)] \approx \frac{[m_0]}{4\pi\mu_0} \end{aligned}\right\}, \tag{5}$$

$[M_d]$ is the absolute value of the magnetic moment, which will be applied in the further estimations.

Let us consider an extreme case, where $r/\lambda < 1$. 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:

$$\left.\begin{aligned} &H_r \sim 2[M_d]\frac{1}{r^3}\cos\theta \\ &H_\theta \sim [M_d]\frac{1}{r^3}\sin\theta \\ &H_\phi = 0 \\ &[M_d] \approx \frac{[m_0]}{4\pi\mu_0} \end{aligned}\right\}, \tag{6}$$

Equations (6) completely correspond to similar formulas for the magnetostatic case [4] and make it possible to theoretically estimate the BJ recording range low frequencies. Note the special features of recording the magnetic pulse data:

(i) The signal of scheme *X* (see Fig. 2), which is twice larger than the signal of scheme *Z*, makes this scheme preferable, and it is used in the experiment (see below). There is no radio signal in this configuration; however, it exists in measurements in accordance with operation scheme *Z*.

(ii) For the CAM dipole with a saturation induction value of $B_S \approx 1$ T (for an Fe-based microwire) and a microwire volume of $V \leq 10^{-11}$ m^3 (for a microwire with a core diameter of ~40 μm and a length of ~10^{-2} m), the equipment for recording the dipole radiation field should be sensitive to magnetic fields of 10^{-7} A/m near the dipole ($r < 1$ m). The small value of this quantity (below the magnetic noise level) is determined by the small value of the dipole volume.

3. Experimental Results

The possibility of recording the LBJ in the near-field zone of the signal by an induction measuring coil was verified in [11, 12]. The signal of the magnetic flow variation owing to component H_r was recorded. The pickup cool was directed perpendicular to the dipole's center.

The external magnetic field, which initiated the magnetization reversal of the dipole, did not generate an induction EMF in the measuring coil. Therefore, in this scheme, a compensating coil is not required. In this case, the far-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]).

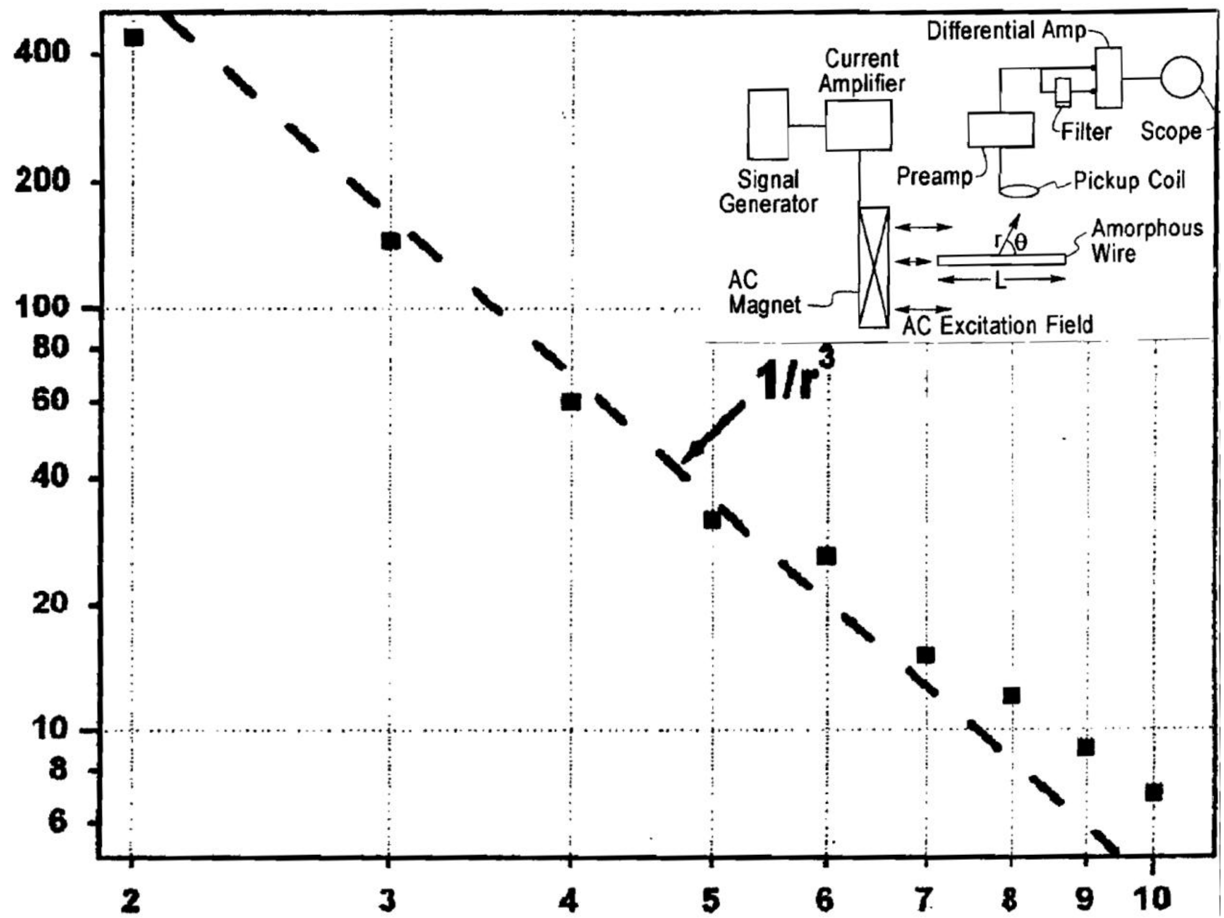

Fig. 3. Dependence of the EMF at the measuring coil plotted in the Y-direction (in mV) on the distance between the center of the dipole and the end wall of the measuring coil in the X-direction (in cm) [12]. Vector *r* (distance from the dipole to the coil) is perpendicular to the center of the dipole and the end wall of the measuring pickup coil. Inset: schematic circuit.

4. Conclusions

The critical length of the CAM sections at which the BF effect with the LBJ is preserved is about 1 mm, being as least ten times smaller than bistable tapes and wires prepared by other methods. The magnetization reversal rate of the CAM is higher than that of the counterparts. It is reasonable to expect that these parameters will be better for nanowires that can be prepared from CAMs by constriction with thinning.

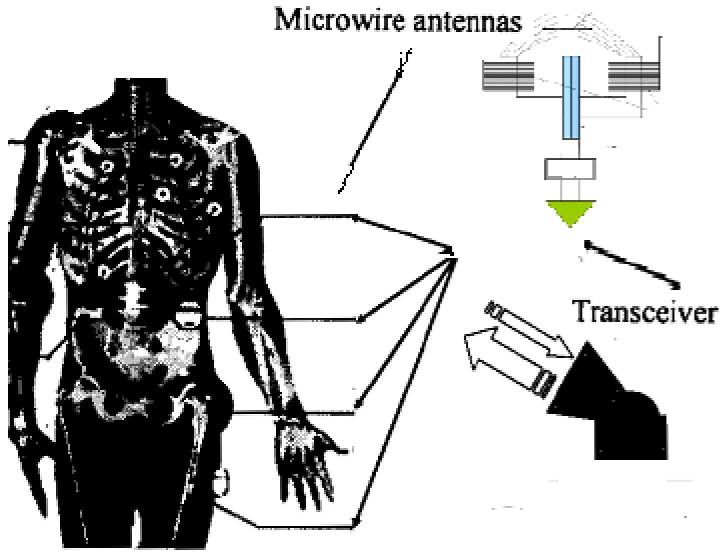

Fig. 4. Schematic possible application of a microwire in medicine.

It is commonly accepted that the widespread practical application of the BF with the LBJ started in 1975 owing to American researcher John Richard Wiegand, who designed the simplest Wiegand transducer based on a Vicalloy wire.

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 design 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 can be controlled by an external magnetic field.

The obtained experimental and theoretical results testify that labels made of magnetic micro- and nanowires can be used only at small distances from the recording units (at distances of about 0.1–1 m) depending on the micro- and nanowire diameter. In this aspect, they are not competitive for the known radio-frequency identification systems.

In addition to the Barkhausen effect, CAM labels are characterized by a natural ferromagnetic resonance, which can be also used as an additional property for identification.

Acknowledgments

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