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OFFSET OF SWITCHING FIELD IN AMORPHOUS Fe-BASED MICROWIRES

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The switching field of bistable magnetic microwires is a carrier of information about several physical quantities such as external magnetic field, mechanical tensile stress or temperature. The uncertainty of the switching field is also a limiting factor in the determination of these indirectly measured quantities. The presented article deals with the magnetic offset of the switching field that was observed during its use as a sensing element in a pulse-position type fluxgate magnetometer. A measuring methodology was developed for the purpose of the offset quantification. Measurement results for two sets of Fe-based glass-coated bistable magnetic microwires are discussed in the conclusion.

Keywords: magnetic microwires, offset, switching field

1 INTRODUCTION

Research in the area of magnetic microwires is very extensive especially in last few decades in view of the fact that many microwire types have been developed and studied. The main reason is that magnetic microwires seem to have a future perspective and, along with other things, they are a frequently discussed material suitable for modern sensing elements [1]. These materials react to physical quantities such as external magnetic field, tensile stress [2] or temperature [3].

Bistable magnetic microwires used as a sensing element in magnetometers promise high linearity with no feedback, simplicity of manufacturing, small dimensions, low cost, no cross-axes effects, no hazy analogue amplifying, direct digital compatibility and other benefits. However, after the construction of a magnetometer development kit, an offset problem occurred during the calibration process. Among other problems, noise for example, even though the electronics of the measurement chain was carefully controlled and balanced. Offset (additive error) of the magnetometer was up to 2 A/m (2500 nT) which, without additional analogue biasing or digital correction disqualified it for most of the application possibilities.

The offset might be explained by the asymmetry of the switching field of the microwire itself, a phenomenon already observed in some magnetic materials. The microwires are quite a complex magnetic material and such a performance could possibly be expected. Additionally, the offset changed with a different wire used, despite the same chemical composition and batch, furthermore statistically varied from the wires of other composition and batch. A specialized measurement workstation was designed for the verification of this hypothesis.

Finally, the aim of the article is to show the measuring method and existence of switching field offset in some bistable microwires. Random behaviour of microwires switching field was already published [4], but offset as DC limit of such noise was not studied and experimentally confirmed so far.

Nowadays, rapid development in the field of magnetic microwires offer much more advanced types for use in the pulse-type fluxgates. The practical utility of this work is to point out that offset of sensor can be effect of magnetic core itself.

The pulse-position fluxgate magnetometers or RTD magnetometers [5,6] using bistable amorphous microwires as a sensing element utilizing bistable magnetization characteristics of the microwire during the excitation by a precision triangular-shaped stimulation field [7]. When the switching field of the microwire is reached, a short voltage pulse is induced in the sensing coil, which can be detected easily and unambiguously. One of the possibilities of these pulses processing is a measurement of the time difference between the pulses arising at the positive or negative slopes of the stimulation field – the RTD method. The measurement principle is presented in the following illustration.

As we can see from the picture, the field generated by the stimulation coil repeatedly saturates the microwire in both polarities. The transitions between the saturations are represented by sharp induced pulses marked as VP. Since the switching field in the presence of offset is different for either positive or negative magnetization, we could define the mean switching field

$$H_{SW} = \frac{1}{2}\left(H^{+}_{SW} - H^{-}_{SW}\right), \tag{1}$$

and the offset of switching field as

$$\Delta H_{SW} = \frac{1}{2}\left(H^{+}_{SW} + H^{-}_{SW}\right). \tag{2}$$

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When measuring time intervals T^+ and T^- as shown in Fig. 1, the two equations can be defined as follows

$$2H_{MAX}\frac{T^+}{T} = H_{SW} + \Delta H_{SW} + H_{MAX} - H_0\,, \qquad (3)$$

$$2H_{MAX}\frac{T^-}{T} = H_{SW} - \Delta H_{SW} + H_{MAX} + H_0\,, \qquad (4)$$

where H_{MAX} is the amplitude of the exciting field, H_0 is the projection of the external magnetic field intensity to the axis of the microwire, T - *is* the half-period of the excitation field. The size of the external field and the mean switching field is obtained out of the difference and the sum of these equations

$$\tilde{H}_0 = H_0 - \Delta H_{SW} = -\frac{H_{MAX}}{T}(T^+ - T^-)\,, \qquad (5)$$

$$H_{SW} = H_{MAX}\left(\frac{T^+ + T^-}{T} - 1\right). \qquad (6)$$

Equation (5) implies that in determining of the external magnetic field H_0 the offset of the switching field will appear, which is the problem that this experiment is motivated by. The quantities (temperature, tensile stress) connected only to the mean switching field are not affected by offset and external field according to (6), as well as measuring magnetic field is not affected by switching field according to (5). The quantities could be then measured simultaneously and separately. The validity of these statements are theoretical only, because the dependences of positive and negative magnetization was not already studied separately, such as tensile stress and temperature dependence on external field.

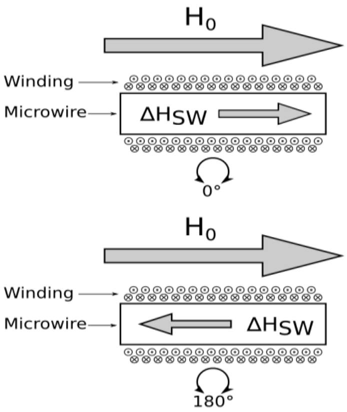

Fig. 2. Illustration of the fields before and after the turning of the sensor

To determine the offset, we suppose a precise turn of microwire and coils in the external field by 180°. Turning of the microwires in the external field has to be performed with a high precision. After that the microwire has to be in the same external field as before, therefore it is necessary to turn the microwire around its geometrical centre, whereby the influence of possible external field heterogeneity is minimized. Interactions of magnetic fields are illustrated as below.

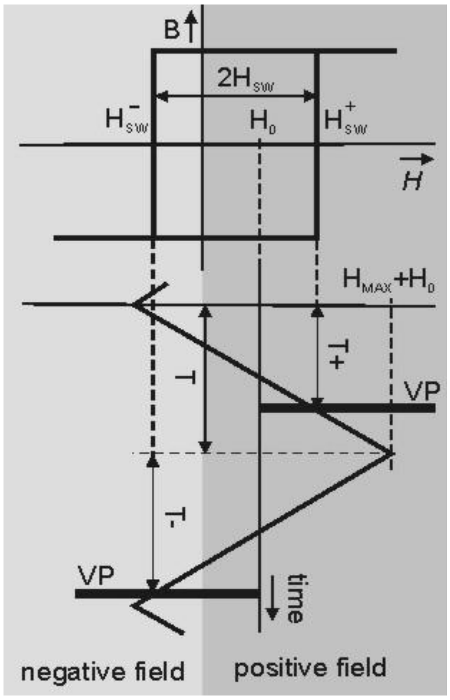

Fig. 1. Induction measurement method including offset of switching field

Turning the microwire in the external field will result in changing the direction of the microwire offset with respect to the external field (Fig. 2) and in regard of the method in switching of times T^+ and T^-. In (3) and (4) the switching will appear as follows

$$2H_{MAX}\frac{T_T^+}{T} = H_{SW} + \Delta H_{SW} + H_{MAX} - H_{0T}\,, \qquad (7)$$

$$2H_{MAX}\frac{T_T^-}{T} = H_{SW} - \Delta H_{SW} + H_{MAX} + H_{0T}\,, \qquad (8)$$

whereby, also (5) for the external magnetic field will be changed

$$\tilde{H}_{0T} = H_{0T} - \Delta H_{SW} = -H_0 - \Delta H_{SW} = -\frac{H_{MAX}}{T}(T_T^+ - T_T^-)\,. \qquad (9)$$

H_{0T} is now the projection of the external magnetic field intensity into the axis of the microwire after turning, T_T^+ and T_T^- are times measured after turning. Summing (5) and (9), the size of the microwire offset can be expressed as

$$\Delta H_{SW} = H_{MAX}\frac{(T^+ - T^-) + (T_T^+ - T_T^-)}{2T} = \frac{\tilde{H}_0 + \tilde{H}_{0T}}{2}\,. \qquad (10)$$

The switching field offset is then half of the sum of the measured fields before and after turning but practically only in case of negligible offset of the electronics and high precision of the turning. This offset could be further eliminated by analogue biasing or digital correction.

However, it is much better when the sensing element is symmetrical itself. Sophisticated estimation of internal offset and noise parameters [8] of microwires should be the first step for application of microwires in RTD magnetometers.

3 MEASUREMENTS

Magnetometer development kit - computer controlled programmable device for measuring the time intervals, generation of stimulation signal, data processing and storage - was designed and in more details is described in [2]. Time resolution of the device was 10 ns which at H_{MAX} = 570 A/m and T = 1 ms gives magnetic field resolution 0.011 A/m. During the measurement the microwire sensor was placed on a turning plane almost orthogonally to the external field in a slightly heterogeneous stimulation field with maximum intensity at one end of the microwire, in order to support the start of domain wall from this part. The error arising due to the turning was 0.0359 A/m, which corresponds to the laser-measured error 0.11° in the earth magnetic field. Thus, the overall uncertainty of the measurement can be estimated at 0.05 A/m. As the entire turning equipment was made of wood and silone, we assume that these materials do not affect the measurement precision. Measurements were performed on two types of microwires, both of them Fe-based. The chemical composition of the microwires was $Fe_{38.5}Ni_{39}Si_{7.5}B_{15}$ marked as N38 and $Fe_{42.5}Ni_{35}Si_{7.5}B_{15}$ marked as N37. The cutting was made mechanically with sharp tool without any additional treatment (cutting is another possible candidate for the uncertainties of switching field, offset included). The prepared samples were 2 cm long and were fixed to a glass base.

4 RESULTS AND DISCUSION

Five samples of both materials were made for the purpose of measurements. Each sample was subjected to two measurements, so Table 1 contains overall 20 results, 10 results per each type of the two microwires. Thus, each sample was measured twice with approximately one minute time delay between measurements. Due to the random behaviour of microwires switching field [4], and to supress it, the results were calculated as mean of taken samples. During every measurement, 500 samples of measured times T^+ and T^- were continuously acquisitioned at the sample rate 500Hz which lasted one second in both positions. H_{SW} and ΔH_{SW} were calculated for each measurement set as an estimated mean values

$$H_{SW} = \frac{H_{MAX}}{T}\frac{1}{500}\sum_{i=1}^{500}\left[T^{+}(i)+T^{-}(i)\right]-H_{MAX} \ . \qquad (11)$$

The overall mean value of H_{SW} and standard deviation of ΔH_{SW} were calculated for each type of microwire. The results are included in Table 1.

Tab. 1. Measured offset of N37 and N38 microwires

Sample No.	H_{SW} (A/m)	ΔH_{SW} (A/m)	Mean ΔH_{SW} (A/m)	σ ΔH_{SW} (A/m)
N37 microwires ($Fe_{42.5}Ni_{35}Si_{7.5}B_{15}$)				
1	131.9	3.69	–0.576	2.324
	131.77	3.73		
2	186.49	–1.02		
	186.3	–0.98		
3	159.65	–2.51		
	159.71	–2.64		
4	174.73	–1.46		
	174.23	–1.77		
5	189.6	–1.37		
	189.39	–1.43		
N38 microwires ($Fe_{38.5}Ni_{39}Si_{7.5}B_{15}$)				
6	75.47	1.45	0.142	0.894
	75.46	1.53		
7	86.68	0.39		
	87.54	0.17		
8	100.04	–1.2		
	99.96	–1.11		
9	87.9	–0.14		
	87.87	–0.098		
10	83.41	0.22		
	83.35	0.22		

According to the measured data overview, we can confirm the existence of asymmetry of the switching field of both two magnetic microwires types, which is significantly higher than the given uncertainty of measurement. Although, the N38 microwires shown much better properties. The average value of offset is –0.576 A/m for microwires marked as N37 and 0.142 A/m for microwires marked as N38. The asymmetries are assumable caused by differences in manufacturing and internal defects of the material. The experiment proved that every single microwire used as sensing element have to be individually calibrated for offset. We can statistically expect offset 2.32 A/m for microwires marked as N37 and 0.89 A/m for microwires marked as N38 without compensation. In addition, data show significant differences in switching field itself and thus sensors utilising H_{SW} as a carrier of information (stress, temperature) also have to be individually calibrated and thus cannot be used as a sensor of absolute type. Asymmetrical behaviour of magnetic materials was also described in [9], where the characteristics are intentionally achieved by the asymmetric structure of the magnetic element. Even though this diode-like behaviour is an excessive example, it points out the fact that magnetic materials can behave asymmetrically as a result of defects and asymmetry in mechanical manufacturing.

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