Sensors and Actuators A 255 (2017) 94–103

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Systematic optimization of the sensing properties of ring-core fluxgate sensors with different core diameters and materials

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ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form 10 January 2017
Accepted 10 January 2017
Available online 16 January 2017

Keywords:
Fluxgates
Amorphous metallic core
Magnetostriction
Annealing
Fluxgate noise
Magnetometer

ABSTRACT

In this study, a series of cobalt-riched alloy compositions $Co_{71-x}Fe_xCr_7Si_8B_{14}$ (x = 0, 2.0, 3.2, 4.0, 6.0 and 8.0) in the form of ribbons were produced to change magnetization characteristics and constants of magnetostriction in a controllable manner. In this way dominant parameters for the design of low-noise fluxgate sensor were determined. The studies were carried out in ring-core geometry for different diameters from 6 mm to 20 mm. Our experiments have shown that low values of the saturation magnetic induction B_s inherent for this alloy system had a crucial role for the noise level. With the cores having B_s of ~0.4 T, we could achieve a noise level of ~1 pT/$\sqrt{}$Hz @ 1 Hz. The specific features of design of the ring-core fluxgates having different dynamical ranges were also discussed thoroughly. The ring-core diameter of 15 mm was found to be optimal geometry for outdoor applications.

1. Introduction

As it is well known that the magnetometers are the devices used for two main purposes: i) the measurements of the strength and, in some circumstances, the direction of the magnetic field and ii) the measurements of magnetization characteristics of magnetic materials [1–4]. Four main sensors are dominating in the magnetic sensor industry. The SQUID sensors are used for very small magnetic fields (1 fT–1 nT), the Fluxgate sensors are used for small magnetic fields (0.1 nT–10 μT), the MR sensors are used for medium values (100 nT–1 mT) and the Hall sensors are used for higher magnetic fields (10 μT–3 T) [5].

Fluxgate magnetometers have many advantages and therefore are commonly used, especially in military applications and space research. They are cheaper, more robust against external factors (i.e. temperature), with high sensitivity (even 10 mV/nT), with a resolution of about 10 pT and with controllable zero offset and cross-field effect [6]. The fluxgates consist of ferromagnetic cores wound with two coils, one of which is driving coil and the other one is pickup coil where EMF voltage is induced. They are known to be sensitive to constant or slowly changing magnetic fields (DC to ~500 Hz) [7,8]. Despite its old history the fluxgates sensors keep their popularity both in science and technology due to ongoing technological developments in materials science and electronic industry. The readers may find brief summaries of the improvement efforts followed by different approaches in Refs. [9–12]. The magnetization characteristics of ferromagnetic cores used in the fluxgates determine the sensing performance of such devices. For instance, nonlinear magnetization curves are preferred in order to increase the signal strength of these sensors, which is contrary to the most used application areas of these cores, like in the transformers, magnetic switches and electromagnets [13]. Most of the fluxgate sensors use now the even harmonic signals (mainly the second one due to its the highest strength compared to the others), which is generated by the pick-up coil by co-applications of AC and the measured DC fields, since the even harmonic signals show perfect linear dependence on DC fields (or low frequency fields) [14–17]. So, the more rounded B-H curves of the cores provide more 2f signal strength. Besides, low hysteresis magnetic cores with high electrical resistance protect the sensor from heating caused by hysteresis and eddy current losses. Thus, the aging effect is minimized. Structural homogeneity is also known to be another important factor determining the sensing performance of these sensors. Local structural discrepancies in the whole mate-

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http://dx.doi.org/10.1016/j.sna.2017.01.013
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rial, like dislocations and impurity atoms, microstresses, etc., may disrupt the coordinated motions of domain wall and causes an additional noise [18–21]. The saturation magnetostriction λ_s reflecting the change of shape or dimensions of ferromagnetic materials during the process of magnetization, has also been reported as having influence on determining the noise level of fluxgate sensors. Altogether, in order to guarantee the best performance of the sensors, like the low noise, the highest sensitivity and the independence to the ambient temperature, we can summarize the optimal values of magnetic, electrical and structural factors as follows; the lowest saturation magnetostriction ($\lambda_s \rightarrow 0$), the high Curie temperature (>400 °C), the saturation magnetic induction B_s of 0.2–0.6 T, the B_R/B_S of ~0.5 (B_R is the remanence), the coercivity of less than 0.1 Oe, the maximum initial permeability μ_i (>100000), the specific electrical resistance of higher than 1.0 μΩm and the thickness of less than 25 μm [22]. Within these constraints, potential magnetic materials seem to be mainly nickel rich alloys (permalloys) and the amorphous cobalt-riched alloys. In the present work, we investigate the suitability of cobalt-rich amorphous alloys in shape of thin ribbons as a fluxgate sensor core and try to reach best sensor performance with experiments in a series of alloys containing different amounts of iron, $Co_{71\text{-}x}Fe_xCr_7Si_8B_{14}$ (x = 0, 2.0, 3.2, 4.0, 6.0 and 8.0). The influence of annealing route on the sensor performance, like stress annealing and annealing after insertion of the ribbons to the ring-shaped core templates, was also examined.

Studies on the fluxgate sensors are mainly concentrated on three types of geometries: the rod core, the race-track geometry and the ring-core geometry [23–26]. In these geometries, the rod core one has poor sensitivity and the noise level with respect to the others due to its open ends near which the flux lines are bended, which contributes to the noises coming from magnetic component. On the other hand, such geometry supplies good response to the cross-fields as a consequence of its large demagnetization factor to the axis perpendicular to the rod length. The race- track shaped sensors benefits from its closed loop geometry and so, the noise from the magnetization is kept minimal, but the cross-field effect is lower than in the rod core due to the lower demagnetization factor if the tracks are obtained from the sheets by etching [26]. If the tracks are formed from wide ribbons with the width of 2–3 mm, then the noise level will be high due to large mechanical stress exerted on the ribbon towards the turning points of the tracks. But, in such a case, the cross-field effect should probably be the best of all mentioned geometries [27]. The main requirements for most of the applications are summarized as i.) zero-cross field effect, ii.) zero offset value iii.) large dynamical range iv.) stability v.) high sensitivity and vi.) robustness. From literature knowledge, all these requirements seem to be fulfilled by the ring core geometry. Sensors with this geometry have additional advantages with respect to the others. On the other hand, while the ring core geometry suffers from its high demagnetization factor in the areas where the sensitivity is important, it benefits from it, if the upper limit is decisive. In addition, depending on the application area, there may also be some limitations on the allowed weight and dimensions of the sensor, like for use in satellites as attitude and orientation determination sensor [28]. So, one must have an opportunity to fulfill the desired sensor specifications (i.e. the sensitivity, dynamical range, etc.) by adjusting the core dimensions. With these reasons the influence of ring core diameter on the sensor performance has also been studied in a systematic way in this study.

2. Experimental

The cobalt rich amorphous alloys of thin ribbons with the width of 3 mm and the thickness of 20 μm having different atomic contents of iron, $Co_{71\text{-}x}Fe_xCr_7Si_8B_{14}$ (x = 0, 2.0, 3.2, 4.0, 6.0 and 8.0), were prepared by planar flow-casting [29]. Hereafter we will call the samples according to the x values of Fe for simplicity. For instance, $Co_{67}Fe_4Cr_7Si_8B_{14}$ composition will be called as Fe4. The melt was overheated to about 150 °C above its liquidus temperature and ejected from a quartz crucible with rectangular orifice by overpressure of argon (about 0.2 bar) onto the surface of smooth cold-rolled copper wheel with a diameter of 550 mm with a circumferential velocity of 40m/s, which is sufficient to prevent the material from crystallization. In order to investigate the influence of annealing on the sensor performance, three different routes were followed. In the first approach, the as cast ribbons were wrapped around cylindrical duraluminium bars having the same diameter as the final diameter of ring core fluxgate and heat treated at 320 °C for 1 h under argon atmosphere. Here it must be noted that the inner diameters of the rings were 6 mm, 10 mm, 15 mm and 20 mm. Then, the ribbons were taken from the bars and gently wrapped around the rings made of PEEK (Polyether ether ketone). The number of ribbon turns was chosen as 6 based on our previous experiences. This route was presented as an alternative to the MACOR (machinable ceramic) due to its relative cheapness, high enough melting temperature (~ 300 °C) and low thermal expansion (15–50 μm/m-K). It means that the mechanical stress occurring on the ribbon due to the mismatch between the thermal expansion coefficients of the ribbon and the template material can be kept at the minimum level. After evaluating the sensing performances of these ring cores for different diameters, we have decided to make further experiments on the one having a diameter of 15 mm due to its weight, dimensions and the sensing performance which seems to be the most appropriate for different application areas. In the second annealing route, all given series of cobalt-based ascast ribbons were wrapped around the MACOR ring templates of having a diameter of 15 mm. Then, similarly to the previous route, the heat treatment was done at 320 °C for 1 h under argon atmosphere, since the MACOR has a quite high servicing temperature (~1000 °C). As the third annealing route, the ribbons were stress annealed under the same thermal conditions. For this purpose, four compositions were selected from the above cobalt series considering their saturation magnetostriction values λ_s. The selected ribbons are $Co_{71\text{-}x}Fe_xCr_7Si_8B_{14}$ (x = 2.0, 3.2, 4.0 and 8.0) having λ_s values of −0.8, +0.03, +0.3 and +2.2, respectively [30]. A load of 1.5 kg was hanged to one end of the ribbons and the other end of the ribbons were pulled slowly (~1 mm/min) by a stepper motor through a tubular furnace stabilized at a temperature of 320 °C and argon atmosphere. A piece of ribbon enough for 6 layers (~30 cm) was cut from the center of all stress annealed part (3 m) in order to ensure its homogeneity. Then, these pieces were wrapped gently around the MACOR ring with 15 mm in diameter. In all cases, annealing was performed in bifilarly wound furnaces to minimize the effect of external magnetic field generated by the heating wires.

The excitation coils (or drive coils) with toroidal windings of 85, 84, 130 and 180 turns were wound on the rings having a diameter of 6 mm, 10 mm, 15 mm and 20 mm, respectively. The diameter of copper wire was 200 μm. The completed rings with excitation coils were put into the center of pick-up coils, which were especially constructed to supply close contact with the toroids, to increase the strength of induced signal. The pick-up coils were wound from copper wire of having 100 μm in diameter. The total numbers of turns were 1040, 1050, 1920 and 2160 for the rings of 6 mm, 10 mm, 15 mm and 20 mm, respectively. Fig. 1 shows the pictures of excitation and sensing coils of the rings for diameter of 6 mm (left) and 20 mm (right). The second harmonic measurements were carried out by using SR830 Lock-in amplifier. A calibrated coil was used as a reference DC field source. The noise analysis was carried out with a dynamic spectrum analyzer 35670A from Agilent in a seven-layered mumetal shield equipped with demagnetizing coil. Measurement data for sensor characterization were collected by an