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ON THE MAGNETIC AND MAGNETOELASTIC UNIFORMITY MEASUREMENTS OF MAGNETOSTRICTIVE RIBBONS AND FIBERS

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Abstract: In this paper we present results on magnetic and magnetoelastic uniformity measurements of magnetostrictive ribbons and fibers. Both magnetic and magnetoelastic measurements are based on the magnetostrictive delay line (MDL) response. Measurements were realized by using an automatic instrumentation device, with parametric control of field and frequency. The device has been calibrated with respect to standard Ni wires. Indicative results are given concerning amorphous magnetostrictive ribbons and fibers, showing a good agreement with other measuring techniques.

Keywords: Magnetoelasticity, magnetization, uniformity.

1. INTRODUCTION

Magnetostrictive materials are mainly used in the industry for various kinds of sensors, measuring displacement, stress and magnetic field [1]. Most of these applications rely solely on the magnetic and magnetoelastic properties of the in use material, which may be different along the length of the material because of the manufacturing process [2]. The need for magnetic and magnetoelastic uniformity testing is especially crucial in amorphous fibers and ribbons used in sensors, due to the fact that a change in the sensing element results in a change in the sensor response and may require a re-calibration of the sensor device [3].

Currently, amorphous magnetostrictive alloys, like ribbons, fibers and glass covered fibers are favorable to be used as sensing cores in sensing applications [4]. Amorphous ribbons are manufactured by melt-spun devices, amorphous fibers by in-water rapid quenching and glass covered wires by crucible drawing.

All these manufacturing techniques are very sensitive to the slightest change in their operating parameters, affecting the final material and most importantly, the uniformity of the response along the length of the material [5]. The dynamics of the manufacturing process are extremely difficult to be modeled resulting in an uncertainty, concerning the final material magnetic and magnetoelastic properties, as well as its composition. Annealing processes are used to tailor the material to specific requirements in the expense of extended manufacturing time.

Existing techniques for material evaluation include destructive metallographic measurements, ultrasonic testing and radiographic testing. These techniques determine the mechanical properties and evaluate the physical uniformity and possible flaws in the structure of the material. They are suitable only for out of production testing and with a limited amount of samples, due to the time they require and the cost involved, both in terms of money and man-hours.

The magnetic properties evaluation is currently performed out of production, because of the different magnetic requirements of the end-users of the materials. The manufacturer of a sensing device is responsible of measuring the coercive field and saturation magnetization of an amorphous ribbon or fiber to see if it is acceptable for his application. But, this is not enough for determining the properties of these materials concerning sensing applications. The determination of the magnetic and magnetoelastic properties and uniformity of these alloys is vital for their repeatable use in sensors and transducers.

Thus, the motivation of this work is to study the feasibility and effectiveness of an in-line magnetic properties uniformity testing apparatus for the documentation of the magnetic properties of a magnetic fiber or ribbon during its manufacturing process. Due to the nature of the manufacturing process itself, such a testing apparatus is best located after the actual manufacturing procedure just before the winding of the final material. Thus it is possible to obtain a magnetic properties documentation sheet for the under test material in respect to its length and include it in the final product, be it ribbon, wire or glass covered wire.

The experimental setup used for the measurements is exclusively based on the MDL technique and in principle is different and complimentary with respect to the arrangement presented in previous experiments [6]. Some indicative obtained results are presented and discussed next for the magnetization measurements, namely coercive field, remanence magnetization and saturation magnetization followed by the magneto-elastic measurement results. Because of the large amount of measured data a selective presentation is deemed necessary.

2. EXPERIMENTAL

The device used for the uniformity measurements was designed so that the measurements of the B(H) and λ(H) functions could be performed on a continuous basis along the length of a long ribbon or fiber in order to inspect the spatial character of the magnetization and magnetostriction. The physical layout is much like that of a tape recorder with the amorphous ribbon or fiber as the metal tape and is presented on Figure 1. A circular loop of ribbon and fibre was used because it was very easy to repeat the measurements for one sample with respect to a fixed 'start' along its length.

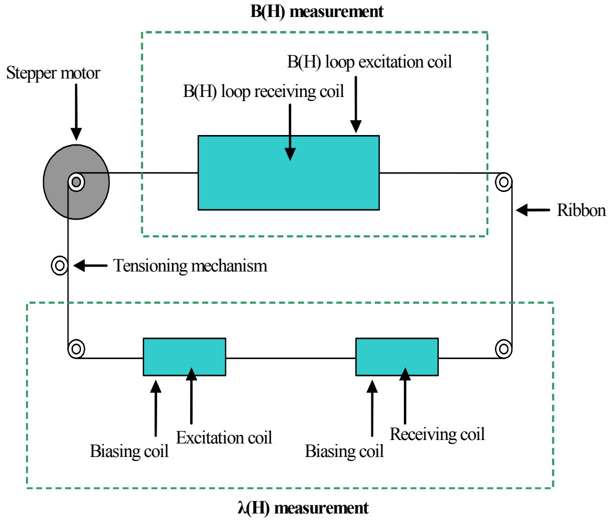

Fig. 1. A schematic layout of the measuring device

The B(H) loop and the λ(H) loop are both extracted from the MDL response of the ribbon or fiber under test. Detailed description of such an arrangement can be found in [7]. For this type of measurements, two sets of coils where constructed, a biasing - excitation coil assembly and a biasing - receiving coil assembly. Both biasing coils are 5 cm in length, 1 cm in diameter, single layer with 80 turns and are used for biasing the under measurement ribbon and fiber with a constant magnetic field locally producing a change in length λ_o. The excitation coil is 3 mm in length with 30 turns of 0.1 mm copper wire. The receiving coil is 2 mm in length with 300 turns of 0.01 mm copper wire. By applying a pulsed voltage to the excitation coil, a change in length $\Delta\lambda$ is produced causing a magneto elastic wave to propagate along the ribbon and the fiber, and a voltage change in the receiving coil. If the pulsed voltage is kept constant in frequency and amplitude, it is possible to measure λ_o by varying the amplitude of the biasing field. The signal from the receiving coil and the current from the biasing coils are measured and stored in a computer for further processing. The variable we are interested in is the change in the peak to peak voltage of the receiving coil with respect to biasing current, which, after digital integration is proportional to the λ(H) function.

These results are compared in the same set-up with ac magnetometry based B(H) loop results, as described in [5]. For the ac magnetometry an excitation coil of 220 turns was made, 13 cm long and 4 cm in diameter using 1 mm copper wire. Two additional coils (2 layers - 2 cm in length with the same wire) were wound on both ends of the excitation coil to improve the magnetic field homogeneity.

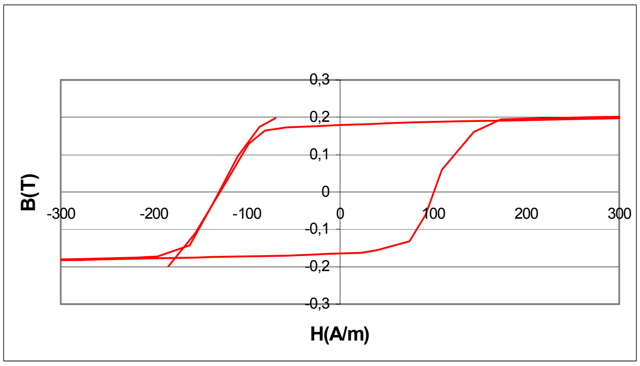

Fig. 2. Typical B-H loop for an as-cast tested amorphous ribbon

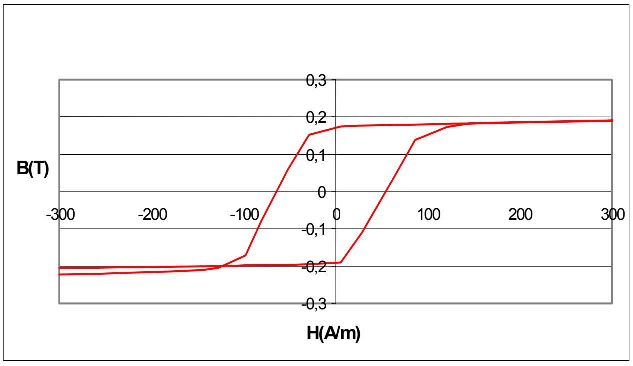

Fig. 3. Typical B-H loop for a stress-current annealed amorphous fiber

The receiving coil depicted on Figure 1 is actually two coils connected in series opposition, with the sample running through one of them. In this way it is possible to measure directly the magnetization of the ribbon or fiber without the sinusoidal excitation superimposed. These two coils are identical in construction, 1 cm long with 20 layers of 0.1 mm copper wire and a rectangular area of 2 mm^2. The signal from the receiving coils along with the excitation coil current is read with a digital oscilloscope and stored in a computer for further processing. This includes signal conditioning, noise removal and finally digital integration to obtain the B(H) loop.

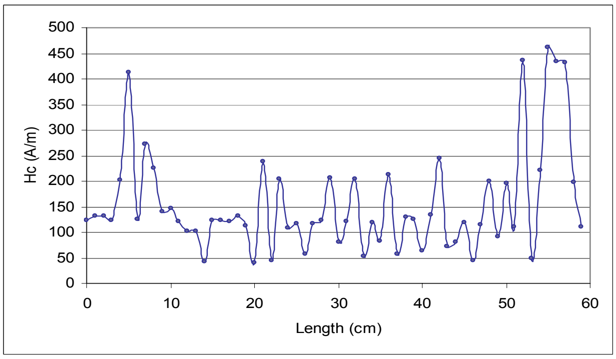

Fig. 4. Coercive field Hc versus ribbon length

Results are illustrated concerning amorphous $Fe_{78}Si_7B_{15}$ ribbons and fibers, mainly because of their high range of sensing applications. The alloys were measured in the as-cast form and after thermal or stress-current treatment.The magnetization measurements were performed along the length of the ribbon and the fiber, giving wide variations in the coercive field and the other characteristics of the B-H loop. The B-H loops for a ribbon and a fiber, are illustrated in Figures 2 and 3 respectively. The characteristic and rather classical bistable response of the fiber is absent in Figure 3, because the alloy has undergone stress-current annealing, thus vanishing the inner single domain. Figure 4 shows the dependence of the coercive field of a ribbon on the length of it, where the non-uniformity of the response is quite visible. By excluding the termination effects, a mean coercive field of 118 A/m was observed.

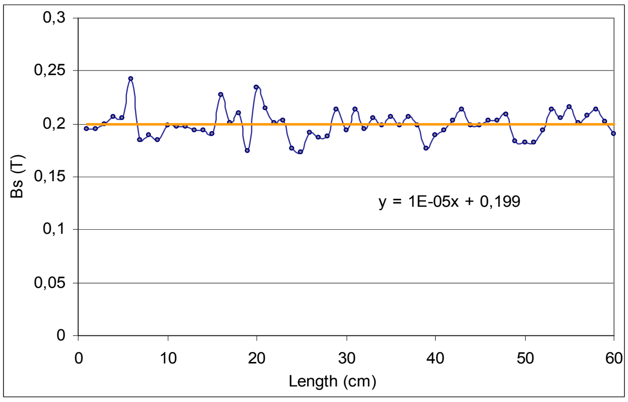

Fig. 5. Saturation magnetization Bs versus fiber length

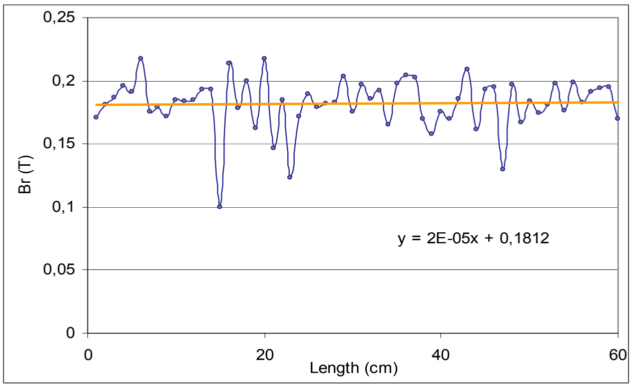

Fig. 6. Remanence magnetization Br versus fiber length

Accordingly, Figures 5 and 6 illustrate the dependence of the saturation and remanence magnetization respectively concerning amorphous fiber of the same composition after stress – current annealing.

Figures 7 and 8 illustrate the MDL response corresponding to the first derivative of the λ(H) function in different ribbon and wire samples respectively after stress-current annealing. The observed non-uniformities are the indication of the difference in chemical composition as well as in microstructure. Another worth mentioning result is the hysteretic effect as illustrated in Figure 9, that was occasionally observed, when measuring the λ(H) function for some samples. In this case the hysteresis is determined by using the MDL technique.

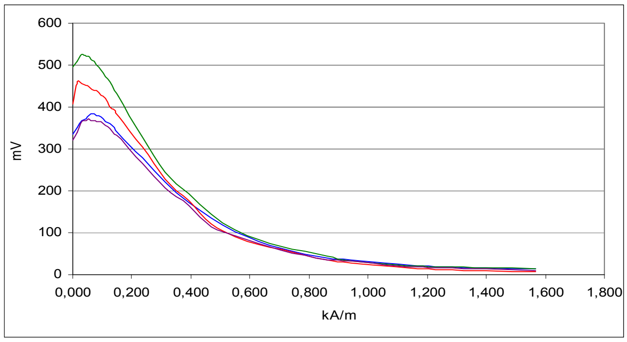

Fig. 7. The first derivative of the λ-H response at various points of a stress current annealed ribbon

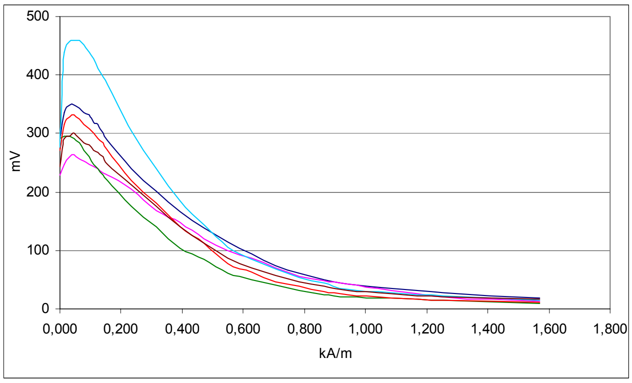

Fig. 8. The first derivative of the λ-H response at various points of a stress current annealed wire

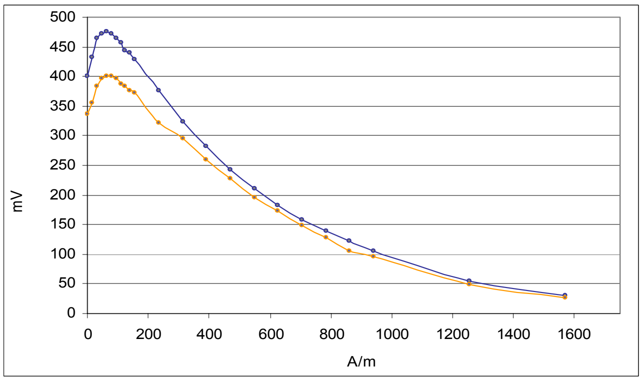

Fig. 9. hysteretic λ-H response in as-cast amorphous ribbon

3. DISCUSSION

The large coercive field variations observed during the experiments is a result of the dependence of the coercive field to the crystalline structure of the material. A fully crystalline material will have a large coercive field, as opposed to a completely amorphous one with the same composition. Various degrees of nano-crystallization fall in between in terms of coercive field value. The measurement of the coercive field with respect to length of the material is an indication of the crystalline structure of the material and can be used as a guide for further processing to obtain the required magnetic properties. Remanence magnetization and saturation magnetization are not affected so much from the crystalline structure, rather than the actual composition of the material. A stability in both remanence and saturation magnetization is expected from magnetic fibers or ribbons produced from the same mother alloy and is an indication of the composition for different runs comparisons. The crystalline structure is the main player in the λ(H) function of the material as well. It is responsible not only for the large variations in the λ(H) function along the length of a ribbon, but for the hysteretic effect observed in same samples. The presence of small nano-crystalline regions with different orientations can affect the response and induce a hysteric effect. A TEM microscopic examination of the material along its length in comparison to the obtained λ(H) data would be revealing of the actual correlation between crystalline structure and nano-crystalline region orientation to the magneto elastic response of magnetic ribbons.

As the description *amorphous metal* is subject to various estimations in respect to its meaning and the manufacturing techniques are not standardized for exact and repeatable results, a magnetic properties uniformity testing apparatus is deemed necessary, preferably at the manufacturing side, so that the end user can have accurate and detailed information for the material in question. The proposed device provides for a suitable means of magnetic and magneto elastic uniformity testing that can be installed both at the manufacturing side and the end-user side.

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