Study and characterization of soft magnetic materials for beam intensity monitors at CERN

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Abstract. At CERN, the circulating beam current measurement is provided by two types of transformers, the DC Current Transformer (DCCT) and the Fast Beam Current Transformer (FBCT). Each transformer is built based on toroidal cores made from a magnetic material. Depending on the type of measurement to be performed these cores require different magnetic characteristics for parameters such as permeability, coercivity and the shape of the magnetization curve. In order to study the effect of changes in these parameters on the current transformers, several interesting raw materials based on their as-cast properties were selected. The materials have been characterised to determine a suitable annealing processes to tailor their properties. As-cast properties such as the permeability, coercivity and Barkhausen noise have also been measured to enable the study of the effect of thermal treatment in the microstructure of the alloys, and the correlation of this with the change in the magnetic properties. The comparison of the measured properties have narrowed down the best materials for further study.

1. Magnetic materials for transformer cores at CERN

At CERN, the electric current of the charged particle beam circulating in the accelerators is measured by a family of devices that include current transformers, such as the DCCTs and FBCTs. This measurement is crucial for the correct operation of the accelerator complex and the experiments that it feeds, as well as for safety measures that rely on these readings.

Transformer cores are made out of a wound ribbon of soft magnetic material. The core couples to the magnetic field carried by the beam of charged particles as it traverses the transformer. Each type of transformer requires different magnetic characteristics in terms of permeability, coercivity and the shape of the magnetization curve. The choice of material affects the performance of the transformer, in particular in terms of the resolution in the case of the DCCT and the bandwidth in case of the FBCT.

Thermal or thermo-magnetic annealing can drastically change the magnetic properties of the raw materials used. The time and annealing heating rate are two key parameters that play a crucial role in the final result, enabling, for example, the fabrication of nanocrystalline materials. By adjusting these parameters the magnetic properties can be tuned in order to produce cores with different characteristics. Testing such cores as current transformers will then give an insight to the effect that different cores have on performance. By producing different cores and studying their behaviour it is possible to define the properties required to improve the characteristics of the instrument.
The magnetic material used at CERN was specified for making the instrument as sensitive as possible. In 1998, Kottman studied the effects of noise on performance and resolution [4]. Simulations indicated that the shape of the magnetisation curve, coercivity and noise influenced the operation of the transformers. However, no measurements of these effects were done on the instruments nor the raw materials to verify these results.

For the DCCTs, soft ferromagnetic material with a relative complex permeability of more than 50 000 has been used up to now. Other characteristics sought include low Barkhausen Noise, a coercive field of around 1 A·m⁻¹ and low magnetostriction. The coercivity limitation comes from the principle of operation, as the asymmetry in the B-H curve caused by the passing beam has to be detectable by the acquisition system. The magnetostriction effect produces changes in the size or shape of the core and can introduce noise if the cores are constrained [1].

2. Summary of materials used
For this study, the materials used were iron-based amorphous and nanocrystalline alloys and cobalt-based amorphous alloys. Two iron-based alloys were purchased from Qinhuangdao Yanqin Nano Science & Technology Co., Ltd., nanocrystalline 107A1 and amorphous 2065. Iron-based amorphous alloy FINEMET® FT-3 was bought from Hitachi Metals Europe GmbH. The amorphous cobalt-based materials were purchased from Nanostructured & Amorphous Materials (Nanoamor), Inc., VACUUMSCHMELZE GmbH & Co. KG as VAC 6025 G40 Z, and Hitachi Metals as alloy 2705M.

3. Material characterization
3.1. Permeability and B-H curve analysis
The relative complex permeability was calculated from the impedance measured with an Agilent Vector Impedance Analyser 4294 in the range of 40 Hz to 110 MHz. Cores of 40 mm of external diameter were used. The real and imaginary parts of permeability were derived from the in-series inductance and resistance of the core following [2]. The results are summarised in Table 1.

| Sample              | Permeability | Coercivity [A·m⁻¹] |
|---------------------|--------------|--------------------|
| Yanqin amorphous    | 1171         | 14.98              |
| Yanqin nanocrystalline | 697         | 19.43              |
| FINEMET FT-3        | 1219         | 14.37              |
| VAC 6025 G40 Z      | 165626       | 7.62               |
| Nanoamor            | 158110       | 4.47               |
| Metglas 2705M       | 250802       | 9.63               |

The high coercivity of the iron-based amorphous and nanocrystalline materials combined with their low permeability, practically rules them out as a suitable candidates for transformer cores, but does not mean that further annealing tests should not be performed on these materials to fully explore the potential magnetic properties that could be achieved by transforming the amorphous materials into nanocrystalline.

3.2. Barkhausen noise
The Barkhausen Effect is a physical phenomenon that manifests itself as a series of jumps in magnetization of ferromagnetic material when exposed to a varying magnetic field. Surrounding
the sample by a secondary coil, the induced voltage can be transformed into acoustic noise, from which the term Barkhausen Noise (BN) derives [3]. This effect is often used as a non-destructive test to check changes in micro structure (grain boundaries, dislocations, inhomogeneities, etc.) and stress configurations of materials, and offers a good overview of changes in magnetic domains.

It is interesting to study the effect of thermal treatment on BN and on the final transformer response. BN tests were performed recreating the setup described in [3] for all the materials, looking at the voltage induced in the secondary coil surrounding the sample while it is subjected to a triangular excitation. The response of the FINEMET sample can be seen in Figure 1, where it is shown that the BN drops to almost zero when the sample is saturated.

![Figure 1. Barkhausen Noise response of the FINEMET sample (top) and excitation voltage (bottom).](image)

Figures 2 to 7 show the BN (proportional to the secondary winding voltage) for all the materials. Once measured as cast, the samples where annealed for half an hour above their Curie temperatures before being re-measured. As can be seen, the BN decreases for Yanqin nanocrystalline and VAC 6025, while it increases for FINEMET. Yanquin amorphous, Metglas and Nanoamor show approximately the same noise level. Further XRD and magnetic domain visualisation studies of the annealed samples are being performed in order to understand these results, which may be caused by stress relaxation, dislocation displacement and crystal growth.

![Figure 2. BN for Yanqin nanocrystalline before and after annealing.](image)

![Figure 3. BN for Yanqin amorphous before and after annealing.](image)

4. Conclusions
The cobalt-based materials (VAC, Nanoamor and Metglas) have the highest permeability and lowest coercivity in their amorphous states and are good base materials. However, the
potential properties of nanocrystalline materials should be taken into account and therefore, the FINEMET material, which has the lowest coercivity and highest permeability of the iron-based materials, will be studied further to analyse the properties of the material in its nanocrystalline form.

References
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