# MAGNETIC MATERIALS FOR CURRENT TRANSFORMERS

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*Abstract*

At CERN, the circulating beam current measurement is provided by two types of transformers, the Direct Current Current Transformers (DCCT) and the Fast Beam Current Transformers (FBCT). Each type of transformer requires different magnetic characteristics regarding parameters such as permeability, coercivity and shape of the magnetization curve. Each transformer is built based on toroidal cores of a magnetic material which gives these characteristics. For example, DCCTs consist of three cores, two for the measurement of the DC component and one for the AC component. 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 with the annealing process used to tune their properties for the individual needs of each transformer. First annealing tests show that the magnetization curve, and therefore the permeability, of the material can be modified, opening the possibility for building and studying a variety of transformer cores.

## CURRENT TRANSFORMERS AT CERN

At CERN's accelerator complex, current transformers have been used to measure the beam's current since the 1960's. Nowadays, there are a total of 96 transformers out of which, 22 are DCCTs and 74 are FBCTs. There also exist 6 spares for DCCTs and 22 spares for FBCTs.

Currently, the oldest installed FBCT dates back to 1970 and the DCCT to 1982. There are also different sized transformers in order to adapt to the different vacuum chamber dimensions.

## MAGNETIC MATERIAL FOR TRANSFORMER CORES

DCCTs consist of three magnetic cores, one for the AC component of the signal and two for the DC, while FBCTs consist normally of only one magnetic core. These cores are made out of wound ribbon of soft magnetic material. The choice of material and its magnetic characteristics for current transformers affects the parameters of the transformer such as the resolution in the case for the DCCT.

The magnetic material in the transformers used at CERN was specified for making the instrument as sensitive as possible. For this, soft ferromagnetic material with a maximum relative complex permeability of more than 50 000 has been used. Other characteristics sought included low Barkhausen Noise, coercive field of around 1 A/m and low magnetostriction [1]. Typically, soft magnetic materials include permalloys (alloys with 80 % nickel and 20 % iron), amorphous alloys composed of about 80 % transition metals (mainly iron and/or cobalt) and 20 % metalloids (boron, silicon and carbon) and nanocrystalline alloys, with nanometer sized grains in an amorphous matrix [2].

The motivation for developing and manufacturing magnetic cores at CERN is driven by the interest of being able to make different sized cores in-house, to acquire the know-how for tuning the cores' magnetic properties and the influence of the magnetic material's parameters in the transformer response in order to improve the instrument's performance and resolution.

### *Influence of Material in Transformer Response*

The thickness of ribbons is known to affect the response of the transformer, as Eddy currents increase with it. For example, cores with different lamination thicknesses can be combined in a single transformer, making the rise time and initial decay in the first microseconds dependent on the core with the thinner lamination, and the time constant dependent on the mass of the core [3].

The power loss of the material is proportional to the area of the hysteresis loop. It is interesting to study the change in the losses with increasing magnetization frequency, produced by the damping from Eddy currents [2]. Losses are an important factor to take into consideration, as the magnetic core will heat up during operation. The maximum service temperature of the material (the limit temperature at which the material still has all of its characteristic properties) should be higher than the operational temperature the material will reach when the transformer is in use. In order to limit the temperature increase and the power loss dissipated in the material, insulation between layers is usually employed.

Insulation in cores can be done in several ways. The most common are producing tape wound cores with an insulator like Dupont™ Kapton® or using a ceramic to insulate the layers. The latter process can be done by means of the Sol-Gel method by immersing the ribbon into a solution that becomes ceramic after a thermal treatment [4].

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### *Shaping the Magnetization Curve*

For the different types of transformers, the requirements of the magnetization (B-H) curve are different. DCCTs require a round-shaped curve with a coercive field of about 3 A/m, whilst the FBCTs require more of a flat-shaped and low coercivity curve.

In order to change the shape of the magnetization curve, it is necessary to thermally treat the alloy (process defined as annealing). Depending on the desired final properties, the annealing must be conducted under a magnetic field in order to achieve the flatter B-H curves required by the FBCTs. It also should be taken into consideration that the adequate temperature to modify these properties should be above the Curie temperature and below the crystallization temperature to maintain its crystalline structure.

### *Barkhausen Effect*

The Barkhausen Effect is a physical phenomenon which is manifested 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 [5].

This effect is often used as a non-destructive test to check changes in microstructure (grain boundaries, dislocations, inhomogeneities, etc.) and stress configurations of materials. It is because of this, that this technique offers a good overview of changes in magnetic domains.

It is clear that the BN influences the transformer performance and its resolution [6], therefore it is an interesting characteristic to study to see the effect of the thermal treatment on the BN and then on the instrument's response.

### *Summary of Materials Used*

For this study, the materials used were iron-based amorphous and nanocrystalline alloys and cobalt-based amorphous alloys. The iron-based alloys were purchased from Qinhuangdao Yanqin Nano Science & Technology Co., Ltd (http://www.yanqin.com), and the Cobalt-based were purchased in Nanostructured & Amorphous Materials (Nanoamor), Inc. (http://www.nanoamor.com), Vacuumschmelze GmbH & Co. KG (http://www.vacuumschmelze.de) as VC 6025 G40 and Hitachi Metals Europe GmbH (http://www.metglas.com) as 2705M.

As can be seen from Table 1, iron-based alloys have a higher Curie temperature than cobalt-based alloys.

Table 1: Materials Summary

| Type | Curie temperature [°C] | Crystallization temperature [°C] |
|---|---|---|
| Iron-based Amorphous | 420 | 560 |
| Iron-based Nanocrystalline | 560 | 510 |
| Nanoamor | 205 | 420 |
| VAC 6025 G40 | 225 | - |
| Metglas 2705M | 365 | 520 |

## TESTS

### *Barkhausen Noise*

Barkhausen Noise tests were performed following the setup described in [5] for all the materials, but using a triangular current for the driving solenoid.

Figure 1 shows a comparison of the BN for cobalt-based amorphous materials. What can be seen is the voltage induced in the secondary coil surrounding the magnetic sample while it is subjected to the triangular current. Time zero indicates when the pulse's value is zero volts. As can be seen, most of the BN occurs around this region, and drops to zero when the sample is saturated. It has been observed that there is not a significant difference between them.

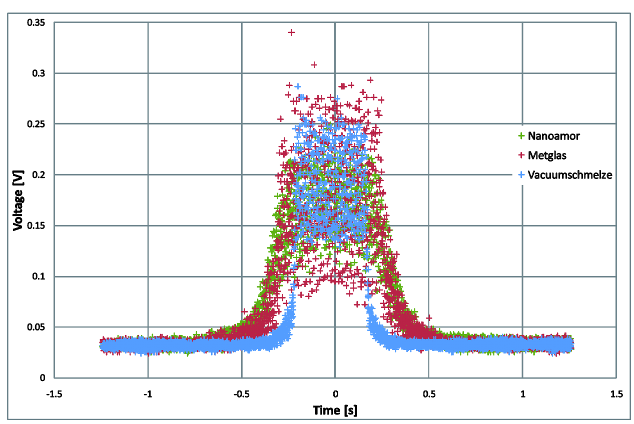


Figure 1: Barkhausen Noise response for amorphous cobalt-based materials (Nanoamor in green, Metglas in red and VAC in blue).

However, Figure 2 shows the difference between the iron-based amorphous and nanocrystalline and the Vacuumschmelze materials. As can be seen, the iron-based materials present a lot more BN than the other sample and does not completely reach saturation as the



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VAC material, which can be observed from the existence of BN throughout the measurement. This means that the samples with more and higher BN signal will have an undesirable effect on the transformer's performance and should be a factor to take into account when choosing the core's material.

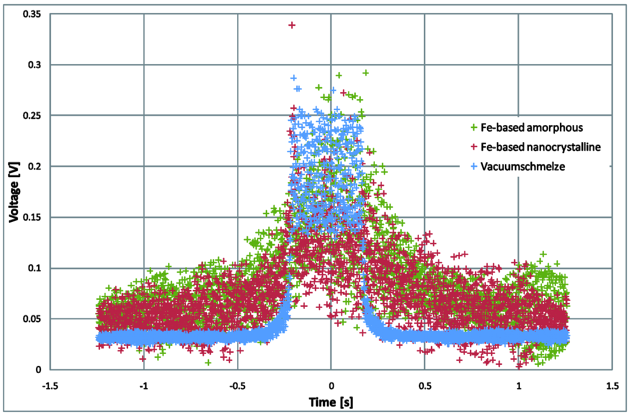


Figure 2: Barkhausen Noise response for iron-based amorphous alloy in green, iron-based nanocrystalline alloy in red and VAC 6025 in blue.

### *Magnetic Properties*

In order to measure the magnetic properties of the materials, an impedance analysis and a study of the B-H curve was performed. The impedanec of the sample were measured and permeability was calculated from the inductance of the measurement. For this purpose, cores of external diameter of 45 mm and section of 10 mm x 10 mm were wound for testing. Table 2 shows the maximum permeability measured for each material.

Table 2: Permeability Summary

| Type | Maximum relative complex permeability |
|---|---|
| Iron-based Amorphous | 2650 |
| Iron-based Nanocrystalline | 4200 |
| Nanoamor | 134 000 |
| VAC 6025 G40 | 64 000 |
| Metglas 2705M | 173 000 |

As can be observed, the iron-based alloys have a too low permeability to be considered as good candidates for transformer cores. The cobalt-based materials would therefore be the most suitable to use.

Figure 3 shows the B-H curve at 200 Hz for the iron-based alloys. Coercivity is extremely high (almost 20 A/m). This, combined with the low permeability of the material, practically rules it out as a suitable candidate for transformer cores. This does not mean, however, that further annealing tests should not be performed on these materials to fully explore the potential magnetic properties that could be achieved.

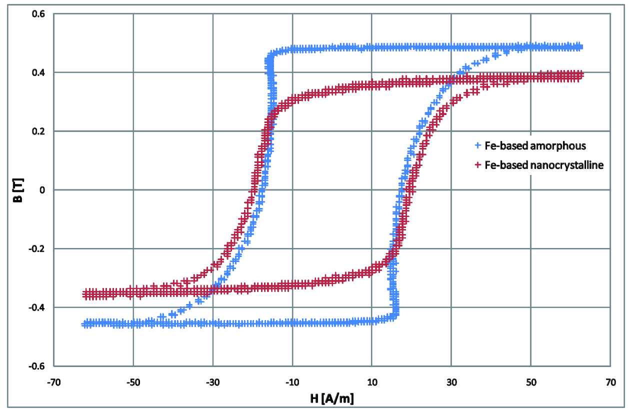


Figure 3: B-H curve for iron-based nanocrystalline in red and iron-based amorphous alloys in blue.

### *Annealing Tests and Measurements*

First annealing tests were performed under vacuum at 250 degrees Celsius during one hour. A Sol-Gel solution was poured over the cores in order to create an insulating layer of magnesium oxide (MgO) as described in [4]. Before and after the treatment, magnetization curves were measured at 200 Hz from wound toroids. This measurement also enables the calculation of the maximum permeability and has been used to cross-check the one calculated by impedance analysis.

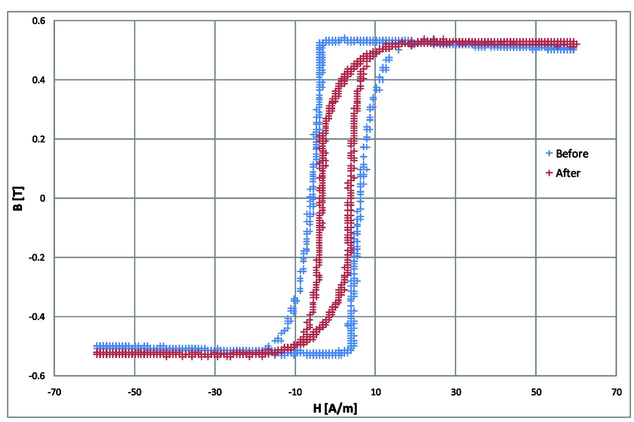


Figure 4: B-H curve before (in blue) and after annealing (in red) for VAC 6025.

As can be seen on Figure 4, the annealing has a "rounding effect" on the B-H curve, with an increase in the maximum permeability of the core. Similar changes were observed for the Nanoamor alloy, although the change in the shape of the alloy decreased the maximum permeability.



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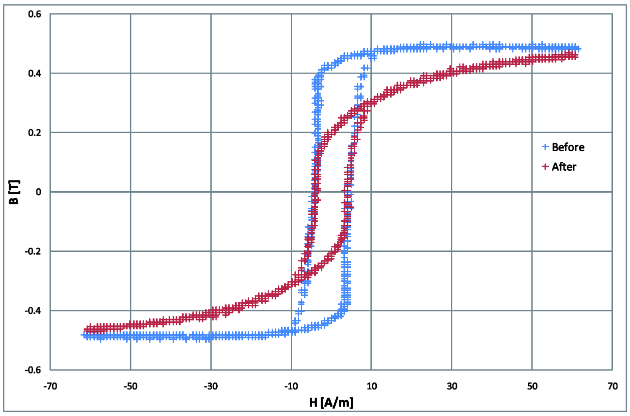


Figure 5: B-H curve before (in blue) and after annealing (in red) for Nanoamor.

The study on the insulation proved that the technique used to create the MgO layer was not good enough and there was no significant difference between the non-insulated and the insulated cores. The technique to use the Sol-Gel method should therefore be researched further and be compared to the insulation given by Dupont™ Kapton®.

## CONCLUSIONS AND OUTLOOK

The iron-based alloys (both amorphous and nanocrystalline) have a maximum complex relative permeability which is too low for the characteristics sought and a coercive field which is too high. The tests performed so far on the cobalt-based materials show good potential characteristics in order to make full cores for CERN's current transformers.

With three very good candidates, the annealing process should be further studied in order to verify how the different B-H curve shapes affect the response on the transformers. In addition to this, the insulation should be further studied, by improving the Sol-gel method technique and comparing to Dupont™ Kapton® insulation. Both annealing possibilities, with magnetic field and conventional heating, should be studied in order to achieve the best magnetic properties for each transformer.

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## REFERENCES

[1] P. Odier, DCCT Technology Review, Workshop on DC Current Transformers and Beam-Lifetime Evaluations, Lyon, p. 3, December 2004, http://inspirehep.net/record/672655
[2] G. Bertotti, *Hysteresis In Magnetism*. (San Diego: Academic Press 2008)
[3] K.Unser, Beam Current Transformer with DC to 200 MHz Range, Particle Accelerator Conference, Washington D.C., (1969)
[4] S.H. Lim et al., Effects of Surface Coating by Sol-Gel Process on the Magnetic Properties of a Co-Based Amorphous Alloy. IEEE Transactions on Magnetics 13, N. 6, (1995)
[5] D. Spasojevic, S. Bukvic, S. Milosevic and H.E. Stanley, Barkhausen noise: Elementary signals, power laws, and scaling relations. The American Physical Society 54, (1996)
[6] P. Kottman, Theoretical and Experimental Investigation of Magnetic Materials for DC Beam Current Transformers. PS/BC/Note 97-06



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