Experimental measuring, theoretical modeling and simulations of ferromagnetic materials made by means of additive manufacturing

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The aim of this doctoral project is the experimental measurements, theoretical modeling and simulations in FEM software of ferromagnetic materials, mainly Fe-Si alloys, made by means of Additive Manufacturing (AM) – Laser Powder Bed Fusion (LPBF) to be used as components for many applications and in particular as magnetic cores for electric motors.

Additive Manufacturing

Nowadays one of the most interesting research field for the enhancement of magnetic components made by Fe-Si alloys is the additive manufacturing (AM) as building process, in particular Laser Powder Bed Fusion (LPBF).

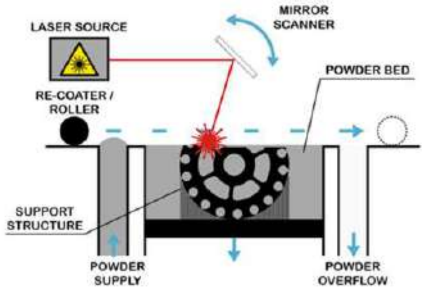

Figure 1: LPBF process summary.

There are several advantages in the use of this technology in comparison with the traditional ones:

- Very complex geometries can be realized for machines with 3D magnetic flux paths.
- The magnetic powder can be obtained directly from ferromagnetic scraps.
- The Si % can be more than double in comparison with traditional techniques.

The last point is very important since the more Si we have, the less conductivity and power losses by eddy currents we have in the material, and that is desirable in a magnetic core. The best performances can be obtained with a Fe-Si with 6.5% wt. Si, almost exclusively made by AM.

On the other hand, materials made by AM exhibit different characteristics with respect to those same materials made with the standard industrial techniques and that affect the magnetic behaviour, so it is very important to study them, starting from the experimental characterization.

Experimental Measurements

Toroidal samples are realized by AM.

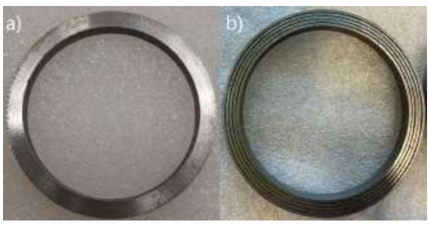

Figure 2: a) full section toroid, b) partial section toroid.

They can also have a partial geometry with air gaps to limit eddy currents. The measurements are made using the Volt-Amperometric setup.

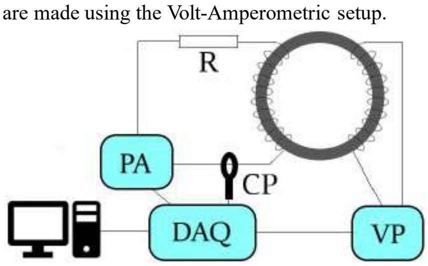

Figure 3: Volt-Amperometric experimental setup.

Feeding a known current to the primary (excitation) coil and measuring the voltage over the secondary (pick-up) coil, by respectively the Ampere's and the Faraday-Neumann-Lenz' laws we can derive the values of the magnetic field H and of the magnetic induction field B.

$$B(t) = \frac{1}{N_2 S}\int_0^t v(t')dt' ; \qquad H(t) = \frac{N_1 i(t)}{l}.$$

$N_{1/2}$ = primary/secondary coil turns, S = section area, l = mean length, $i(t)$ = exciting current, $v(t)$ = induced voltage.

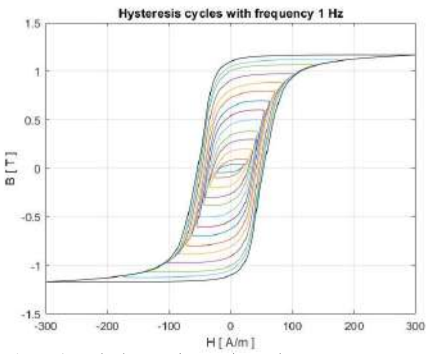

Figure 4: Scalar hysteresis experimental measurements.

Theoretical Modelling

From the experimental data measured at 1 Hz we can calibrate phenomenological models to reproduce the magnetic behaviour of the material.

Jiles-Atherton (JA) model: computes the magnetic induction B = μ₀[H + M(H)] as a response of an exciting magnetic field H, where the relationship between the magnetization M and the magnetic field H is given by the following

$$H_e = H + \alpha M;$$

$$M_{an} = M_s\left[\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}\right];$$

$$\frac{dM}{dH} = \frac{M_{an} - M + ck\delta\frac{dM_{an}}{dH}}{k\delta - \alpha(M_{an} - M)};$$

Artificial Neural Networks (ANN): we apply machine learning (ML) to magnetism splitting the experimental dataset in a training set, to train the ANN, and a test set, to validate its predictions, respectively of 80% and 20% of the original dataset. The ANN is usually designed with 3 hidden layers as in the architecture in Fig. 5.

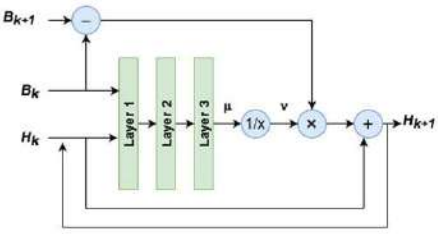

Figure 5: ANN architecture.

The non-linear activation function is as follows

$$f_{act}(x) = \frac{2}{1+e^{-2x}} - 1.$$

Simulations

Finite Element Method (FEM): to simulate finite materials with well-defined geometries we must use FEM software, in our case usually COMSOL® Multiphysics. We simulate the material in frequency using models identified in the quasi-static case (1 Hz) and compare them with the measurements in frequency to validate the results.

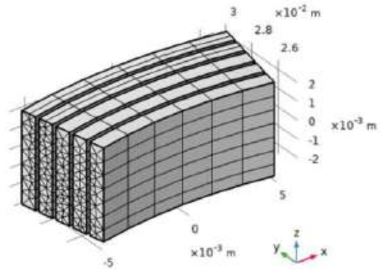

Figure 6: mesh of a partial section toroid with air gaps.

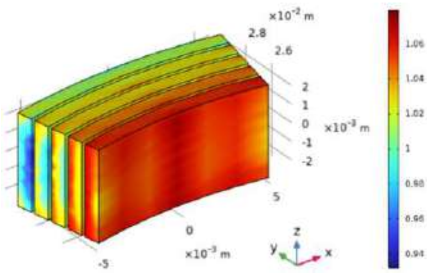

Figure 7: simulation of the distribution of the induction field in a Fe-Si 3.7% wt. Si toroid at a given time step.

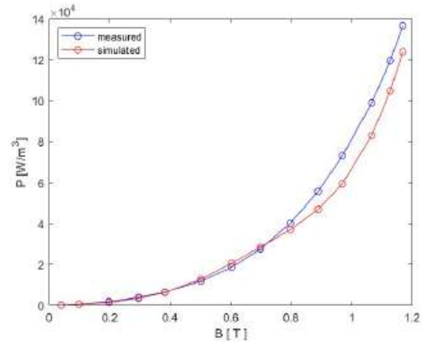

Figure 8: Comparison of simulated and measured power losses of a full section toroid made by AM using ANN.

Applications

CubeSat: The FEM simulations with the identified theoretical models were used to simulate the losses of hysteresis rods that will be made by AM and used to stabilize the orbit of the satellite CubeSat. The oscillation of the geomagnetic field in the rods leads to hysteresis and energy losses at cost of the kinetic energy of the satellite. The simulations were used to find the diameter which yields the maximum losses, given the maximum length of 5 cm that could fit the rod in the CubeSat.

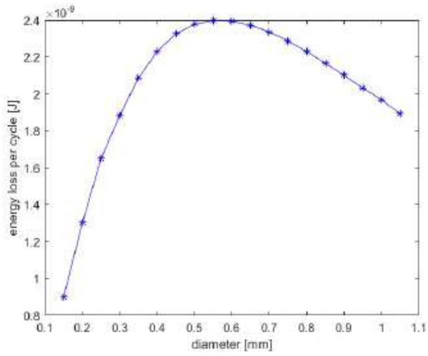

Figure 9: simulation of energy loss per cycle in hysteresis rods as a function of the diameter.

References

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[2] V. Bertolini, M. Stella and R. Scorretti, "Circuit Modelling of Static Magnetic Losses of Ferrite Cores and Application on an LLC Converter," *IEEE EUROCON 2023 - 20th International Conference on Smart Technologies*, Torino, Italy, 2023, pp. 429-433, doi: 10.1109/EUROCON56442.2023.10198989.

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