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Study of the magnetic flux density distribution of nickel coated aluminum foams

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Abstract. Open cell aluminum foams are metal cellular structures with a large volume fraction of pores. Due to their high stiffness to weight ratio, they are commonly used in applications for energy absorption and mechanical damping. The stiffness of the aluminum foam was increased by a nanocrystalline nickel coating via an electrodeposition process. The deposition process and thus the coating thickness strongly depend on mass transport limitations. To visualize the coating thickness distribution of the foam, we measured the magnetic flux density distribution by scanning the surface of cuts of coated foams with a commercial Hall probe. By measuring the magnetic flux density distribution, deposition parameters as the current density and flow conditions could be optimized with regard to a more homogeneous coating thickness distribution. Furthermore, a model of the mass transport limitation at a complex three dimensional foam electrode could be evaluated from the magnetic flux density distribution of the nickel coated foam cuts.

1. Introduction
Metal foams are metal cellular structures containing a large volume fraction of gas-filled pores. They are a relatively new class of materials, which has been developed for applications in lightweight structures. They offer low densities and, due to their high stiffness to weight ratio, they show potential for energy absorption and mechanical damping [1].

Coating of metal foams with nickel by electrodeposition [2, 3] increases the stiffness and energy absorption capability of the foams. The coating of such complex three dimensional electrodes strongly depends on mass transport limitations. There will be a non-uniform coating thickness distribution from the outer site to the centre of the foam. To improve the coating process, a procedure for scanning the metal distribution of the foams, in analogy to the studies of inhomogeneities in the flux density distribution of superconductors, has been evaluated for giving information about the coating thickness distribution of the foams.
2. Experimental procedure
Cubic aluminum foams with a pore size of 10 ppi (pores per square inch) were coated with nickel via direct current plating using a nickel sulfamate electrolyte at a temperature of 50°C. In the plating process, the foam acted as cathode and was placed in the center of a double walled cage like anode, filled with nickel pellets as sacrificial anode.

Nickel coated aluminum foams were cut into rectangular plates. On each plate, the metal distribution on the foam plates has been determined by measuring the remanent magnetic flux density distribution by scanning the surface of the foam with a commercial Hall probe (Arepec, Bratislava); similar to the field scan of bulk high-$T_c$ superconductors [4]. Figure 1 shows a schematic drawing of the setup for scanning the magnetic flux density distribution and an image of an uncoated 10 ppi aluminum foam. It consists of an $x$-$y$-$z$-table with a holder on which the Hall probe is attached. The foam plates are placed in the center of a rectangular area of $120 \times 120$ mm$^2$. For scanning, a step size of 2 mm was selected in $x$- and $y$- direction. The distance between the probe and the sample surface was about 1.5 mm.

To force a defined initial magnetic state on the foam plates, each foam has been magnetized with a homogeneous magnetic field of 256 mT by placing the foam cuts into a Helmholtz coil before the scanning.

![Figure 1: Schematic drawing of the measuring setup and image of a 10 ppi aluminum foam.](image)

Foams electrocoated at different current densities and under different flow conditions have been investigated to improve the homogeneity of the coating thickness and to optimize the coating parameters.

3. Results and discussion
Figure 2 shows the maximal relative magnetic flux densities of each cut of the cubic foams with an edge length of 40 mm which were coated at different current densities normalized by the magnetic flux density at the bottom of the complete foam and the scans of the magnetic flux density for a foam coated at 1 mA/cm$^2$. If the coating were homogeneous, each cut would have a coating thickness of 20 μm. The cuts had a thickness of 10 mm. At higher current densities, there is a bigger decrease of flux density from the outer to the inner parts of the foam. With increasing current densities, for each cut, the flux density reaches a nearly constant value. This might be due to the limited diffusion of metal ions during the electrodeposition process. So, the decrease of the flux density to the inner foam cuts is forced by the decrease of the limiting diffusion current from the outer surface to the centre of the foam.

Based on these results, there should be a direct proportionality between the magnetic flux density and the limiting diffusion current and thus the metal ion concentration of the electrolyte in the foam structure. So, the magnetic flux density should be proportional to the coating thickness distribution of
the foam via the limiting diffusion current: magnetic flux density $\propto$ limiting diffusion current $\propto$ metal ion concentration $\propto$ coating thickness.

Figure 2: Relative magnetic flux density of cuts of nickel coated foams (left) and scans of the magnetic flux density distribution of a foam coated at 1 mA/cm²(right).

(cut (1): outer surface top; cut (3): inner surface; cut (5): outer surface bottom)

Based on these assumptions, increasing the limiting diffusion current will enhance the homogeneity of the coating thickness distribution of the foams. The limiting diffusion current has been increased by increasing the flow of the electrolyte through the foam. An increased electrolyte flow has been realized by pumping the electrolyte through the foam during the coating process.

Table 1 shows the magnetic flux densities of foams coated at current densities of 1 and 20 mA/cm² with and without pumping. The cut 3 defines the values at the center of the foam. Increasing the flow intensity of the electrolyte enhances the homogeneity of the magnetic flux density distribution and so the coating thickness distribution both at low current densities and at high current densities. In comparison to the flux densities without pumping, at higher current densities, there is a bigger enhancement effect but the absolute values are already lower than at low current densities.

Table 1 Relative magnetic flux densities [%] of nickel coated foams with and without an additional electrolyte flow by pumping.

|                | 1 mA/cm² | 1 mA/cm² with pump | 20 mA/cm² | 20 mA/cm² with pump |
|----------------|----------|---------------------|-----------|---------------------|
| cut 1          | 92,1     | 98,7                | 88,4      | 91,2                |
| cut 2          | 75,7     | 86,8                | 37,2      | 46,1                |
| cut 3          | 55,5     | 61,3                | 31,3      | 44,0                |
| cut 4          | 85,7     | 77,8                | 55,6      | 60,2                |
| bottom         | 100      | 100                 | 100       | 100                 |

To have a closer look on the deposition mechanism and the concentration of metal ions during the deposition in the foam, a nickel coated cubic foam (without pumping) with an edge length of 50 mm has been cut into plates with a thickness of 5 mm and the magnetic flux density of the cuts was scanned. Figure 3 shows the relative magnetic flux density as a function of the foam thickness progressing from the outer surface to the centre of the foam. The measured values have been properly fitted according to eq. (1).
The decrease of the flux density from the outer surface to the center of the foams increases with the distance from the foam surface and finally comes to a saturation point. This result shows, that without an enhancement of the electrolyte flow through the foam, even at low current densities, there would be a non-uniform coating thickness distribution. To enhance the homogeneity of the coating thickness, an enhancement of the hydrodynamic conditions of the electrolyte during the deposition is necessary.

Figure 3 Behavior of the magnetic flux density from the outer surface to the centre of a nickel coated foam cube with an edge length of 50 mm.

Figure 4 Behavior of the metal concentration in the electrolyte during the electrodeposition on a complex three dimensional foam cathode.

\[ y = A_1 \cdot \exp \left( -\frac{x}{t_1} \right) + A_2 \cdot \exp \left( -\frac{x}{t_2} \right) + y_0 \]  

(1)

Figure 4 shows a model to describe the results. The model is based on a superposition of Helmholtz layers \( \delta_n \) with increasing layer thickness towards the centre of the foam. With increasing distance to the bulk electrolyte, the concentration gradient between the Helmholtz layers becomes smaller. A possible explanation is, that the metal ions will be abruptly deposited at the outer surface. This repeats at each Helmholtz layer up to the centre of the foam. Due to the big decrease of the concentration of the metal ions, the concentration gradient towards the foam centre lowers more and more. At the limiting diffusion current, the concentration at the foam centre might be zero.

4. Conclusions
Scanning the magnetic flux density of foam cuts is an easy method to determine the coating thickness distribution of the foams coated with a magnetic material. The coating thickness distribution strongly depends on the limiting diffusion current. The homogeneity of the coating thickness can be improved by low current densities and an enhanced electrolyte flow through the foam during the deposition process. A model to describe the concentration as a function of the distance to the centre of the foam based on a superposition of Helmholtz layers with increasing layer thickness from the outer surface to the centre of the coated foam is presented.

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