Additive manufacturing of pure copper electromagnetic coils

CCAMA

Executive Summary Report

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1. Background

Electromagnetic coils are used as actuator coils in various space applications, such as magnetic bearings, axial electrical motors, or solenoid valves. New geometric shapes for electromagnetic coils can be realised using additive manufacturing (AM) processes. Conventionally, metal coils are produced using winding processes which are very restrictive with respect to the coils' shape, i.e., circular core or air core coils are usually used. The design freedoms offered by AM processes enable the production of coils with complex shapes to generate dedicated magnetic field shapes.

A first GSTP study on AM of metal coils demonstrated that AM of aluminium alloy coils was beneficial. Compared to aluminium, copper alloys and especially pure copper are characterized by significantly better electrical conductivity which is an important factor for the performance of electromagnetic coils. Whereas, pure copper could not be processed by AM until recently, several AM processes for AM of pure copper are now available. However, the state-of-the-art of copper AM is still largely focussed on parameter set development and manufacturing of dense and high electrically conductive samples, instead of applications. The focus of this activity was to take advantage of the state-of-the-art, but transfer the existing know-how into a space application.

2. Objectives

The main objective of the activity was the development of an end-to-end AM process for pure copper electromagnetic coils. The most suitable of the available AM processes for processing of pure copper was to be selected based on an AM processes benchmark. The end-to-end AM process was supposed to include not only the AM processing itself, but also pre- and post-processing steps as well as validation, such as feedstock validation, surface treatment, and non-destructive inspection.

The end-to-end process was to be validated on a demonstrator for which an electromagnetic coil for application in magnetic bearings was selected. The objective of the coil was to generate a volcano-shaped magnetic field which shall guide the rotor of a magnetic bearing. The dedicated magnetic field shape required a specific coil geometry which was not manufacturable by conventional, but additive manufacturing processes.

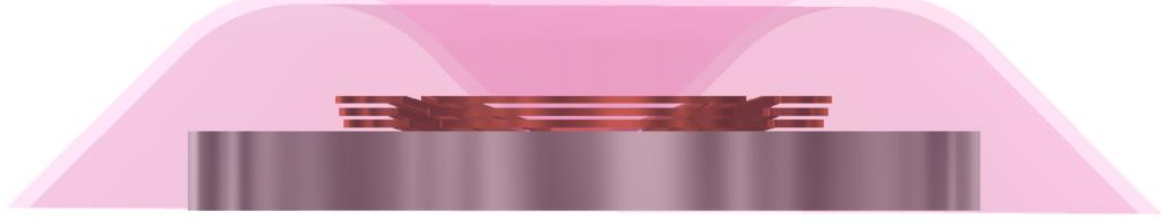

Figure 2-1: Targeted volcano-shaped magnetic field

3. METHODS / PROGRAMME OF WORK

Based on a state-of-the-art analysis performed at the beginning of the activity, commercially available AM process for processing of pure copper were compared in a process benchmark. For this benchmark, two coil geometries were ordered at different suppliers. The first geometry was developed in a previous aluminium AM coil activity and used as benchmark geometry for comparison between the more sophisticated aluminium L-PBF process and copper AM processes. The other benchmark geometry was a cycle segment coil based on the first design of the magnetic bearing coil. The main criteria for the evaluation and ultimately selection of the AM process for the remaining manufacturing tasks within the activity were geometric accuracy and electrical conductivity.

For the selected AM process, the end-to-end AM process was defined and validated on samples and prototypes level. Samples were used to characterise the material's density, tensile strength, but also functional characteristics, such as thermal and electrical conductivity. Prototypes based on the preliminary demonstrator coil design with a reduced number of windings were manufactured and post-processed to test individual process steps, such as support removal and blasting as well as non-destructive-inspection.

The activity concluded with the manufacturing and testing of a demonstrator coil to verify its critical functions. Environmental testing was performed to ensure that the functionalities were not affected by exposure to a relevant environment.

4. KEY RESULTS

Laser powder bed fusion (L-PBF) with a green laser source was selected for AM processing of pure copper to produce electromagnetic coils. In the performed AM processes benchmark, it was the process with the best trade-off between geometric accuracy and electrical conductivity.

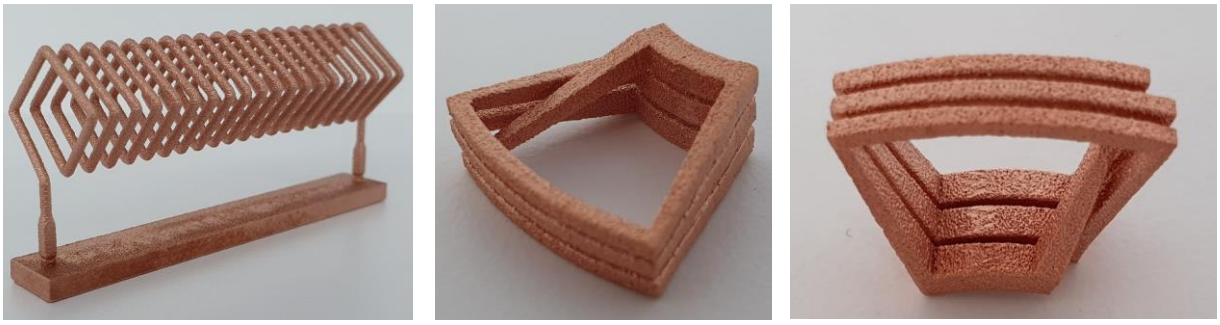

Figure 4-1: Benchmark geometries produced by L-PBF with green laser source

An end-to-end AM process chain for processing of pure copper for electromagnetic space applications was specified and tested on samples, prototypes, and demonstrator level. It consists of pre-processing steps, L-PBF processing, AM-related post-processing steps as well as application-related post-processing steps.

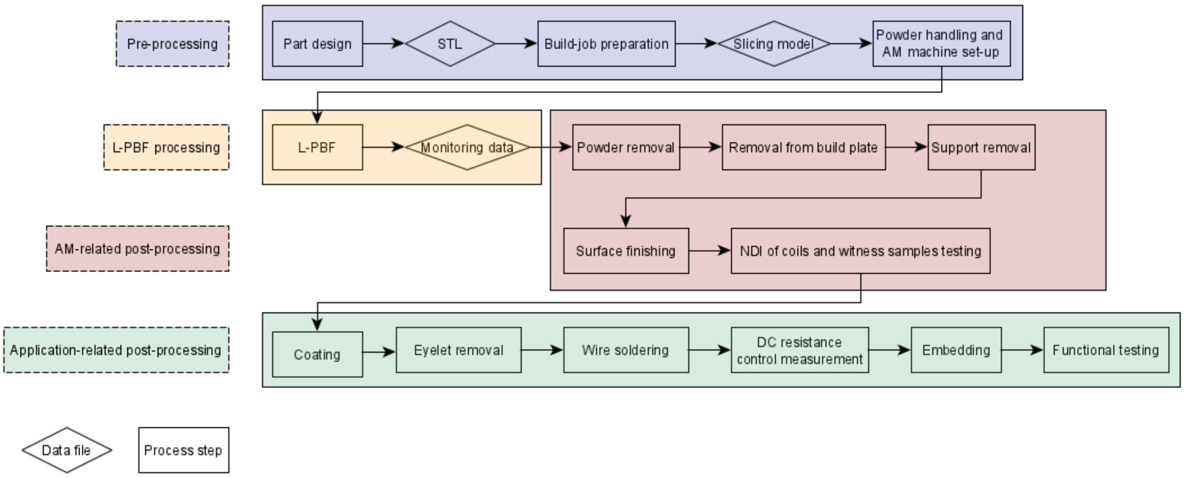

Figure 4-2: End-to-end AM process for the production of pure copper electromagnetic coils

The process was validated with a material characterisation on sample level. High relative density up to 99.99% and electrical conductivity of >98 %IACS was achieved. NDI of coil prototypes with a reduced number of windings revealed a porous molten particle surface layer around the inner dense volume of each winding. The dense volume diameter was smaller than the targeted winding diameter by the layer thickness of this porous surface layer. Reduction of the beam compensation and an increase of the laser power in the outer contour parameter set resulted in an increase of the inner volume diameter of 0.12 mm. The porous molten particle surface layer was not affected by the parameter improvement and remained the restricting factor for increasing the winding diameters to achieve a higher fill factor.

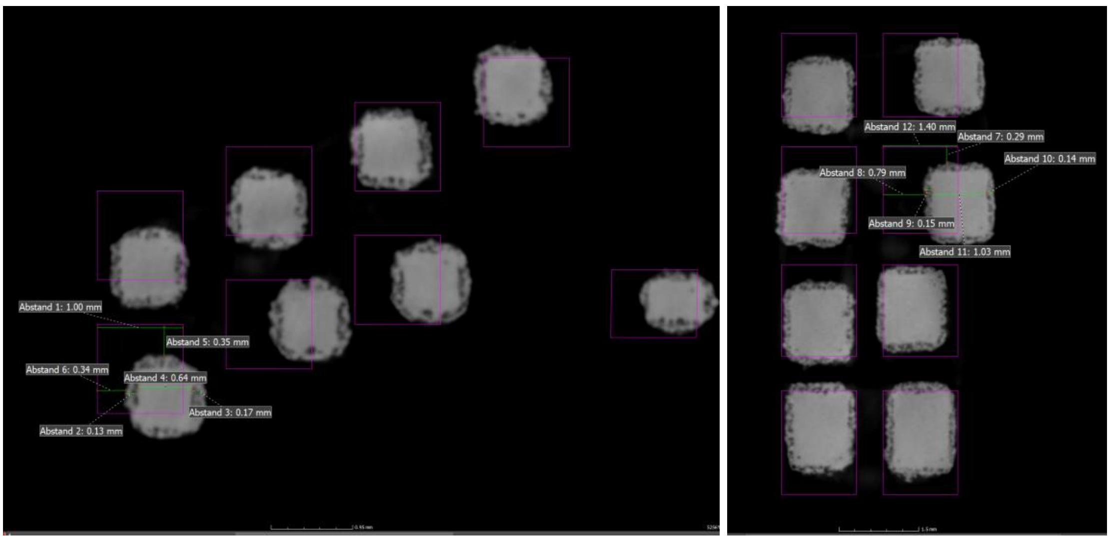

Figure 4-3: Dense volume size and porous molten particle surface layer around windings of prototype

Demonstrator coils were successfully manufactured according to the specified end-to-end AM process using the improved parameter set. Their critical functions, i.e., electrical and magnetic characteristics, were tested before and after environmental simulation. The specified requirements were met, the targeted magnetic field shape was generated by the coil, and environmental simulation did not have a significant effect on its performance data.

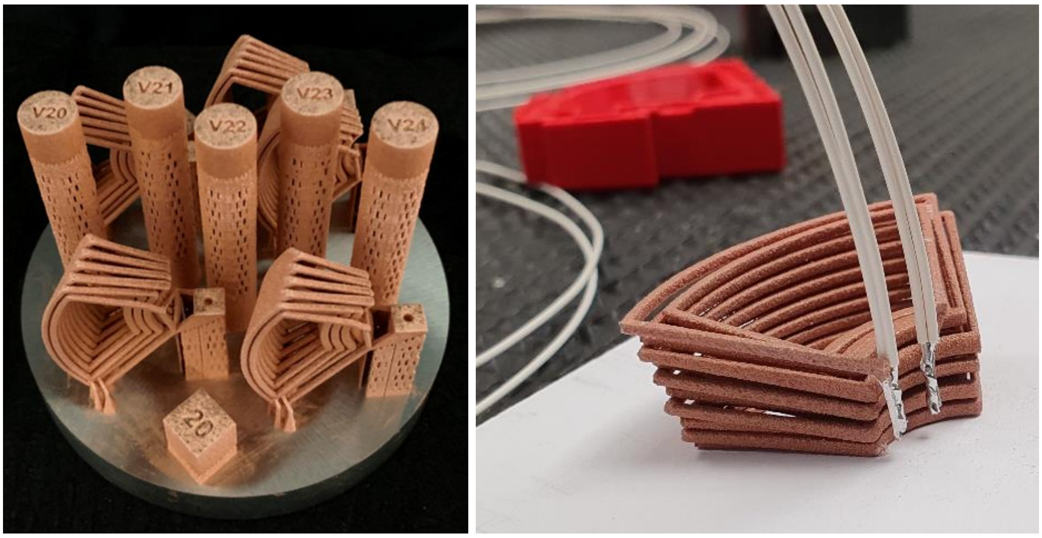

Figure 4-4: Demonstrator coils on the build platform (left) and coil after post-processing (right)

5. CONCLUSION

The results of the presented activity are a building block in the development of a low-vibration magnetic bearing for application in Earth Observation (i.e., high resolution or SAR) and Astrophotography missions. Using additive manufacturing to produce an electromagnetic coil, the targeted magnetic field shape was achieved due to the complex geometry of the coil which would not have been manufacturable using conventional processes.

Even though the specified requirements for the magnetic bearing coil were fulfilled, there remain some open points for further development and improvement:

To industrialise the AM of copper electromagnetic coils and specifically AM of the developed magnetic bearing coil, the end-to-end process needs to be qualified together with a commercial service provider. Additional tests on sample level are required to establish a fully qualified process according to ECSS-Q-ST-70-80C.

The magnetic bearing coil is only one component in the stator unit of the targeted magnetic bearing development. The increase the magnetic field strength, a magnetic core shall be placed inside the coil. The interdependencies of core and coil have to be investigated. The core coil then has to be integrated with a base plate, permanent ring magnet, power unit, and sensors to form the stator.