

# CHART Scientific Report (Final Report for Phase 2)

---

## Additive Manufacturing for Structural Components in Superconducting Coils

### CHART MagAM

PSI:

Dr. Bernhard Auchmann  
Dr. Douglas Martins Araujo  
Dr. André Brem

ETH Zürich / inspire:

Prof. Dr. Mirko Meboldt  
Dr. Julian Ferchow  
Patrick Beutler  
Aurel Schüpbach  
Prof Dr. Theo Tervoort  
Pascal Studer

30.06.2024



---

*Figure 1 Segment of a metal additive manufactured CCT winding former.*

## 1. Introduction / Original goals of this project

Nb<sub>3</sub>Sn-based coils of superconducting accelerator magnets are impregnated along with their structural components (wedges, endspacers, winding formers, etc.). The adhesion and force transmission between the impregnated winding and the structural parts is a potential weak point, often linked to excessive training of Nb<sub>3</sub>Sn magnets. Metal Additive Manufacturing (AM) can produce highly complex structures such as the winding formers of canted-cosine-theta coils (CCT). At the same time, functionality can be enhanced for increased adhesion and force transmission, thus contributing to improved magnet performance. This project aims to integrate these potential benefits into superconducting accelerator magnets.

## 2. Realisation

### Experimental Investigation

The project initially began by exploring the adhesive properties of structured adherends integrated with epoxy resin. Experimental studies of different bonding structures were conducted to evaluate the mechanical bonding strength at both ambient and cryogenic temperatures. The designs included metal foam structures with capillary action, milled surfaces, and lattice structures such as octet trusses without horizontal elements and TPMS Gyroid structures. These configurations aimed to enhance the impregnation process and improve the tensile and shear strength of bonds which is crucial for the longevity and reliability of superconducting coils.

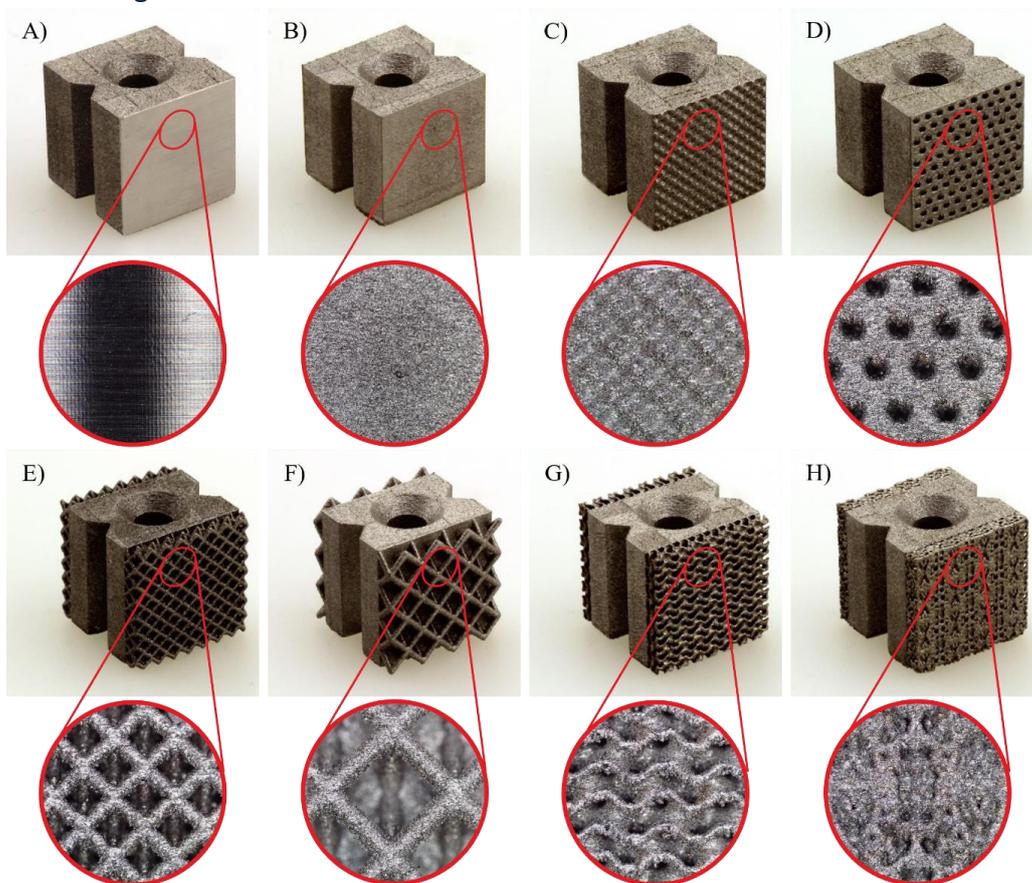


Figure 2 Compressive shear sample designs for the explorative study: A) Milled, B) Plain, C) sinusoidal dimples, D) Undercut, E) octet structure w/o horizontal trusses, F) large octet structure w/o horizontal trusses, G) gyroid, H) irregular

## Digital Workflow and Hybrid Manufacturing

A design automation for the creation of irregular adherend structures was created, to test their effect on the performance of powered superconducting samples under realistic conditions. Since these bonding experiment samples (BOX) are too large for commercial PBF-LB printers, the design was adapted for hybrid a manufacturing strategy, combining machining and additive manufacturing and followed by joining through electron beam welding.

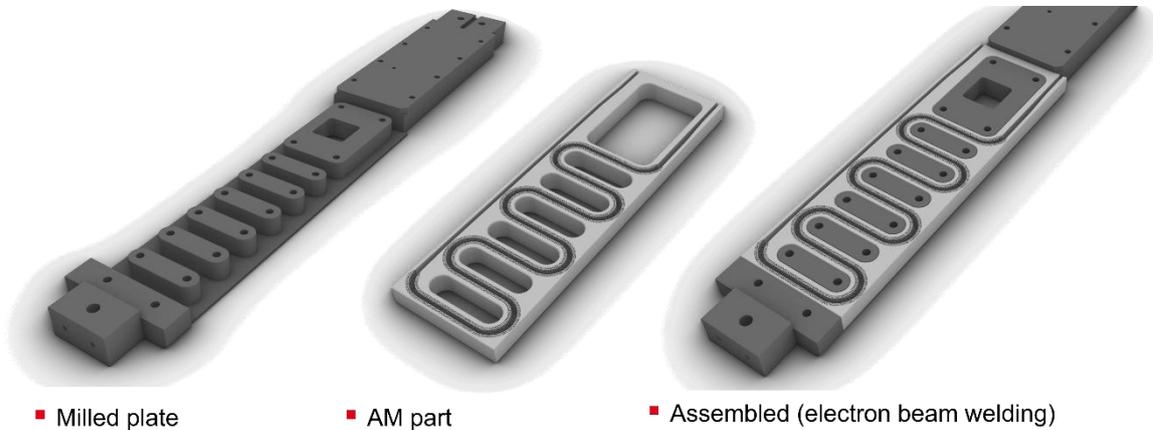


Figure 3 Design of hybrid manufactured BOX sample with the milled plate and the AM part that contains the channels.

## Simulation and Verification

Extensive Finite Element Analysis (FEA) was used to simulate the adhesive joints and evaluate stress distributions across different bonding structures. Although initial simulations suggested enhanced performance, subsequent physical testing did not always confirm these results, highlighting the complexities of accurately predicting real-world behaviors in AM processes and the exact boundary conditions between the adhesive and the adherend. This led to a shift in the project to further explore the advantages of AM in superconductive coil design.

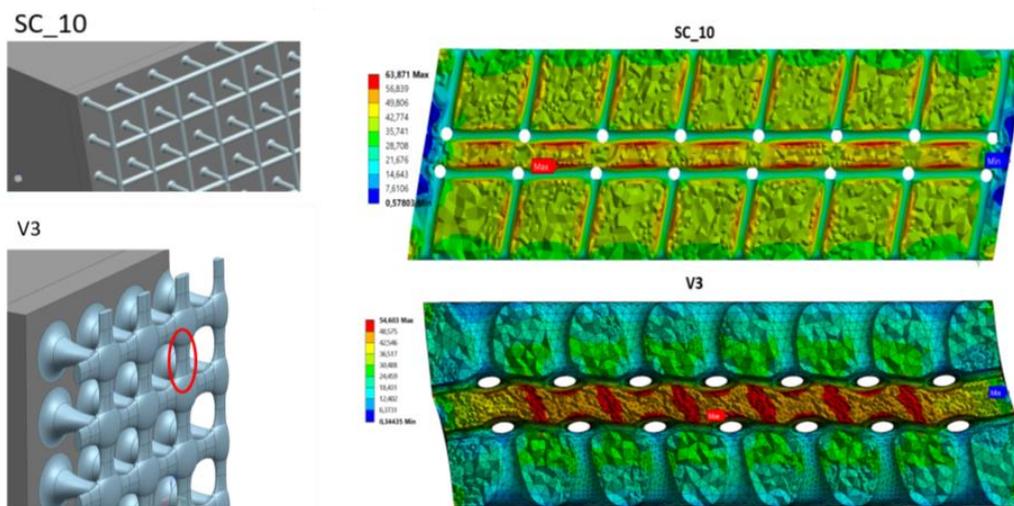


Figure 4 FEM simulation of a simple cubic (SC10) and a hammerhead design (V3)

**Shape Adaptive Endspacers**

Shape adaptive endspacers are additively manufactured compliant structures that adjust to variations in the superconducting Rutherford cable geometry, reducing gaps in the magnet winding process. Two designs were explored: the compliant spring concept and the compliant gripper concept, both of which enhance the assembly efficiency and the magnet stability.



Figure 5 From left to right: Compliant Springs, Compliant Gripper and Compliant Spring Gripper Components

**Stress Based Material Grading**

A primary cause of magnet degradation in Nb3Sn coils is local stress concentration in the coils and the bonding structure. Extending the standard approach to pre-tension the coils, the stiffness of the support structure was locally adjusted to better distribute stress peaks. Various approaches based on minimal surfaces, spherenes, and stochastic lattices and orthofoams were designed, optimized for additive manufacturing, and evaluated through finite element analysis. The results showed very promising simulative results in the ability of the structures to minimize stress peaks in unbalanced load cases. However, a physical validation of the results was not performed yet.

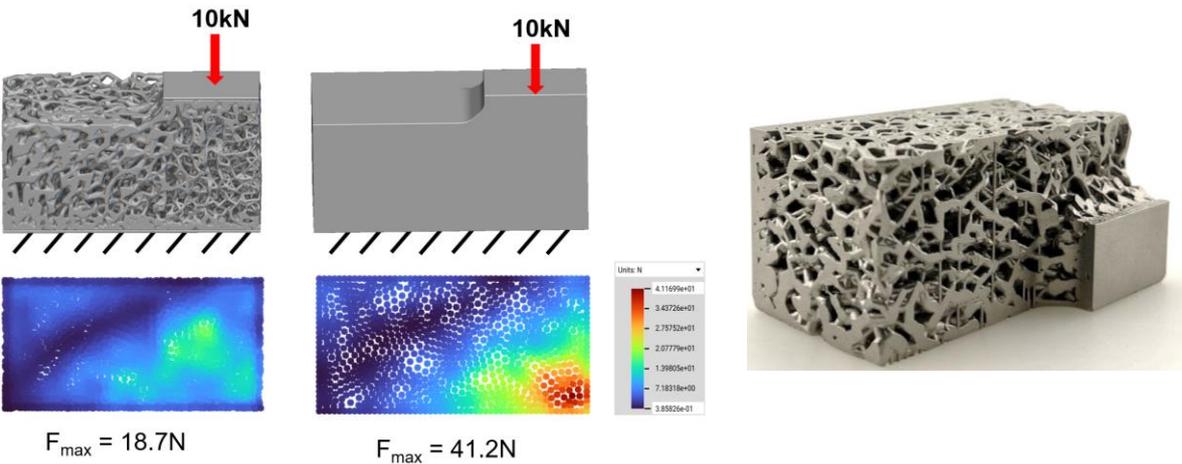


Figure 6: Left - Comparison of a graded and oriented orthofoam with a solid geometry. The peak reaction forces in this unbalanced load cases can be halved by redistributing the load over the full contact surface. Right – Metal additive manufactured component to showcase manufacturability of the orthofoam

### 3. Results / Conclusions / Deliverables

#### Key Findings:

- **Adhesive Joint Strength:** Despite initially promising results, structured surfaces did not consistently outperform plain surfaces under cryogenic conditions. However, some surface structures showed potential in reducing the initiation of mechanical failures and increasing epoxy impregnation through capillary effects.
- **Hybrid Manufacturing:** The hybrid manufactured BOX successfully demonstrated that large parts with complex geometries can be manufactured and joined through a combination of additive manufacturing and conventional milling.
- **Compliant Structures:** The incorporation of compliant structures in additive manufactured geometries has shown promise in improving assembly ease in confined spaces and interlocking geometries.
- **Stress Reduction through Material Grading:** The introduction of structurally graded materials within the magnet support structures has shown promising results in redistributing stress and minimizing peak stress concentrations, although physical testing of these structures is still pending.

#### Conclusion

Although the initial goal of improving the bonding strength between epoxy and metal surface structures was not fully realized, the subsequent milestones clearly demonstrated the benefits of additive manufacturing. Additionally, as additive manufacturing may prove more economical than milling for complex coil formers, incorporating the investigated structures could offer significant potential benefits at no additional tooling cost.

### 4. Publications and Outreach

- [Subscale Stress-Managed Common Coil Design](#) | Araujo et al. - IEEE Transactions on Applied Superconductivity - 2024
- [Increasing the design freedom in Additive Manufacturing](#) | Ferchow et al. - Additive Manufacturing - 2021

This final report is only a very brief summary of all activities. More detailed scientific reports are published at <https://chart.ch/reports/>