CHART MagAM

Additive Manufacturing for Structural Components in Superconducting Coils

This report gives an overview of the progress of the CHART MagAM project. The following list contains the work packages (1-3) that were defined in the CHART MagAM project proposal, complemented by additional work packages (4, 5) that were defined during the project together with our project partners at PSI:

1. Experimental investigation on the strength of adhesive joints between structured adherends and epoxy resin.
   Status: Completed (see section 1)
2. Digital design workflow for structured adherends for the powered subscale experiment (MagDev project)
   Status: Adjusted & Ongoing (see section 2)
3. Finite element analysis of adhesive joints to predict and optimize the bond strength.
   Status: Aborted (see section 3)
4. Infiltration experiments to quantify the advantage of porous structure for the infiltration process with epoxy resin.
   Status: Ongoing (see section 4)
5. Shape adaptive endspacer geometries that contain compliant structures that allows an assembly of a CT-magnet avoiding gaps between endspacers and winding.
   Status: Ongoing (see section 5)

Some of the work packages described in the CHART MagAM project proposal became obsolete after completing the experimental investigation on adhesive joints. Indeed, the results did not show an advantage of structured adherends on adhesive strength at cryogenic test conditions in comparison with AM plain surfaces. Therefore, the FEA investigation for further optimization was aborted after a first investigation (Workpackage 3). Furthermore, the digital design workflow for the structured adherends was adjusted. A digital design workflow only for the *irregular design* was developed and will be applied to design a BOX sample with this type of adhesive interface. Afterward, two additional work packages were developed to further investigate the use of metal additive manufacturing for the application of superconductive magnets.

1. Adhesive Joints

An explorative study on the effect of surface structures on the bonding strength of adhesive joints was designed based on the promising results of the pilot study [1] [2]. The designs shown in Figure 1 include triply periodic minimal surface (TPMS, Gyroid) structures, lattice structures (octet without horizontals) and structures with surface textures (sinusoidal dimples, undercut). The idea behind lattice and TPMS structures is to create an interpenetrating phase layer (IPL) where both epoxy and metal are present and thus a smooth transition between their mechanical properties in the dissimilar material joint should be achieved. The adhesive joints are tested under tension and shear loads. The tests are both conducted at ambient and cryogenic temperature (liquid N2). For the shear experiments, additional samples that are not shown in Figure 1 were produced with other IPL geometries: a metal foam IPL with capillary action capabilities, which should allow for better impregnation; a sample with milled surface and one with a rough surface for the investigation of the impact of surface roughness on the adhesive joint; and a octet truss structure IPL with larger unit cell size for the investigation of the effect of truss diameter on the strength of the adhesive joint.

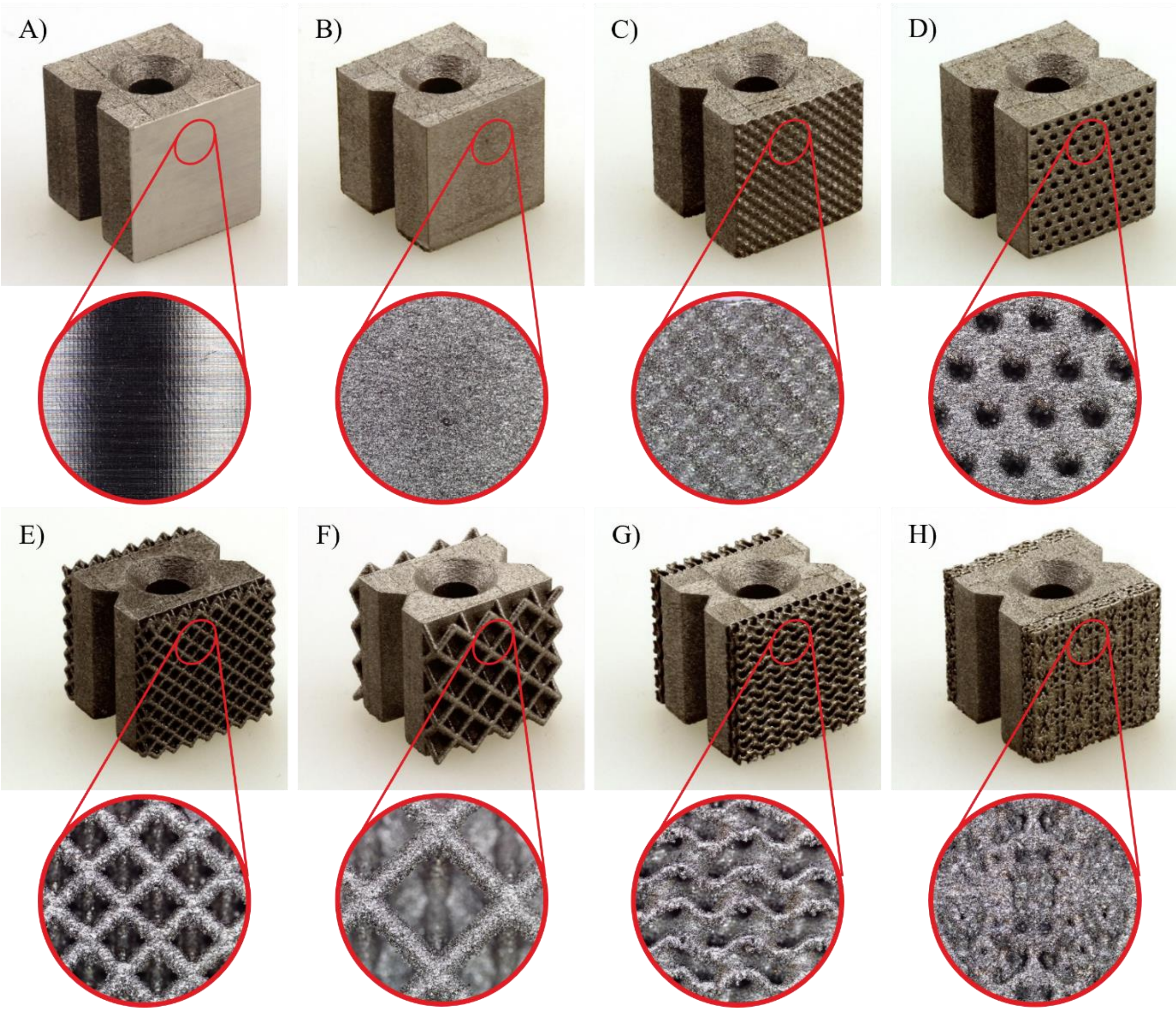

Figure 1 Compressive shear sample designs for the explorative study: A) Milled, B) Plain, C) sinusoidal dimples, D) Undercut, E) octet structure w/o horizontal trusses, F) large octet structure w/o horizontal trusses, G) gyroid, H) irregular

The optimization of the impregnation process of testing samples with the epoxy system has been completed. A mold design has been developed to repeatably place the samples with a defined adhesive gap and orientation to each other. Further, a lab scale impregnation process was developed to impregnate the samples under vacuum with the epoxy to avoid gas bubbles. [3] All the samples were tested, and the data was analyzed. While under ideal conditions a plain surface yields the best results, the relative loss of polluted plain samples in adhesive strength is larger than that of IPL adherend structures.

Publication:
Patrick Beutler, Pascal Studer, André Brem, Bernhard Auchmann, Theo Tervoort, Mirko Meboldt; *Metal Additive Manufacturing for Improved Adhesive Joints at Superconducting Magnets: An Exploratory Study*
Status: submitted (12.2022)

2. Digital Design Workflow for Structured Adherends

Irregular design performed relatively well in the experiments. Therefore, in the next steps, irregular design structures will be implemented in bonding experiment samples (BOX) to test their effect on the performance of powered superconducting samples under realistic pollution, cooling, and Lorentz-force-induced shear loads. This BOX sample is developed and tested in collaboration with PSI. Since the BOX part is too large for all PBF-LB printers, the BOX design is adapted and must be manufactured as a hybrid part: The channel geometry, whose walls are equipped with the structured surface of the irregular design and which is used to carry the superconducting cable, is manufactured additively. The remaining part of the component is produced by milling and the two parts are then joined by an electron beam welding process. It must be ensured that the joined component is sufficiently rigid for the application and can withstand the high physical stresses during the experiment. The design of the individual components has been completed, whereas some clarifications regarding manufacturability with the electron beam welding process are pending. Subsequently, the production of the hybrid AM BOX can begin. The manufacturability of the irregular structured adherend on the manufacturing site of an AM supplier has been demonstrated by the manufacturing of one segment of the final AM part.

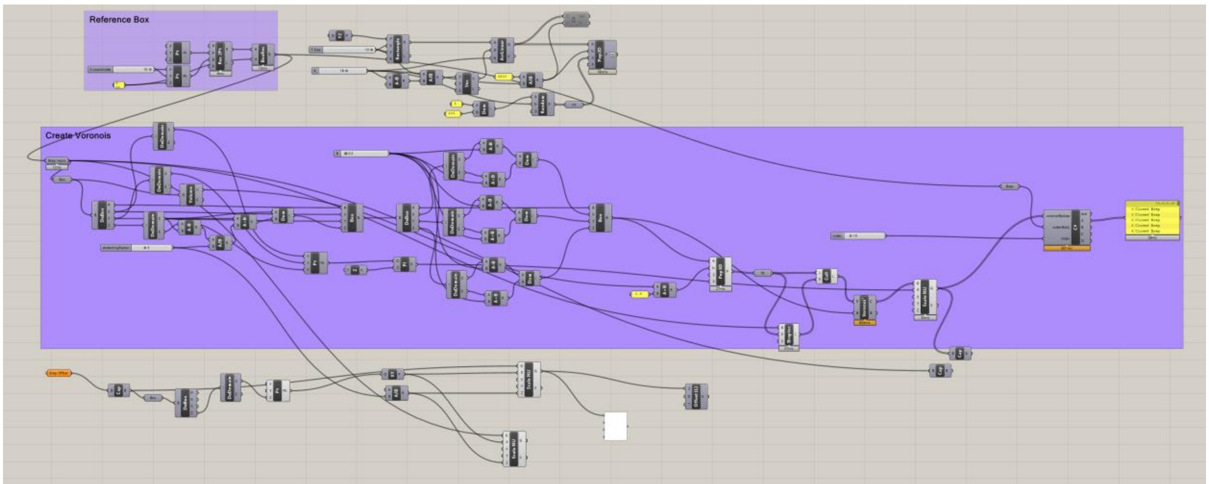

Figure 2 Digital design workflow for the design of irregular structures within a defined volume body.

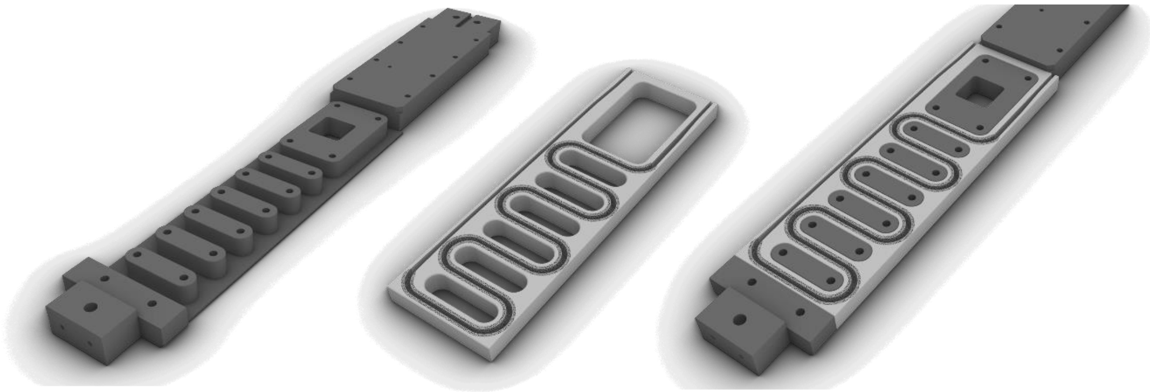

Figure 3 Design of the hybrid manufactured BOX sample with the milled plate and the AM part that contains the channels.

3. FEM Simulation of Adhesive Joints

The strength of adhesive joints was investigated with a focus on the epoxy resin, since the experimental tests show that the adhesive is the weak point within the adhesive joint. Therefore, the goal of this investigation is to minimize the maximum stresses that occur within the epoxy resin for a given shear or tensile force. In the first step analytical formulas for the calculation of adhesive joints were used and a reference simulation has been set up such that there is a good match between those two methods. After this reference simulation was defined, several designs of IPL structures were simulated. Among these designs are the simple cubic (Figure 4 SC_10) structure, which is a common and regular lattice, and the hammerhead design (Figure 4 V3) which was designed within this study. The goal of the hammerhead design is to benefit from properties of lattice structures, such as the interpenetration of the resin into the structure and the possibility to reduce the stiffness mismatch between the adherend and the adhesive by using a lattice structure. Additionally, the hammerhead design has larger contact area to the adhesive at the transition between the IPL and the pure resin, and avoid any sharp edges to avoid stress concentrations. While the simulations show a positive improvement for the hammerhead design as the von Mises stresses are reduced, the physical experiments were not able to verify this result. In fact, the physical experiments showed poorer performance of the hammerhead design compared to the other structures. One explanation is that the additively manufactured hammerhead designs had relatively large defects on the surface, producing large stress concentrations. This study shows that a numerical simulation of adhesive joints is very difficult, as there are many unknowns such as effects from the manufacturing process. Furthermore, the experimental validation is challenging as there are factors that are difficult to integrate into a numerical simulation, such as the exact boundary conditions between the adhesive and the adherend.

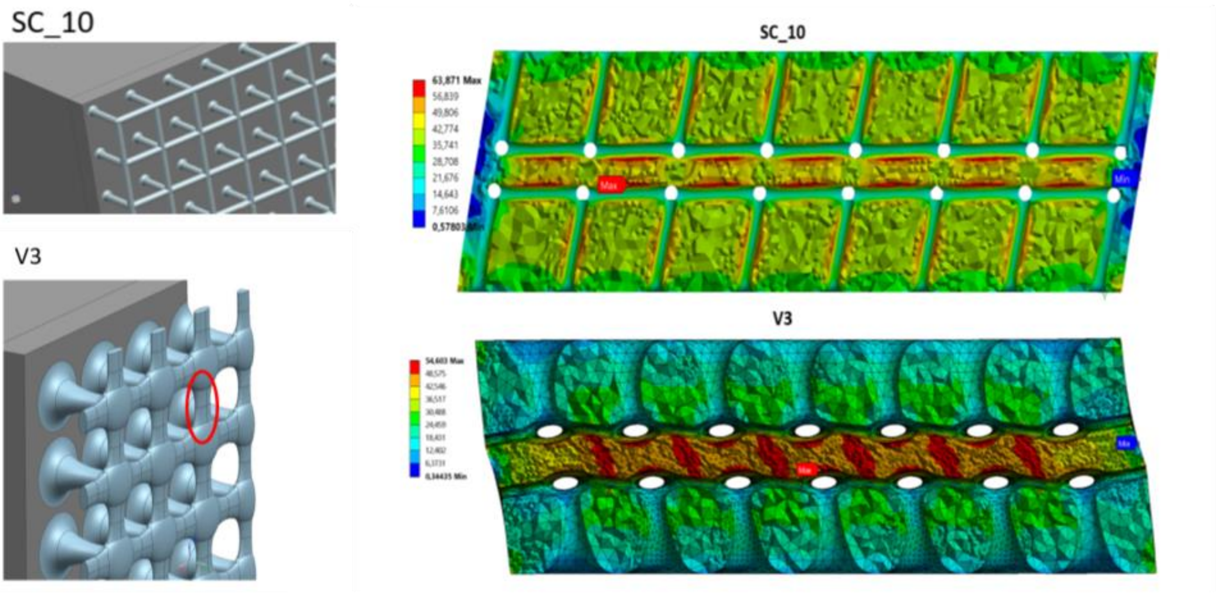

Figure 4: FEM simulation of a simple cubic (SC10) and a hammerhead design (V3) [4]

4. Infiltration Experiment

The structured adherend surfaces with the irregular design primarily enable the mechanical interlocking of the adhesive within the adherend and a transition between the two materials. The effect of these structures on the adhesion properties was studied in the adhesion experiments and is further investigated in the AM box as a simplified magnet. A secondary effect of the structures are the potential to facilitate infiltration of the cables with the adhesive by reducing the resistance to flow. This could allow the use of epoxy resins, which have shorter pot lives because the resin spreads faster. To investigate this, straight channel sections with three different structures on the surface were designed and fabricated: without porous structure, dense porous structure and wide porous structure (Figure 5). In a pending experiment, a piece of a Rutherford cable is inserted into the samples shown and then the effect of the structures on the flow of a liquid is tested.

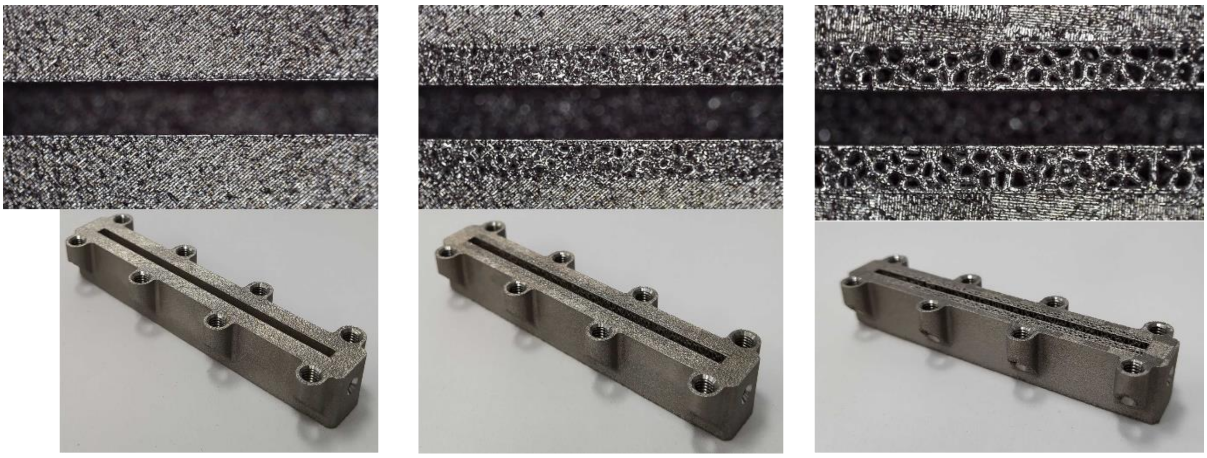

Figure 5 Infiltration samples without porous interface, very dense porous interface and broad porous interface (from left to right).

5. Shape Adaptive Endspacers

One challenge in manufacturing superconducting magnets is the repeatable winding of Rutherford cables. Due to small deviations in the cables, their fiberglass sleeve or the structural metal parts such as the central post or wedges, the windings can deviate from the designed geometry. As the winding continues, smaller gaps are created between the metal components that are added like end spacers and the cable. These gaps can cause local failure during magnet operation. The goal of this work package is to design a new type of end spacer that contains adaptive elements to compensate for these deviations and thus reduce the gaps. The design freedom of additive manufacturing and the possibility of integrating compliant mechanisms into complex structures is used in this context. In a first semester project, two different approaches were developed to design an end spacer that can adapt to the shape of the cable: the compliant spring concept (CSC) and compliant gripper concept (CGC) [5]. The CSC has a segmented inner surface of the end spacer, with each segment connected to the outer geometry by a spring element. These spring elements can elastically deform individually and thus lead to a local adaptation to the geometry. The CGC is inspired by the finray effect, which is used for grippers in robotics. By actuation, the entire structure can open, close and finally embrace the cable. Both designs have its individual advantages: With CSC, the elements can adapt locally and are individually very compliant; and with the CGC, the end spacer can be opened wide before it is pushed onto the fiberglass covered cables, reducing stress on the insulation. The final prototypes of the semester thesis are shown in Figure 6. In these prototypes, it was seen that the two designs work in principle, but that the adaptation to the cable is not yet satisfactorily achieved. Therefore, a master thesis was subsequently started, which continues the work and includes an investigation on the reasons for the large gaps, a further development of the design and the transfer to a metal AM design.

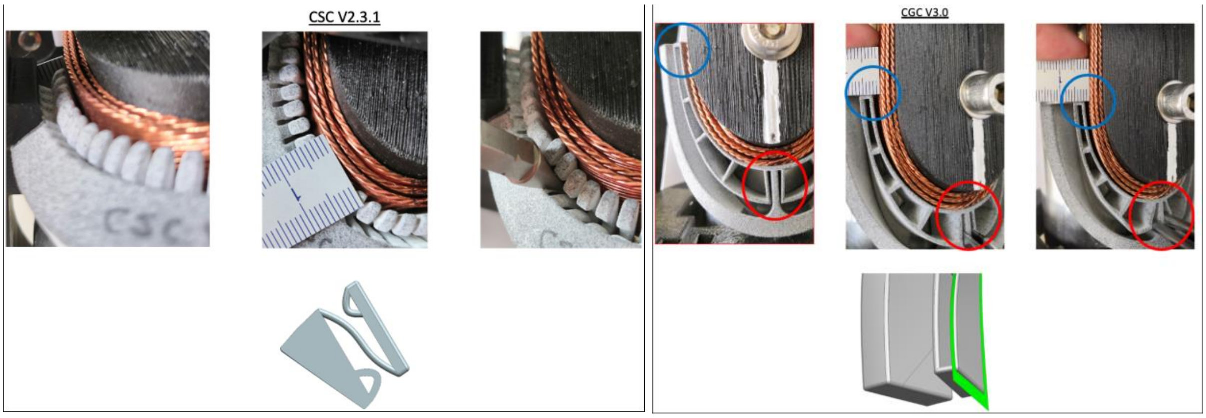

Figure 6 Shape adaptive endspacer concepts: Compliant spring concept (CSC) and Compliant gripper concept (CGC) [5]

6. Team

A comprehensive list of team members in the past year of the project is reported below.

Julian Ferchow	PostDoc	Jan 22 - Dec 22	8%	CHART
Patrick Beutler	PhD	Jan 22 - Dec 22	100%	CHART
Patrick Wipfli	Master thesis	Sep 22 - Dec 22	100%	n/a
Patrick Wipfli	Semester thesis	Mar 22 - July 22	100%	n/a

7. References

[1] J. Ferchow, M. Biedermann, P. Müller, B. Auchmann, A. Brem und M. Meboldt, «Opportunities and Fundamental Challenges of Part Segmentation in Metal Additive Manufacturing - A Case Study on a Superconducting Solenoid Coil,» Under Blind Peer Review, 2021.

[2] P. Müller, «Master Thesis - Enabling Complex SLM Parts Based on a Process Parameter Model,» *ETH Zürich - Product Development Group pd|z,* 2020.

[3] P. D. Palma, «Master Thesis - Investigation of L-PBF Lattice Based Interpenetrating Phase Layer for Adhesive Joints,» *ETH Zürich - Product Development Group pd|z,* 2021.

[4] T. Ogris, «Master Thesis - Optimization of Adhesive Joints by Implementing AM Interpenetrating Phase Layers,» *ETH Zürich - Product Development Group pd|z,* 2021.

[5] P. Wipfli, «Semester Thesis - Development of Additive Manufactured Endspacers with Adaptive Structures,» *ETH Zürich - Product Development Group pd|z,* 2022.