MagAM – Additive Manufacturing for Structural Components in Superconducting Coils

This report gives an insight into the progress of the CHART MagAM project within the past 12 months. During this period, the following work packages according to the research proposal were pushed forward:

- Experimental investigation on adhesive joints between structured adherends and epoxy resin.
- Finite Element Analysis of adhesive joints to predict and optimize the strength of adhesive joints.

Impregnation and Adhesive Joints

An explorative study on the effect of surface structures on the ultimate 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 is 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.

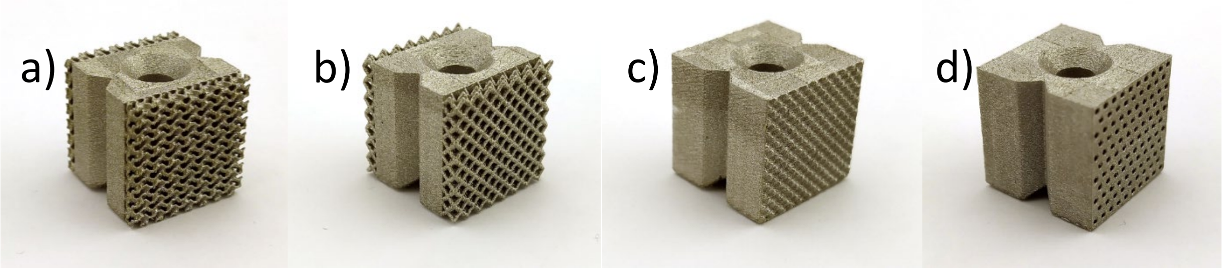

Figure 1 Compressive shear sample designs for the explorative study: a) TPMS Gyroid structure, b) Lattice Octet w/o horizontals structure, c) sinusoidal simple structure, d) Undercut structure

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 is currently analyzed. It is planned to publish the results of this study in the next year. While under ideal conditions a rough plain surface yields the best results, the relative loss of polluted plain samples in adhesive performance is larger than that of IPL samples. For this reason, in the next steps, IPL 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. These BOX samples will be developed and tested in collaboration with PSI. To do so, a surface structure will be applied to a BOX sample. Within this step, the box sample design is also adapted such that the additive manufactured parts can be integrated into the milled parts of a BOX sample.

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 2 SC_10) structure, which is a common and regular lattice, and the hammerhead design (Figure 2 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 difficult 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.

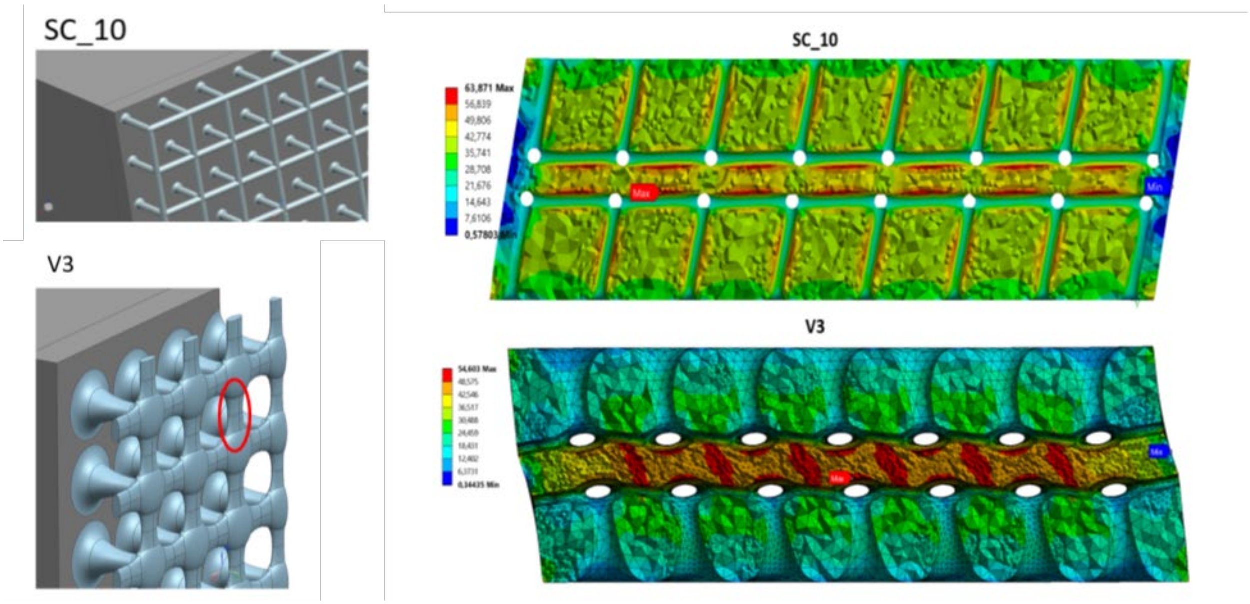

Figure 2: FEM simulation of a simple cubic (SC10) and a hammerhead design (V3)

Outlook

Since the results of the experiments on the adhesive joints did not show the expected outcome, it was decided together with Bernhard Auchmann from PSI to pivot the project focus to other topics. The overall goal of the MagAM project is still the improvement of superconducting magnets with the use of metal additive manufacturing. The pivoting includes the following points:

- The studies on the adhesive properties are finalized and the results should be published.
- Two to three different BOX samples will be manufactured and tested to test adhesive joints within a magnet in collaboration with PSI.

To focus on the overall structure of a magnet, the following topics will be looked at:

- Endspacers and wedges are considered as potential parts that can be manufactured additively. The goal is to analyze the functions of these structural parts and try to improve the current designs with more functionality. One example is to add compliant elements to the endspacers, which adapt to the cable windings and thus reduce gaps in the assembly, and improve the assembly process.
- Another potential improvement could be the integration of cooling channels within the structural parts of the magnet. These features could potentially help to speed up the cool down process during operation of the magnets and reduce the liquid helium inventory of future circular colliders.

Team

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

Christoph Klahn	PostDoc	Jan 21 - May 21	8%	CHART
Julian Ferchow	PostDoc	July 21 - Dec 21	8%	CHART
Patrick Beutler	PhD	Jan 21 - Dec 21	100%	CHART
Philip Dalla Palma	Master thesis	Jan 21 - Feb 21	100%	n/a
Tiago Ogris	Master thesis	Jan 21 - Apr 21	100%	n/a

Publications

[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.