Custom Design to the Application of Open-Cellular Metal Structures

Claudia Drebenstedt[1,a*], Christian Hannemann[1,b], Jörg Hohlfeld[1,c],
Steve Siebeck[1,d], Thomas Hipke[1,e] and Dilay Kibaroglu[2,f]

[1]Fraunhofer IWU, Reichenhainer Str. 88, 09126 Chemnitz, Germany

[2]RWTH Aachen University, Intzestr. 1, 52072 Aachen, Germany

[a]claudia.drebenstedt@iwu.fraunhofer.de, [b]christian.hannemann@iwu.fraunhofer.de,
[c]joerg.hohlfeld@iwu.fraunhofer.de, [d]steve.siebeck@iwu.fraunhofer.de,
[e]thomas.hipke@iwu.fraunhofer.de, [f]dilay.kibaroglu@iehk.rwth-aachen.de

Keywords: Cellular Metals, Open Cellular Structures, Design, Investment Casting

Abstract. There are many potential applications for lightweight open-cellular metal structures, such as energy absorption, filtering, or thermal management. Such metallic open-cellular structures are often produced by additive manufacturing. Another option is the use of investment casting, for example by using open polymer foams as a template. By designing structures via Computer-Aided-Design (CAD), these can be used directly for additive manufacturing, either directly in metal or in wax as a template for casting. In this way the structure can be adapted very well to the needs, possible applications are shown in [1]. Using polymeric templates reduces the adaptability of the structure immensely. To use the full potential, it is necessary to develop the structure according to its future purpose. The 'ProZell' project is developing the basis for realizing such structures in high-manganese steels by investment casting using the lost wax process.

Introduction

The project ProZell aims to develop a programmable cellular metal structure made of high manganese steel. An open cellular structure is to be designed, consisting of a single unit cell, which can be scaled in size and number to fit a particular geometry depending on the later application. The aim is to combine a high lightweight potential with a high energy absorption potential. Two production routes and the influence on the resulting structure are to be compared, for example by means of compression tests. RWTH Aachen University is responsible for the additive manufacturing process and Fraunhofer IWU for the casting process.

Design and Process Setup

Based on the requirements described above, various designs for the cell geometry and the resulting structures were implemented in Catia. Some of them cannot be considered with regard to the feasibility of horizontal struts by additive manufacturing. Based on previous studies [2, 3] the structure shown on the left side of Fig. 1 was chosen as a starting point for a similar structure. The structure has vertical z-struts, which bend in a random direction when loaded in the z-direction.

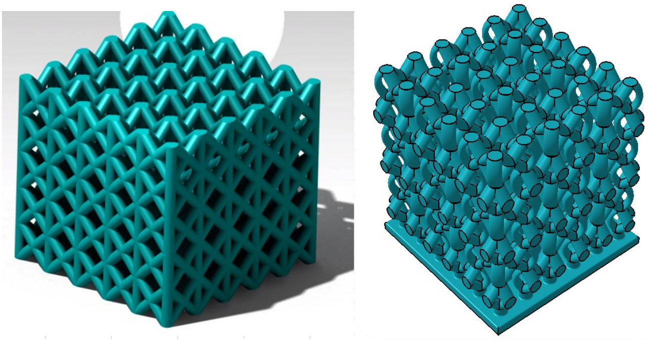

Fig. 1: “f2cc,z structure” [2, 3] (left), CAD design of the ProZell structure (with base plate)

A structure with curved struts in the z-direction was designed for more predictable and controllable behavior (Fig. 1, right).

Process – Investment Casting

Wax printing with a ProJet 2500 (3D SYSTEMS) was used to create the positive placeholder for the structure. After removing the support wax in a heated isopropanol bath, the feeder was added. The structure was attached to a base plate via the feeder and placed in a cuvette. The next step was to fill the flask with the mold material using a KWS Investment Mixing Machine. After drying, the mold was placed in an oven to melt out the wax. The mold was bruned according to the pre-defined program and then held at the temperature selected for casting until it was transferred to the casting machine. A vacuum pressure casting machine, the BluePower INDUTHERM VC 480 V, was used for melting the material and casting. The chamber was flushed with argon to prevent oxidation. After cooling, the flask and the mold material were removed mechanically and additional with a high pressure water jet.

Materials

X30Mn22 was used for the casting as well as for the additive route. ProHT Steel and ProHT Platinum (Goodwin Refractory Services Limited) were used as mold material, the composition is stated in Table 1.

Table 1: Composition of ProHT mold material [4]

	Cristobalite	Quartz	Mono Ammonium Phosphate	Magnesia (MgO)	Fiber Glass
%	10 - 30	70 - 90	< 10	> 4	> 2

Furthermore, the mold materials Carath 1800 NC sf, Carath 1804 ULC (RATH Sales GmbH & Co. KG), and Keroyxd (Oxyd-Keramik GmbH & Co. KG) are used. The compositions are stated in Table 2.

Table 2: Composition of Carath 1800 NC sf, Carath 1804 ULC and Keroyxd [5, 6]

		Al_2O_3	SiO_2	CaO	MgO	Fe_2O_3	Na_2O
Carath 1800 NC sf	%	92.5	6.8	0.1	-	0.15	-
Carath 1804 ULC	%	97.8	0.15	1.5	-	0.15	-
Keroxyd	%	96.5	< 0.2	2.7	0.1	< 0.1	0.2

A zirconium-based coating from the manufacturer Ransom & Randolph was used as an additional intermediate layer. The wax model was dipped into a zirconium oxide slurry to a thickness of approximately 0.5 mm. The model was then sprinkled with zirconia sand and dried for at least 2 hours.

Experimental Setup

Initial trials showed that the cavity could not be completely filled, and strong reactions between the molding material and the molten X30Mn22 occurred. This resulted in very difficult / unfeasible demolding and geometric inaccuracy (Fig. 2). It is assumed that the molding reactions are based on the reaction of the manganese in the trip steel with the silicon in the molding material at higher temperatures and that compounds such as $MnSiO_3$ are formed. This has yet to proven by appropriate investigations.

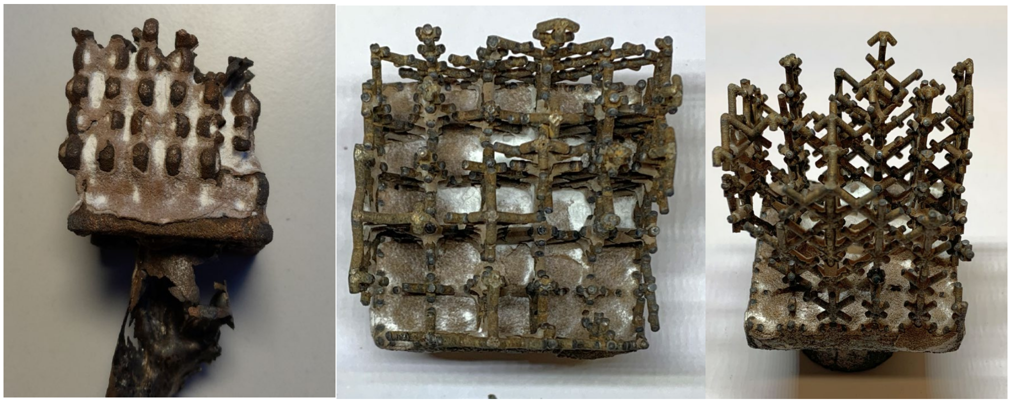

Fig. 2: Results of the first trials for casting structures with high manganese steel

Due to the poor results shown in Fig. 2, it was decided to start with a geometry that was easier to evaluate: a wedge with three steps of different thicknesses (0.3 mm, 0.5 mm, 1 mm), each 15 mm long, in order to study the influence of the different parameters. The initial aim was to compare different temperatures and molding materials and the limits of feasibility in terms of melt flow in relation to thickness, which would allow an estimate of the possible strut diameters of the structure. The geometry specifications are shown in Fig. 3 and Fig. 4.

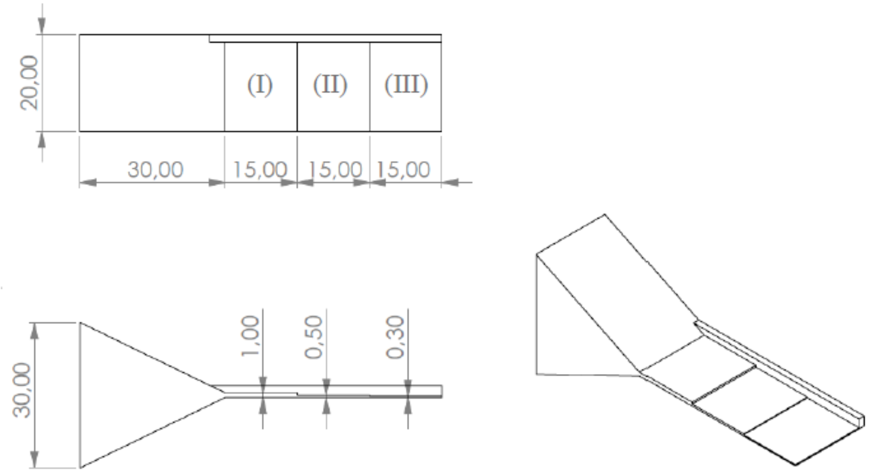

Fig. 3: Geometry of the wedge [1]

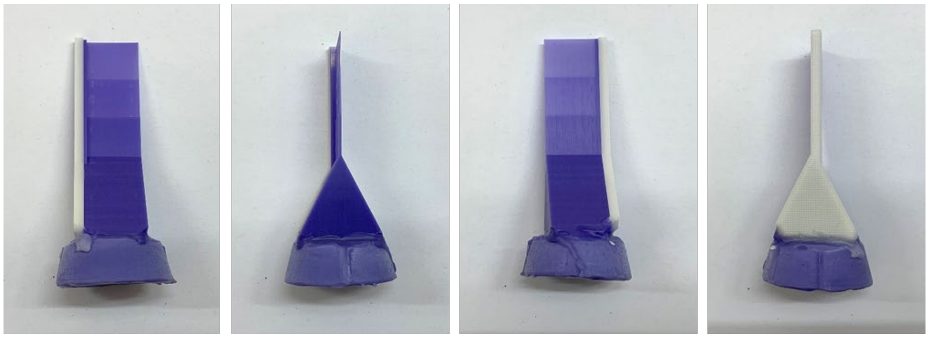

Fig. 4: Printed wax wedge with added feeder

Experimental

The casting molds were prepared as described (Process – Investment Casting). In addition to the high manganese steel, 316L steel was used as a reference as this material appeared to be easier to cast. The flow length was evaluated according to the steps 15 / 30 / 45 mm. The further steps were decided by evaluating the results of the previous steps.

Stage 1:

A DoE (design of experiments) was prepared for the first stage of castings. Two mold temperatures in the combination of with two ProHT mold materials and the 316L and high manganese steel were included as shown in Fig. 5.

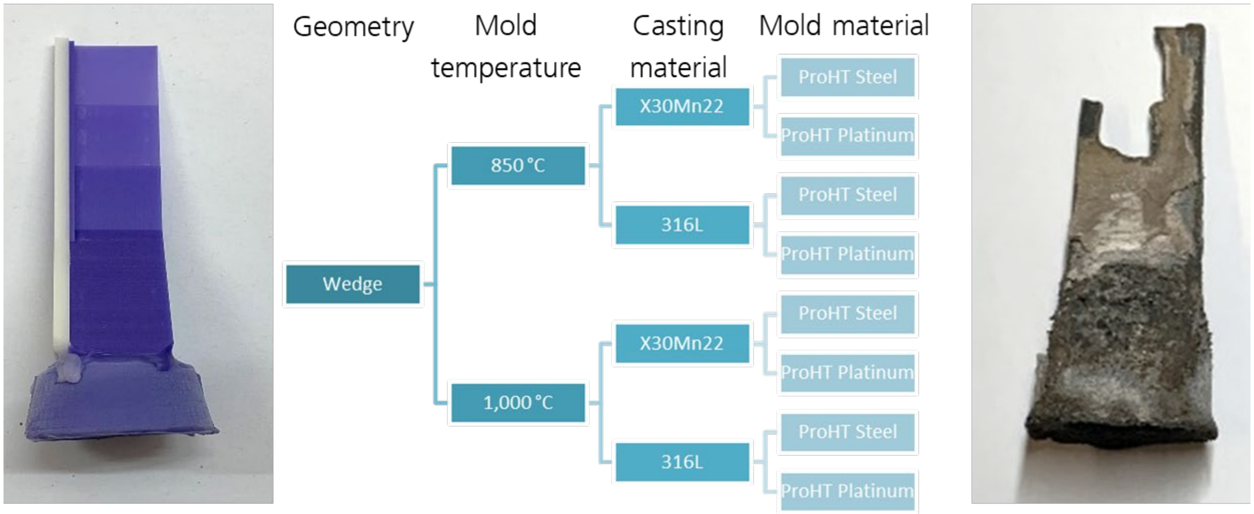

Fig. 5: Overview experiments stage 1

Results Stage 1:

The evaluation and the results of the experiments show a significant influence of the mold material on the flow length and thus on the degree of filling (0.5 mm step filled for the ProHT Steel mold, 0.3 step more than half filled), but no influence on the unwanted reactions between the mold and the casted steel (Fig. 6). The reactions between the high manganese steel and the mold material also caused a blowhole almost the size of the feeder itself (Fig. 8, center green frame), whereas for the casted 316L samples the surface, including the feeder, is smooth and straight (Fig. 8, left). Changing the mold temperature between 850 °C and 1,000 °C had no significant effect on any of the criteria evaluated.

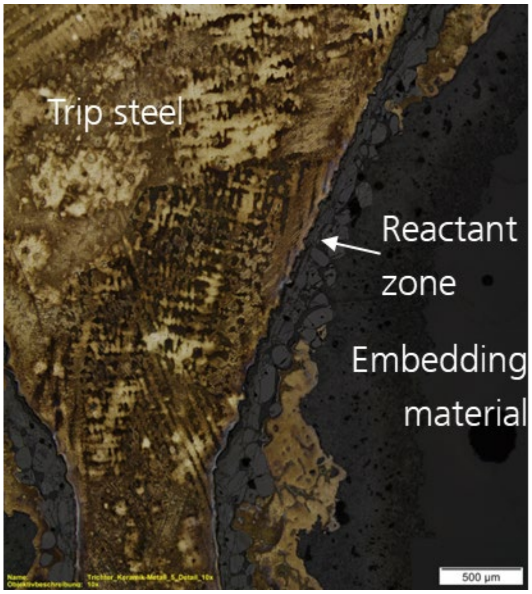

Fig. 6: Microsection of a Trip wedge with the reaction products at the surface

Stage 2:

In order to prevent the reactions described above, further trials were carried out with an additional intermediate layer on the wax models by adding a zirconium oxide slurry, Fig. 7. In addition, the mold temperature was reduced to 700 °C to investigate whether the reactions were reduced and whether there was an effect on the filling level. The mold material ProHT Steel was selected due to the better filling degree in stage 1.

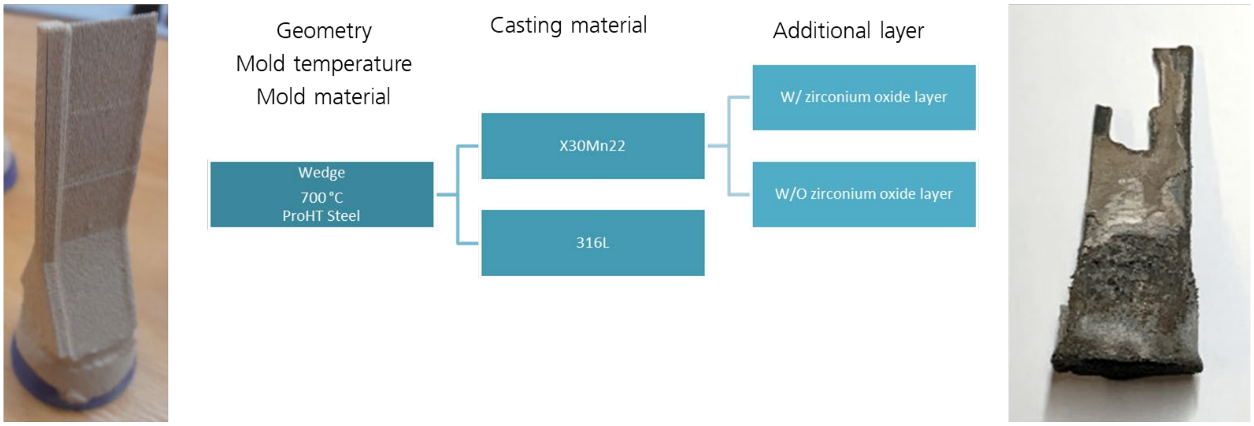

Fig. 7: Overview experiments stage 2

<u>Results of Stage 2:</u>

The degree of filling in 316L was slightly reduced due to the lower mold temperature of 700 °C. For the X30Mn22, there was little difference. The additional layer had no effect on the fill level. It reduces the reactions significantly, but the samples show that the layers had been damaged in some areas, so there are areas with a smooth surface and rough areas with reaction marks. The blowholes in the feeder are also smaller compared to the samples without the layer, as marked with a green frame in Fig. 8.

Fig. 8: (A) 316L, (B) X30Mn22, (C) X30Mn22 made with additional layer

Stage 3:
In order to evaluate and avoid the cracks in the interlayer, single and less vulnerable double layer samples were prepared and tested with mold temperatures of 850 °C and 1,000 °C, shown in Fig. 9. Only the X30Mn22 in combination with the ProHT steel was investigated at this stage.

Results Stage 3:
A higher degree of filling can be observed at 1,000 °C, but this could be due to a crack in the mold in two or three cuvettes. In general, the surface quality of the samples with two layers of zirconia slurry is much better and sharp edges are reproduced. Where the layer was intact there were no discernible reactions.

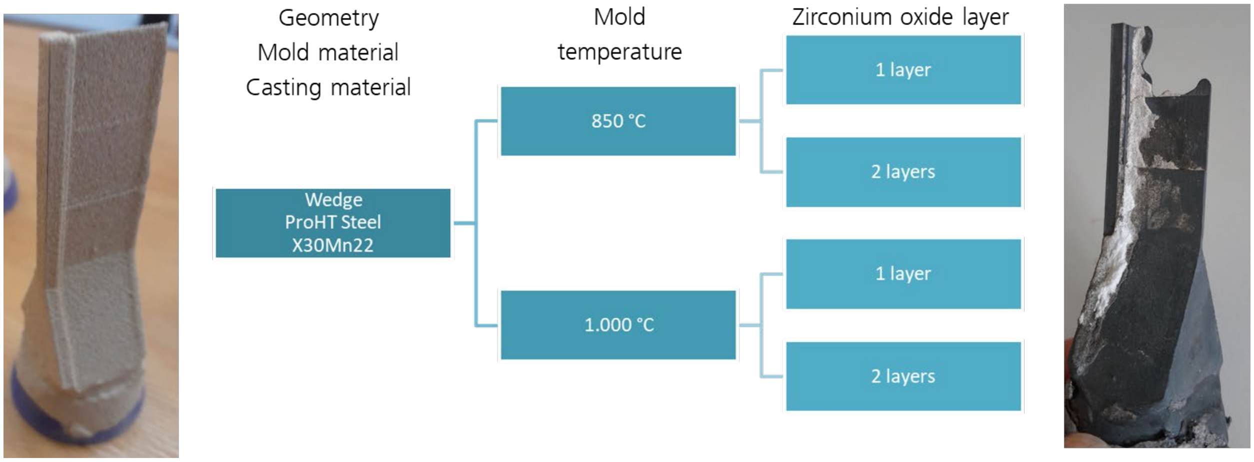

Fig. 9: Overview experiments stage 3, left: wax wedge with zirconium layer, right: sample made with 2 layers

Stage 4:
In order to avoid the reactions between the molding material and the trip steel, probably due to the high silicon content of the ProHT molding materials, 3 low silicon molding materials were tested in parallel with the zirconium layers, compare Fig. 10. Additional metallographic studies are ongoing.

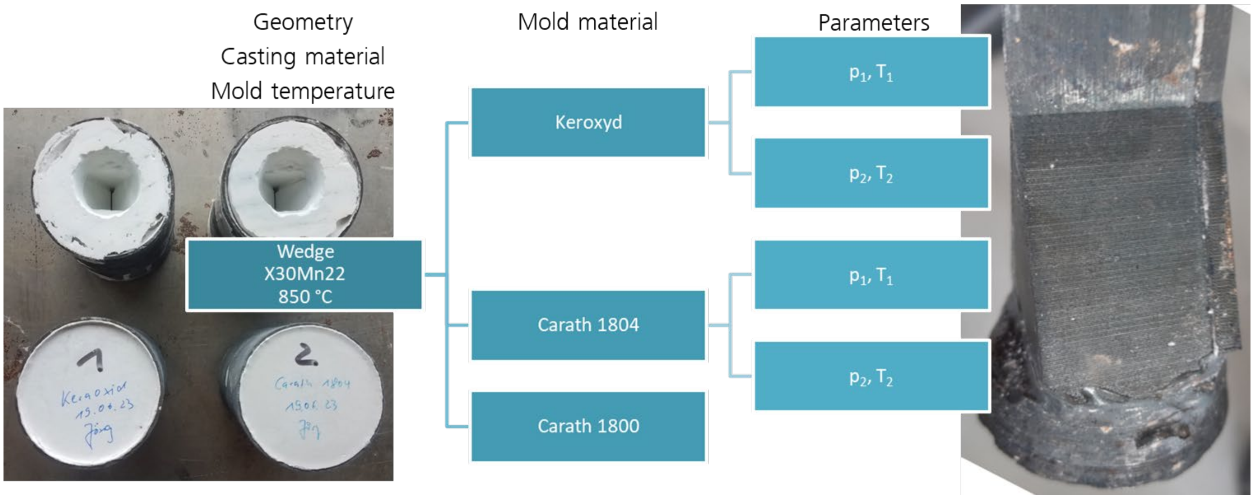

Fig. 10: Overview experiments stage 4, left: prepared molds, right: in Keroxyd casted Trip wedge

Results Stage 4:
Molds could not be manufactured using Carath 1800 NC sf ULC. However, Keroxyd and Carath 1804 ULC were successful in mold manufacturing with no noticeable melting reactions. The

surface quality of the molds was excellent, and even the horizontal lines from the wax's additive built-up were visible (Fig. 9, right). Keroxyd had a better filling degree / flow length (15 - 30 mm) compared to Carath 1804 ULC (0 - 15 mm). The material used for the mold was very sturdy, making it challenging to remove the part without causing damage, especially for delicate structures.

Summery and outlook

Casting experiments were conducted in four stages using various materials and parameters. The main criteria evaluated were flow length and reactions to the mold material. Some parameters were identified as significant. Treating the ProHT molds with an additional zirconia-based layer looks very promising. Additionally, using mold materials such as Keroxyd shows high potential. In the following steps, the mold material will be modified so that the mold can be removed more easily. 3-point flexure tests will be used to verify the effectiveness of this modification and transfer the results to the casting of the structures.

Acknowledgements

This work has been funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the project ‘ProZell’ (project ID 437986279).

We would like to thank NRU GmbH for supporting us by adding the zirconia layer to our wax structures.

References

[1] Hannemann, C., Uhlig, M., Hipke, T., & Meier, I. (2020). The Challenge of Open Cellular Metal Foam Production. In Proceedings of the 11th International Conference on Porous Metals and Metallic Foams (MetFoam 2019) (pp. 149-157). Springer International Publishing. https://doi.org/10.1007/978-3-030-42798-6_14

[2] Köhnen, P., Haase, C., Bültmann, J., Ziegler, S., Schleifenbaum, J. H., & Bleck, W. (2018). Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel. Materials & Design, 145, 205-217. https://doi.org/10.1016/j.matdes.2018.02.062

[3] Köhnen, P., Létang, M., Voshage, M., Schleifenbaum, J. H., & Haase, C. (2019). Understanding the process-microstructure correlations for tailoring the mechanical properties of L-PBF produced austenitic advanced high strength steel. Additive Manufacturing, 30, 100914. https://doi.org/10.1016/j.addma.2019.100914

[4] PRO HT- Rev 07.pdf (srs-ltd.co.uk)

[5] https://www.rath-group.com/produkte/ungeformte-produkte/carath-d-carath-mc-dichte-betone, accessed: 07/11/2023

[6] https://www.oxyd-keramik.de/, accessed: 11/07/2023