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# Tailor-Made Net-Shape Composite Components by Combining Additive Manufacturing and Hot Isostatic Pressing

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**Abstract.** A promising production route for high quality tailor-made parts can be established by combining Additive Manufacturing (AM) and Hot Isostatic Pressing (HIP): By using a numerical simulation routine, the shape change during HIP can be controlled. These shape-controlled parts are built by Laser Powder Bed Fusion (L-PBF) and consolidated by HIP. After HIP, they exhibit a net-shape geometry that requires only little or even no post-processing at all. In this study, open thin-walled capsules are manufactured by L-PBF, filled conventionally with metal powder, evacuated and sealed and hot-isostatically pressed. Using this processing route, it is possible to combine different materials for the capsule and the powder filling. If capsule and bulk material are identical, the expensive removal of the capsule after HIP can be omitted. By using two different powders, it is possible to produce composite components with a core of high strength and toughness and a wear- or corrosion-resistant surface layer, offering an alternative and competitive production route to conventional HIP cladding. Here three materials are investigated in different combinations: austenitic stainless steel AISI 316L (DIN X2CrNiMo17-13-3), martensitic tool steel AISI L6 (DIN 55NiCrMoV7) and the wear resistant high carbon steel AISI A11 (DIN X245VCrMo8-5-1). A number of technical challenges need to be addressed: the production of dense, thin-walled capsules by L-PBF; L-PBF of carbide rich steels; and controlling the diffusion between corrosion resistant steel and carbon steel. The success of the new process route is demonstrated by metallographic and geometrical investigations.

## Introduction

Hot-Isostatic Pressing (HIP) and Additive Manufacturing (AM) are two process routes to build powder-metallurgical (PM) components. Whereas HIP is a well-established process that has been actively developed for decades, the whole bouquet of beam-based AM processes has only built up momentum over the last years. [1,2]

Combining AM and HIP properly, the benefits of the processes can be exploited and deficiencies can be compensated [3,4]. While AM can be used to produce complex geometries directly from the CAD/CAM process chain in a material-saving manner, production is comparatively time-consuming and thus costly due to the layer structure. The mechanical

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material properties, which depend significantly on internal defects, lag behind those of conventionally manufactured components. The latter applies in particular to toughness and fatigue strength.

On the other hand, components manufactured by means of HIP have a very fine, isotropic microstructure free of segregation and pores. This makes the mechanical properties comparable to or even better than those of conventionally manufactured components [5]. Due to the conventional capsule design, classical powder HIP is a comparatively complex process, which is limited to simple geometries and small series.

In this study, thin-walled capsules are built by Laser Powder Based Fusion (L-PBF). The actual building time can thus be minimized. Furthermore, L-PBF allows producing complex capsule geometries, which cannot be achieved by conventional welding of sheet metal capsules. In addition, the shape of the capsules prior to construction is optimized with a numerical simulation so that a near-net-shape component is created after HIP.

## Materials and Methods

The aim of this study is to produce complex-shaped fully dense composite components with a corrosion- or wear-resistant outer layer and a tough core built in comparatively short time. Thus, the materials have to be suitable both for L-PBF and for HIP. Table 1 shows the material selection for this study.

*Table 1: Material selection for monolithic and composite components.*

| | Capsule | Bulk |
|---|---|---|
| Monolithic 1 | Austenitic stainless steel AISI 316L (DIN X2CrNiMo17-13-2) | |
| Monolithic 2 | Martensitic tool steel AISI L6 (DIN 56NiCrMoV7) | |
| Composite 1 | Austenitic stainless steel AISI 316L (DIN X2CrNiMo17-13-2) | Martensitic tool steel AISI L6 (DIN 56NiCrMoV7) |
| Composite 2 | Carbide rich, wear resistant steel AISI A11 (DIN X245VCrMo8-5-1) | Martensitic tool steel AISI L6 (DIN 56NiCrMoV7) |

The “Monolithics” were meant for preliminary tests where capsule and bulk are made from the same material. This article focusses on the “Composites”: The capsule is made either from corrosion-resistant 316L or from wear-resistant A11. The tough core consists of L6 steel. Chemical compositions of the steel powders can be found in Table 2. Powder of ferritic steel 430L is used to facilitate crack-free processing of A11 by mixing A11 and 430L.

*Table 2: Chemical composition of used steel powders measured at Fraunhofer IFAM [wt-%].*

| | C | Si | Mn | P | S | Cr | Ni | Mo | Cu | V | N | B | O | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L6 | 0.52 | 0.28 | 0.96 | <0.01 | 0.002 | 1.22 | 1.99 | 0.5 | 0 | 0.11 | 0 | 0 | 0 | Bal |
| 316L | 0.021 | 0.8 | 0.95 | 0.009 | 0.004 | 17.3 | 13.2 | 2.5 | 0.05 | 0 | 0.14 | 0.001 | 0 | Bal |
| A11 | 2.45 | 0.98 | 0.42 | 0.02 | 0.087 | 5 | 0 | 1.49 | 0 | 8.28 | 0.098 | 0 | 0.035 | Bal |
| 430L | <0.018 | 0 | 0 | 0 | 0 | 16–18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Bal |

The experiments regarding L-PBF were conducted at Fraunhofer IFAM (Bremen/Germany) with an L-PBF unit “M270 Dual Mode” from EOS GmbH. This unit is equipped with an extended powder bed heating option of up to 300 °C.

In order to find suitable parameters for the L-PBF process, a multi-step parameter variation study was done. At first, by variation of scan velocity and laser power and thus by variation of energy density, thin lines and walls and small cubes were produced. In a second step, an appropriate parameter set was fine-tuned by building overhangs and different angles. Finally, the HIP capsules used in this study could be built successfully. [6]

The HIP cycles were performed at IWM of RWTH Aachen University using a HIP unit "Shirp 20/30-200-1500" by ABRA Fluid AG (Widnau/Switzerland). Prior to HIP, the capsules were prepared for the cycle. They were cleaned with isopropyl alcohol and a long filling pipe was TIG-welded to the L-PBF-built socket. A minimum quantity of powder was calculated as the product of capsule volume and tap density. At least this minimum quantity was filled into the capsules using a vibration table. After filling, the capsules were evacuated and sealed.

As the results of the study should be transferable into industrial applications as seamless as possible, HIP parameters were chosen which are considered standardized industrial parameters: $T_{HIP}$ = 1125 °C, $p_{HIP}$ = 110 MPa and $t_{Hold}$ = 3 h. The pressure was applied starting at 750 °C.

## Results & Discussion

*L-PBF of Capsules.* The capsule design used for the investigations is shown in Figure 1: The technical drawing on the left illustrates the dimensions. The wall thickness, which is specified as 2 mm, is variable: Capsules with 1.0 mm, 1.5 mm and 2.0 mm wall thickness have been built. The experiments showed that using L-PBF, a minimum wall thickness of 1.0 mm is required in order to build gastight walls.

The wall thickness of 1.5 mm in the upper part of the capsule according to Figure 1 was not varied. This thickness was necessary to join a filling and evacuation tube by means of TIG welding.

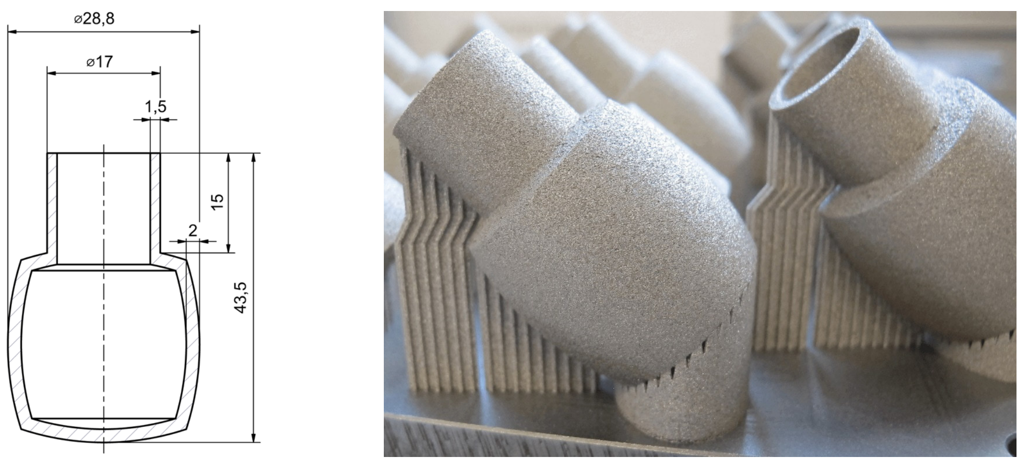


*Figure 1: Capsule design. Left: capsule geometry, right: L-PBF-made capsules of 316L.*

Capsules made of 316L and L6 could be successfully built with several combinations of L-PBF process parameters [6].

For A11 however, the L-PBF-building turned out to be challenging. The material forms martensite when it cools down because of the high C content. As martensite is brittle and leads to high stresses, cracks and delaminations occur after L-PBF. Two possible solutions were examined:

Martensite start temperature of A11 is about 230 °C to 300 °C. Using a heating system which is capable of heating the building plate to 300 °C in order to build above martensite start

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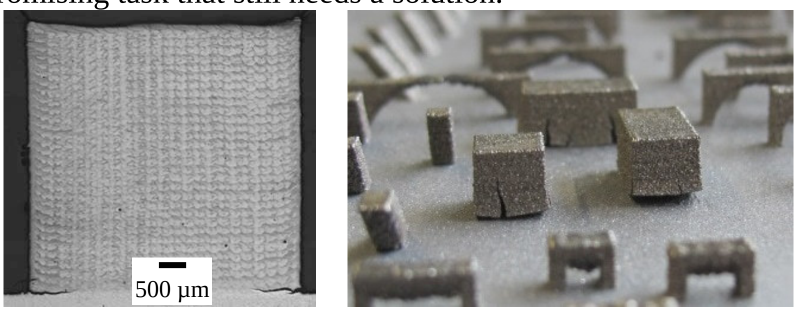
temperature was not successful either: Cubes with a height of about 5 mm could be built. However, they showed cracks, some of which reached almost through the entire component.

The second approach was to develop an alloy that makes it possible to process the high-carbide steel. A11 was mixed with different ratios of 430L. Using a 430L content of over 17.5 wt-% and pre-heating to 300 °C, cubes with only few cracks could be produced (Figure 2, left). The same result could be reached for a mixture of 50 wt-% 430L and using 80 °C substrate temperature (Figure 2, middle).

A major disadvantage of the powder mixture is a loss in hardness, see Figure 2, right. Since the capsules are intended to serve as wear protection, the hardness must be sufficient for the application. Whether the hardness loss can be accepted must be decided on a case-by-case basis. Developing a HIP can of wear resistant material, such as A11 through AM, remains a very promising task that still needs a solution.




| Ratio 430L [wt-%] | HV10 [-] |
|---|---|
| 0 | 836 ± 29 |
| 17.5 | 784 ± 10 |
| 50 | 475 ± 20 |

*Figure 2: Nearly crack-free cube of A11 + 17.5 wt-% 430L (left); small parts of A11 + 50 wt-% 430L (middle); hardness HV10 of A11 and mixtures (right).*

*HIP of Capsules and Numerical Finite Element Simulation.* All L-PBF-built capsules could be successfully compacted by HIP to full density. When the wall thickness was below 1 mm, the capsules could not be densified successfully. Obviously the capsules were not gastight.

Using a numerical simulation routine that was developed by IWM it is possible to predict shrinkage and densification during HIP [7]. For this simulation, the capsules were modeled in the FEM software Simulia Abaqus and provided with input parameters: certain material parameters and relative powder density from filling. A homogenous density distribution was assumed. Figure 3 shows a comparison between the real HIPed and the simulated capsule shape of a capsule where capsule and bulk are made of 316L.

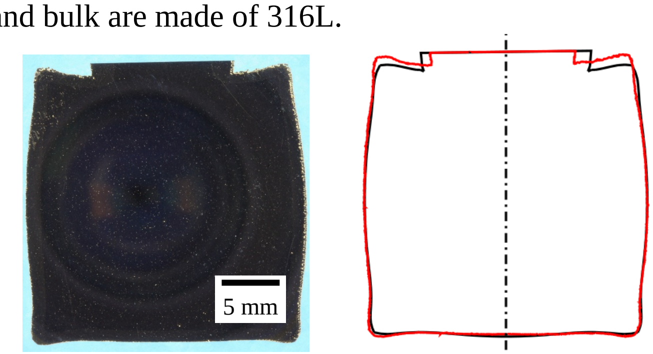



*Figure 3: Outline of real HIPed vs. simulated capsule shape: capsule/bulk 316L.*

*Metallographical Investigation.* In Figure 4 two benefits of the HIP treatment are illustrated for A11 and for 316L respectively: For each material, on the left side a component as-built, i.e. after L-PBF, is shown. A number of pores and voids are visible and structures similar to welding

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beads, that are artifacts of the L-PBF building. On the right side, the condition after HIP is shown: All inner pores are closed. Furthermore, the L-PBF structure is vanished. Obviously, HIP resulted in a macroscopic homogenization of the material. For 316L after HIP, the grain boundaries were highlighted by etching.

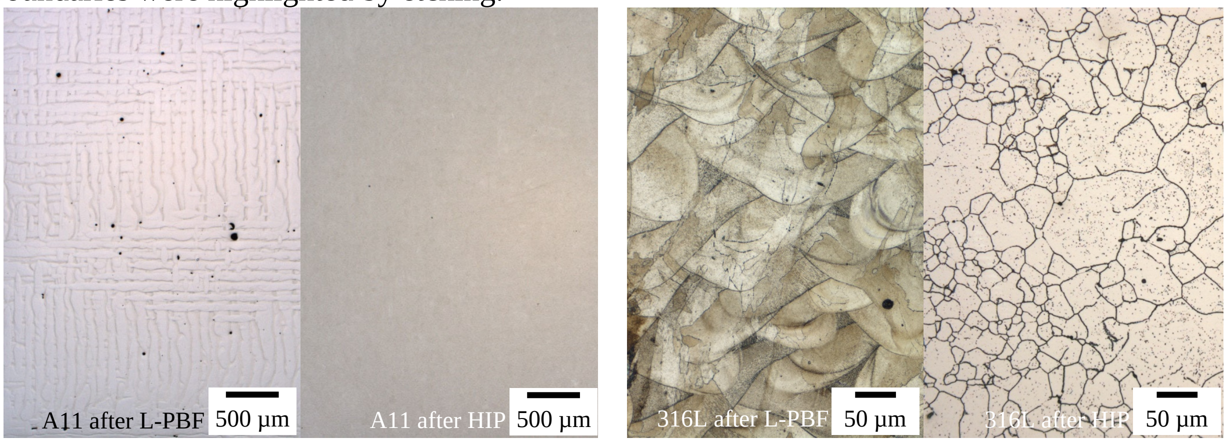


*Figure 4: Optical light microscopy images before and after HIP of A11 (left) and 316L (right).*

The structure after HIP (capsule and filling: 316L; wall thickness: 1 mm) is shown in Figure 5. The metallographic cross section was prepared by grinding, polishing and etching according to Beraha III. The different colouring from light blue to orange-brown may be misleading: It does not allow any conclusions to be drawn about the microstructure.

Although different 316L powder grain sizes were used for capsule (grain size: -53 +20 µm; D50 = 46 µm) and filling (grain size: -500 +0 µm; D50 = 197 µm), the grain sizes no longer differ after HIP. HIP obviously causes recrystallization in capsule and bulk, thus generating evenly sized grains.

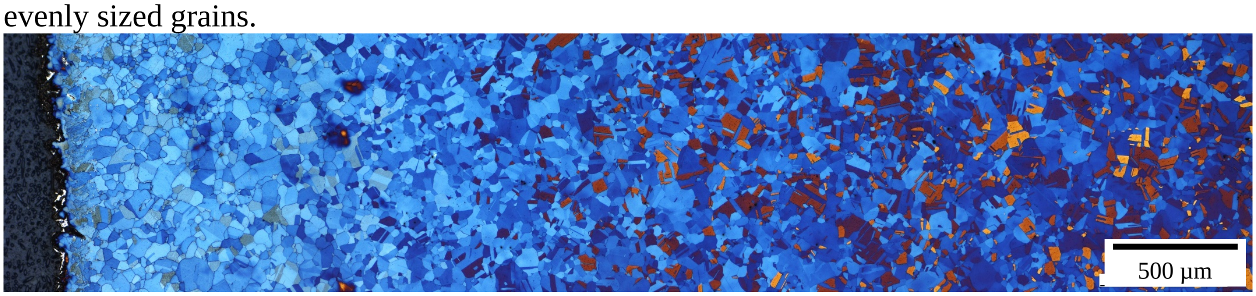


*Figure 5: Microstructure after HIP: capsule 316L, bulk 316L.*

Figure 6 shows a cross section of a composite capsule after HIP, where the walls are made of 316L and the filling of L6. At the outside of the wall, some open porosity is clearly visible, reaching up to 200 µm inwards. This jagged surface must be appropriately considered in industrial applications. The interface between these two materials can be well seen, though there is no separation or voids. The quality of the HIP bond still needs a special evaluation

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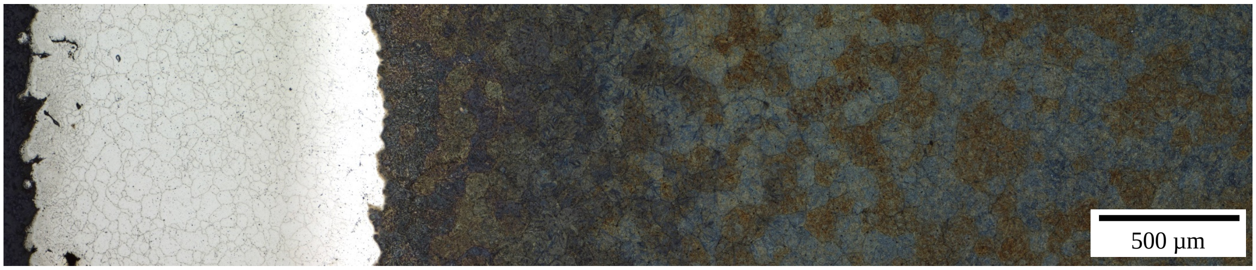


*Figure 6: Microstructure after HIP: capsule 316L, bulk L6.*

A higher magnification of the interface between capsule and bulk can be seen in Figure 7. The numbers indicate the approximate locations where EDX measurements were made. The diagram shows how the content of chromium and nickel decreases at the transition from the capsule to the inside. Apparently, a diffusion zone of 20 µm to 30 µm is formed.

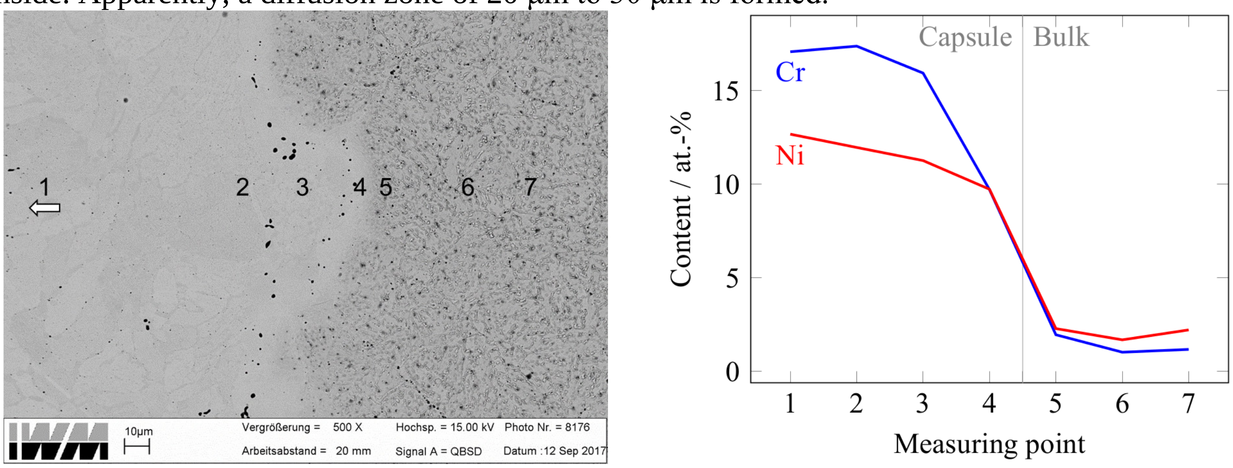


*Figure 7: EDX at intersection between capsule (316L) and bulk (L6).*

## Summary and Outlook

The combination of AM and HIP can be used to easily build complex and irregular-shaped capsules. A hollow capsule is made of wear- or corrosion-resistant steel and filled with a tough steel powder. 316L and L6 can be well manufactured via L-PBF. In order to process the high-carbide steel A11, further parameter investigations must be carried out.

First microscopic examinations of the capsules produced in this way after HIP seem promising. Pore-free compaction was achieved and the materials bonded well. In further investigations, the components must be qualified in comparison to conventionally manufactured components, especially regarding key features such as hardness of A11 and bonding of capsule and bulk.

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