Hybrid additive manufacturing of hot working tool steel H13 with dissimilar base bodies using Laser-based Powder Bed Fusion

Lukas Langer¹, Matthias Schmitt¹, Jaime Cuesta Aguirre¹, Georg Schlick¹, Johannes Schilp¹,²
¹Fraunhofer Institute for Casting, Composite and Processing Technology IGCV, Am Technologiezentrum 10, 86159 Augsburg, Germany
²University Augsburg, Eichleitnerstr. 30, 86159 Augsburg, Germany
lukas.langer@igcv.fraunhofer.de

Abstract. Hybrid additive manufacturing (HAM) describes the combination of additively built structures onto a conventionally manufactured base body. The advantages of both manufacturing processes are combined in one process chain. As a result, new applications can be achieved with higher cost-effectiveness. With the Additive Manufacturing (AM) process a bonding zone is created that is comparable to a welded joint. In order to evaluate the quality and mechanical properties of the bonding zone, two steels (42CrMo4 and 25CrMo4) are investigated as base body materials with the hot working tool steel X40CrMoV5-1 (AISI H13) for the AM structure. Process parameters for Laser-based Powder Bed Fusion of X40CrMoV5-1 are developed to achieve a crack and defect free structure as well as an optimized bonding zone in dependency of the base body material. Furthermore, the chemical and mechanical properties are examined in the as-built and heat-treated state. It is observed that a crack-free material bonding is possible and samples with relative densities above 99.5% are obtained. The size of the bonding zone depends on the material of the base body as well as post-process heat treatment. An average hardness of 600 HV1 can be achieved in the “as-built” state.

Keywords: dissimilar joint; hybrid manufacturing; hot working tool steel; bonding zone; AISI 4130; AISI 4140

1. Introduction

1.1. Initial situation
The motivation for Hybrid Additive Manufacturing (HAM) is the combined use of the advantages of Conventional Manufacturing (CM) and Additive Manufacturing (AM). Due to short lead-times and design freedom of prototypes AM and especially Laser-based Powder Bed Fusion of Metals (PBF-LB/M) is gaining relevance, not only in research applications [1]. The advantages of CM like turning and milling are the very well approved and common technologies, as well as fast and price-efficient
manufacturing with high lot-sizes. By using HAM it is possible to manufacture economical and resource-efficient parts with challenging design or individualized structures on top of repeating and simple structures in the base body, as well as worn out parts [2–4]. By HAM 2D multi-material can be realized for even higher resource efficiency and ideal material properties of the final part. In Fig. 1 a schematic illustration of HAM is displayed. In comparison to regular PBF-LB/M the AM part will be not built upon a base plate and separated from it after the build job. The final, hybrid part consists of the base body and the AM part. By re-melting the base body and solidifying the powder layers of the AM part, a bonding zone is created. The joining of the two alloys is critical for the mechanical properties of the whole part. In this research the properties of the bonding zone will be investigated.

Fig. 1. Schematic illustration of a hybrid additive manufactured part. Magnification of bonding zone with heat affected and re-melting zone in base body with first, solidified layer in AM part. AM part with stylized melt pools in the bonding zone.

1.2. Material combination

Two alloys as base body material will be compared. Since 25CrMo4 and 42CrMo4 are only differentiated by their nominal carbon content, the influence of the carbon content in the base body for the properties and quality of the bonding zone will be directly compared. In Table 1 the nominal element composition of the alloys are displayed. The actual element composition of the powder feedstock (X40CrMoV5-1) was measured by Optical Emission Spectroscopy.

Table 1. Element composition of 25CrMo4 and 42CrMo4 according to DIN EN 10250 [5], X40CrMoV5-1 according to ASTM-A681 [6].

| Element composition |
|----------------------|
| Alloy | C | Cr | Mo | V | Fe |
| 25CrMo4 | 0.22-0.29 wt.% | 0.90-1.20 wt.% | 0.15-0.30 wt.% | - | balance |
| 42CrMo4 | 0.38-0.45 wt.% | 0.90-1.20 wt.% | 0.15-0.30 wt.% | - | balance |
| X40CrMoV5-1 | 0.32-0.45 wt.% | 4.75-5.50 wt.% | 1.10-1.75 wt.% | 0.8-1.2 wt.% | balance |

For better readability X40CrMoV5-1 will be named according to the ASTM standard AISI H13, while the base body alloys will be named according to their shortened European names 25CrMo4 and 42CrMo4. Since there are broad applications for hot working tool steels like H13 several research for AM has been conducted. The Carbon content of H13 is high, compared to alloys commonly processed in PBF-LB/M (e.g. 0.02 wt.% Carbon content in 316L), so weldability is reduced with tendency for cracks [7]. This can be compensated by higher platform heating or optimized process parameters [8].

In this research process parameters with 200 °C platform heating have been developed for producing dense and crack free parts of H13 and dissimilar joinings with 25CrMo4 and 42CrMo4.

1.3. Objective and approach

Hot working tool steels offer a broad range of industrial applications. Due to the design freedom especially in AM there is a rising demand for new materials [1]. Objective of this research is to develop process parameters for PBF-LB/M and to analyze the bonding zone of two material combinations in hybrid manufactured parts for gaining insight in 2D material combinations and hybrid manufactured parts in particular.
Initially the powder feedstock is characterized, a parameter study is conducted, hybrid parts are manufactured by PBF-LB/M and subsequently heat treated. Metallurgical and mechanical properties are systematically investigated on cross sections.

2. Experimental methods

Before specimens were produced, the powder feedstock of AISI H13 from Nanoval GmbH, Germany, was characterized. Gas atomized powder with a Particle Size Distribution (PSD) of +10/-45 µm was used for all the investigations. Samples were taken from virgin, unused powder, as well as after approx. 10 recycling stages used in PBF-LB/M process and sieved with 63 µm mesh size. Carbon content was determined with a LECO CS-200 in accordance to ASTM E1019-18 [9] and DIN EN ISO 15350-10 [10]. For qualitative inspection of powder morphology, the microstructure of etched cross-sections and local element composition of cross-sections a Hitachi TM3030Plus Scanning Electron Microscope (SEM) with Energy Dispersive X-ray Spectroscopy (EDS) was used. Heat treatment was performed with mono material, as well as HAM specimens in a chamber furnace from Nabertherm GmbH, Germany. The chamber was constantly flushed with 8 L/min Argon inert gas. For determining the influence of the PBF-LB/M process and the heat treatment on the element composition, Optical Emission Spectroscopy (OES) was carried out with a SpectroLab M10. The surfaces analyzed by OES were grinded before measurement. The qualitative metallographic analysis of cross-sections was performed with an Olympus BX53M upright light microscope. Relative density was measured by threshold analysis with a Keyence VK-9710 Laser microscope. Micro hardness was measured with a Zwick ZHU/Z2.5 hardness machine. Cross-sections are polished and etched with 5% Nital at room temperature for approx. 120 s.

All specimens were manufactured on a SLM 125 HL PBF-LB/M machine from SLM Solutions Group AG, Germany. It is equipped with an Ytterbium fiber laser with 1070 nm wave length and spot diameter of 65 µm. All specimens were manufactured with 200°C platform heating and a layer height of 30 µm.

For manufacturing dense and crack free mono material (MP) and hybrid parts (HP) a parameter study was performed. The PBF-LB/M process parameters laser power (P), scanning velocity (v) and hatch distance (h) are initially based on literature research [11–15].

The parameter study consists of 60 parameter sets within the following range:

- P: 120-400 W
- v: 350-1000 mm/s
- h: 0.09-0.11 mm

Three parameter sets with highest density were used to manufacture HP on two different base materials (42CrMo4 and 25CrMo4). The base materials were selected by means of carbon content (high and low), price of bulk material and by promising material properties for the application in injection parts of piston engines.

After investigating the micro hardness and microstructure of MP in as-built (AB) and two different quenched and tempered conditions (QT\textsubscript{1}, QT\textsubscript{II}) the bonding zone of HP was investigated by means of micro hardness, microstructure (qualitatively) and local element composition. In Table 2 the pre-selected heat treatment parameters are given. All heat treated specimens were austenitized and quenched according to Table 2, differing in the temperature during the tempering step.

| Stage            | Temperature | Time (holding) | Medium   |
|------------------|-------------|----------------|----------|
| Austenitization  | 1050 °C     | 15 min         | Argon    |
| Quenching        | Room Temp   | -              | Oil bath |
| Tempering I      | 550 °C      | 4 h            | Argon    |
| Tempering II     | 610 °C      | 4 h            | Argon    |

Table 2. Parameters of heat treatment. QT\textsubscript{1} corresponds to Austenitization + Quenching + Tempering I. QT\textsubscript{II} differs in the temperature during tempering (610 °C).
The transition from the base body to the AM part in HP is described by the following terminology:

- **Interface**: The interface in HP is described as the physical boundary between the base body and the AM part. It is defined by the first solidified lower melt pool on the base body, (see Fig. 1 and Fig. 2). It is visualized in cross sections by etching with 5% Nital. The difference in microstructure causes a visible contrast in the interface. Re-melting, and heat affecting the base body lead to an expanded interface in build direction. Below the interface it is assumed to be pure base body material. In order to characterize the size more accurately the interface is used to define a zero point for micro-hardness profile and element composition.

- **Bonding zone**: The bonding zone is defined as the area, where due to re-melting and diffusion in particular a transition in metallurgical and mechanical properties is measured. Below the bonding zone it is assumed to be pure base body material and above the bonding zone in build direction it is pure AM part material. In the investigated two material combinations the base body has a lower hardness than the AM part. Therefore the end of the bonding zone is defined by an abrupt increase in hardness with a high gradient. It is followed by a region with a low gradient until the mono material properties are reached.

![Fig. 2. Cross section of a 25CrMo4 | H13 hybrid part parallel to build direction. To visualize the terminology of interface and bonding zone the specimen is etched for 120 s with 5% Nital and relevant regions are marked.](image)

3. Results and discussion

3.1. Powder characterization

Since in PBF-LB/M only a small fraction of the utilized powder is solidified, the majority is sieved after the buildjob and can be reused. The powder feedstock in virgin (unused) and recycled (approx. 10x sieved and reused powder) state is compared.

Compared to the virgin feedstock no significant loss in qualitative morphology, carbon content \( C_{\text{virgin}} = 0.386 \text{ wt.\%}, C_{\text{recycled}} = 0.381 \text{ wt.\%} \) was measured. The Basic Flow Energy (BFE) of the Rheometer analysis is a parameter for comparing the cohesive force between the powder particles by applying a constant force. In Table 3 BFE, Stability Index (SI, tendency for de- or agglomeration) and Flow Rate Index (FRI, change in flowability by applying changing force) for virgin and recycled Powder is given. The reduced BFE is in the same scale as the standard deviation (SD), hence no significant change in flowability could be found.
Table 3. Results of Rheometer analysis of virgin and recycled AISI H13 powder. BFE: Basic Flow Energy; SI: Stability Index; FRI: Flow Rate Index; SD: Standard Deviation

| Powder condition | BFE  | SI   | FRI  |
|------------------|------|------|------|
| Virgin           | 601.7 mJ | 0.95 | 1.18 |
| SD               | 38.8 mJ  | 0.09 | 0.04 |
| Recycled, 10x    | 575.0 mJ | 0.91 | 1.12 |
| SD               | 32.3 mJ  | 0.07 | 0.04 |

3.2. Mono material specimens
Initially a full parameter study with 60 parameter sets (see section 2) was conducted. Cubes with an outline of 10 x 10 x 10 mm$^3$ were manufactured directly on the build plate (material: X2CrNiMo17-12-2). The relative density was measured by Archimedes method. The highest densities achieved were between 98.0 and 98.3% (with 7.9 g/cm$^3$ as reference). Due to the quite low densities, the four best parameter sets were used to manufacture MP specimens again. These specimens were cut parallel to the build direction for metallographic analysis. Relative density was measured by threshold analysis and resulted in densities over 99.9%. In Table 4 three parameter sets are given with the corresponding densities by Archimedes and laser microscopy. A detailed comparison of both methods is given by Spierings et al. with a similar deviation in densities using microscopy compared to Archimedes method [16]. Since the size, morphology and distribution of defects were taken into account, densities were calculated by microscopy for selecting the best process parameter. Images were taken at 50x magnification at three random points of the cross section.

Two parameter sets were selected by their highest density (E1.2 and A1.6). Since the scanning velocity is effecting the process productivity, one set with highest scanning velocity v (C1.8) was selected for comparison. These three parameters were used for manufacturing hybrid parts.

Table 4. 3 of 60 parameter sets for further analysis, chosen by means of max. relative density and scanning velocity

| Parameter set | h   | P    | v    | Archimedes density | Microscopy density |
|---------------|-----|------|------|--------------------|--------------------|
| E1.2          | 90 µm | 245 W | 650 mm/s | 98.36%             | 99.96%             |
| A1.6          | 100 µm | 306 W | 700 mm/s | 97.95%             | 99.93%             |
| C1.8          | 100 µm | 369 W | 1000 mm/s | 97.87%            | no data            |

No cracks could be determined in MP cross-sections. EDS analysis shows an evenly distributed element composition. In Fig. 3 two polished cross sections are displayed. There are partially non-spherical defects, as well as spherical pores visible. No cracks in the volume are visible. In the etched cross section (Fig. 3b) the melt pools are visible.

Fig. 3. Polished cross sections at 50x magnification. Parameter E1.2. a) Arrow is marking a non-spherical shaped defect. b) Etched with 5% Nital. Arrow is marking a spherical pore.
The main alloying elements (Iron, Chromium, Molybdenum and Vanadium) are measured by OES comply with the requirements of ASTM A681-08 (see Table 2). The comparison between as-built and heat treated conditions shows no significant influence of quenching and tempering in terms of element composition. The inspected surface of each specimen was grinded before measurement, therefor the values given in Table 4 are mean values close to the surface. A mean carbon loss of 2.5% is measured, comparing the powder feedstock before the build job and the mean OES values of the manufactured parts. Carbon and other alloying elements loss after solidification can be expected due to the high energy density and the process temperature. In this case just a small amount of carbon is lost due to vaporization in the PBF-LB/M process.

| Element | As-built | QT<sub>I</sub> | QT<sub>II</sub> | Reference |
|---------|----------|--------------|---------------|-----------|
| Fe      | Balance  | Balance      | Balance       | Balance   |
| C       | 0.372    | 0.369        | 0.38          | 0.32-0.45 |
| Cr      | 5.13     | 5.14         | 5.09          | 4.75-5.50 |
| Mo      | 1.34     | 1.35         | 1.34          | 1.10-1.75 |
| V       | 0.97     | 0.98         | 0.97          | 0.80-1.20 |

Micro hardness was measured across the whole cross section to obtain a mean value. In as-built condition hardness over 600 HV1 is reached. This can be established due to the rapid cooling rates in the PBF-LB/M process. In QT<sub>I</sub> condition hardness is similar to ASTM reference of wrought material. By SEM of the etched micro structures the dissolving cellular fine grain in as-built condition is observed with raising tempering temperature and longer holding time. Though QT<sub>II</sub> results in a hardness below the reference a high toughness is expected. Therefore both heat treatments were carried out at HP, too. Higher deviations in As-built condition were reduced by QT<sub>I</sub>, without a huge loss in hardness.

![Table 6. Mean hardness and standard deviation (SD) of as-built and two heat treatments were measured at bottom, middle and close to the top in build direction. ASTM reference (QT<sub>I</sub>) is given as reference.](image)

| Hardness | Heat treatment condition | Mean   | Standard deviation |
|----------|--------------------------|--------|--------------------|
| As-built | 683.3 HV1                | 23.1 HV1 |
| QT<sub>I</sub> | 570.2 HV1            | 4.4 HV1 |
| QT<sub>II</sub> | 436.7 HV1             | 4.5 HV1 |
| ASTM reference QT<sub>I</sub> | 525 HV1 (min. 52 HRC) |        |

3.3. Bonding zone in hybrid manufactured parts

For characterizing the HP the defects and cracks are measured by microscopy in the full length of the bonding zone (diameter of specimens 24 mm). Parameter E1.2 and A1.6 result in almost the same mean and total length of defects. Although using E1.2 a slightly higher total defect length of 340 µm is measured, higher density in the AM volume was achieved (see Table 4). Parameter set C1.8 with the fastest scanning speed resulted in far longer defects in total (> 1000 µm). It is assumed, that the melt pool morphology in the bonding zone is negatively affected by too high scanning velocity. For further research a combination of E1.2 in the bonding zone and C1.8 in the AM volume will be investigated for optimal bonding and high productivity.
In Fig. 5 the bonding zones of parameter sets E1.2 and C1.8 are displayed. The lower half of the base material (42CrMo4) is identified by the regular pores and defects in build direction. This is due to the rolling direction of the wrought material while production and was already determined in cross sections of the base body without PBF-LB/M. In the first 5-10 layers of the AM part (150-300 µm) accumulated cracks and pores were investigated in all HP. Starting at the interface (see Fig. 5) the bonding zone is formed (see micro hardness profile of HP). Due to their small size (mean defect length < 20 µm), using parameter E1.2 and their presence in the base body before PBF-LB/M it is assumed to be not critical for realizing hybrid parts. This will be validated e.g. by tensile tests in future research.

In Table 7 the results of defect analysis in HP with 25CrMo4 as base body are displayed. The base body with less carbon content resulted in comparable mean length of defects but almost twice the total length of defects, compared with parameter E1.2 and 42CrMo4. It cannot be explicitly explained by the lower carbon content, since lower carbon content should lead to less susceptibility for cracks. Bischof et al. investigated the crack affinity of hot working tool steel H11 with and without elevated carbon content in detail [8]. It is assumed, that the height of the first powder layer in HAM is crucial for crack propagation, since Bischof et al. are linking melt pool stability and geometry to the layer height, too. Cracks were reduce by adjusting process parameters in the bonding zone, though further research demand concerning the influence of layer height is present. Heat treatment, especially quenching does not lead to propagation of cracks in the bonding zone and have no negative effect on the microstructure in the bonding zone.
Table 7. Defects in HP with 25CrMo4 as base body. It is compared as-built and two heat treatment conditions

| Sample                  | Total number of defects | Mean length   | Total length of defects |
|-------------------------|-------------------------|---------------|-------------------------|
| As-built (E1.2)         | 52                      | 12.42 µm      | 646 µm                  |
| QT_I                    | 64                      | 8.85 µm       | 566 µm                  |
| QT_II                   | 59                      | 9.55 µm       | 564 µm                  |

For quantifying the bonding zone, micro hardness profiles parallel to the build direction were conducted. In Fig. 6 the hardness measurement in a HP with 42CrMo4 is displayed. The starting point of the measurement is marked by the interface. The heat treatments (QT_I and QT_II) did not influence the size of the bonding zone, though a slightly lower gradient was determined compared to the as-built condition. The elevated tempering temperature of QT_II should lead to faster diffusion and therefore to a change in hardness profile, which could not be stated in this research. The hardness in the base body was slightly lower with 25CrMo4 (270-370 HV0.5, compared to 300-400 HV0.5) due to the lower carbon content. The influence of the carbon content on the bonding zone was one scope of this research. There is no significant effect on the size of the bonding zone, though on the resulting hardness. The as-built hardness in the AM part is slightly lower in HP (600 HV0.5) than in MP (683 HV1). This was assumed to be correlated to the 3x higher thermal conductivity of the base body materials compared to the build plate material of the MP build jobs. It was stated, that as long as a sufficient, solid bonding is manufactured in a hybrid manufactured part, after 180-200 µm of build height similar mono material conditions can be reached.

Fig. 6. Micro hardness measured in 42CrMo4 | H13 part parallel to the build direction.

Fig. 7. Chromium distribution by EDS in 25CrMo4 | H13 specimens.
Additionally EDS measurements parallel to the build direction were performed (Fig. 7). Comparing the Chromium distribution, after 600-1000 µm of build height the mono material conditions were reached. This means, in terms of e.g. corrosion resistance the bigger diffusion zone of the elements needs to be considered in hybrid manufactured parts.

This research was finalized with demonstrator geometries (see Fig. 8) for measuring surface and down-skin properties. Further optimization is necessary for reducing post-process machining. For testing the hybrid material combination with bigger volumes a hybrid demonstrator with cooling channels was manufactured on 25CrMo4 (Fig. 8 c). Similar microstructure with low porosity and no cracks in the AM part was observed. The bonding zone was similar to the HP of the previous study.

Fig. 8. a) Test geometries for geometrical accuracy, down-skin quality and minimal resolution. b) Mono material demonstrator for piston application. c) Hybrid demonstrator with cooling channels on top of base body.

4. Conclusion and outlook
The conducted parameter study resulted in mono material parts with density > 99.5%. It was shown, platform heating with 200°C is sufficient for manufacturing crack-free parts, although only small sized geometries (diameter 20 mm, build height 35 mm) were inspected in cross sections.

The influences of base body materials, process parameters, and post-process heat treatment on hybrid manufactured parts were investigated. For evaluating a hybrid part, characterizing the bonding zone is crucial for in HAM. The gained knowledge for manufacturing hybrid parts with dissimilar base bodies can be summarized in:

- Process parameters for manufacturing mono material parts were utilized without further adjustment necessary for manufacturing hybrid parts in two material combinations 42CrMo4 | H13 and 25CrMo4 | H13. No defects in the bonding zone were observed and the density is comparable with mono material parts.
- For evaluating the interface between base body and AM part a bonding zone was defined. It is quantified and characterized by micro hardness profile, element composition and optical inspection of etched cross sections. This procedure can be transferred to other material combinations and LPBF-LB/M machines.
- Depending on the heat treatment and the base body material, a bonding zone of 200-500 µm is determined. Element diffusion, re-melting and heat affected zone are affecting the size and hardness in the bonding zone and need to be considered in hybrid parts according the application and the heat treatment.
- Inside the bonding zone no cracks greater than 50 µm, in total 350 µm after optimization and a gradient in hardness is observed. Outside the bonding zone the mono material properties are present (hardness >600 HV1). Outside the bonding zone the element composition in quenched and tempered AISI H13 is not affected by the material combination and no cracks in the AM part are observed.

For a transfer to industrial applications the following topics need to be investigated in further research:
• In piston engine application not only hardness, but also toughness are relevant. Static tensile tests at room and elevated temperature need to be performed at hybrid manufactured specimens.
• The poor surface roughness (Ra=12.3 µm, Rz=128 µm at vertical walls) makes post-process machining crucial for industrial applications. To improve surface roughness and reduce machining costs, advanced contour and down-skin parameters have to be developed.
• The manual positioning of the AM part to the base body resulted in off-sets > 0.1 mm. An enhanced positioning method supported by software is necessary for accuracy < 0.1 mm of the AM part to the base body.

ORCID iDs
L. Langer https://orcid.org/0000-0002-5170-5428
M. Schmitt https://orcid.org/0000-0002-2632-5052
G. Schlick https://orcid.org/0000-0001-5448-0482

References
[1] Wohlers T, Campbell R I, Huff R, Diegel O and Kowen J 2019 Wohlers Report 2019: 3D printing and additive manufacturing: state of the industry (Fort Collins, Colo: Wohlers Associates)
[2] Jacob A, Steimer S, Stricker N, Häfner B and Lanza G 2019 Integrating product function design, production technology optimization and process equipment planning on the example of hybrid additive manufacturing Procedia CIRP 86 222–7
[3] Strong D, Sirichakwal I, Manogharan G P and Wakefield T 2017 Current state and potential of additive – hybrid manufacturing for metal parts Rapid Prototyping Journal 23 577–88
[4] Zhang X, Cui W, Li W and Liou F 2019 A Hybrid Process Integrating Reverse Engineering, Pre-Repair Processing, Additive Manufacturing, and Material Testing for Component Remanufacturing Materials (Basel, Switzerland) 12
[5] 2020 DIN EN 10250-3, Open die steel forgings for general engineering purposes - Part 3: Alloy special steels (Berlin: Beuth Verlag GmbH)
[6] 2008 A 681 – 08 Standard Specification for Tool Steels Alloy (West Conshohocken, PA: ASTM International)
[7] Wenz T, Kirchner A, Klöden B, Weißgärber T and Jurisch M 2020 Processing of high carbon steel by Selective Electron Beam Melting (SEBM) steel research int.
[8] Bischof C, Scheitler C and Kniezel L 2016 Influence of preheating Temperature and Carbon Content on crack formation during Laser Beam Melting of AISI H13 Tool steel iCat 2016
[9] 2018 ASTM E1019-18, Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys by Various Combustion and Inert Gas Fusion Techniques (West Conshohocken, PA: ASTM International)
[10] 2010 DIN EN ISO 15350, Steel and iron - Determination of total carbon and sulfur content - Infrared absorption method after combustion in an induction furnace (Berlin: Beuth Verlag GmbH)
[11] Åsberg M, Fredriksson G, Hatami S, Fredriksson W and Krakhmalev P 2019 Influence of post-treatment on microstructure, porosity and mechanical properties of additive manufactured H13 tool steel Materials Science and Engineering: A 742 584–9
[12] Šafka J, Ackermann M and Voleský L 2016 Structural properties of H13 tool steel parts produced with use of selective laser melting technology J. Phys.: Conf. Ser. 709 12004
[13] Hengsbach, F., Koppa, P., Holzweissig, M.J. et al. 2018 Inline additively manufactured functionally graded multi-materials: microstructural and mechanical characterization of 316L parts with H13 layers Prog Addit Manuf 3 221–31
[14] Laakso P, Riipinen T, Laukkanen A, Andersson T, Jokinen A, Revuelta A and Ruusuvuori K 2016 Optimization and Simulation of SLM Process for High Density H13 Tool Steel Parts *Physics Procedia* **83** 26–35

[15] Ren, B., Lu, D., Zhou, R. et al. 2019 Preparation and mechanical properties of selective laser melted H13 steel *Journal of Materials Research* **34** 1415–25

[16] Spierings A B, Schneider M and Eggenberger R 2011 Comparison of density measurement techniques for additive manufactured metallic parts *Rapid Prototyping Journal*