SEBM processing of 42CrMo4

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Abstract
Powder bed fusion of difficult-to-weld-steels such as the 42CrMo4 applied in this study is a challenging task. These materials are often susceptible to crack formation. To minimize thermal gradients and residual stresses, laser beam technologies generally require preheating of the substrates. Selective Electron Beam Melting (SEBM), on the other hand, is based on preheating the powder bed and, thus, enables crack-free printing even at greater heights. The present study demonstrates the processing of 42CrMo4 by SEBM. Besides parameter optimization, powder analysis, microstructural characterization as well as mechanical testing were carried out both for the as built and heat-treated conditions. The results indicate that the mechanical properties are comparable to those of conventional manufacturing technologies. Furthermore, a generic demonstrator with complex structures shows the high potential of SEBM for these particularly challenging steels.

Keywords Additive manufacturing · Selective electron beam melting · Martensitic steel · Hardness · Microstructure

1 Introduction
42CrMo4 belongs to the high strength martensitic steels. Due to their well-defined mechanical behaviour and good ductility as well as wear resistance and toughness, these steels have a wide range of applications. For instance, they are used in the automotive sector, as gearing components, drive or camshafts, diesel injection systems or in hydraulic systems for pumps, vessels and pistons [1]. From an economic point of view martensitic tempering steels are less expensive compared to austenitic stainless steels [2].

Heat treatments based on quenching and tempering and sometimes also nitriding are common.

The extraordinary properties, however, are accompanied by a more difficult machinability and weldability. This can be explained by the comparatively high carbon content (0.4 wt%), which has a direct influence on crack susceptibility and wear resistance.

To reduce machining efforts, Additive Manufacturing (AM) is of particular interest, the powder bed fusion (PBF) technologies for fabricating metallic components especially.

Nevertheless, the limited material diversity is still an obstacle for the industrial implementation of AM processes like laser or electron beam PBF (L-PBF or E-PBF) in the steel sector.

According to literature, 1.3340 (AISI M2) [3], 1.2344 (H13) [4–7], 1.2343 (H11) [8], FeCrMoVC [9], X110CrMoVa1 8–2 [10], X40CrMoV5-1 [11], X65MoCrWV3-2 [12], CP2M® [13] and Rapidur PM-23® [14] belong to the martensitic steels that are evaluated for PBF. The formation of martensite leads to high residual stresses during laser PBF, which can lead to cracking and distortion of the components [6]. These problems can be reduced by substrate heating [4]. In the case of larger component heights, however, distortions can occur again as a result of the temperature gradients and inhomogeneous microstructures.

Heating the powder bed within each powder layer instead of heating the substrate, like it is done with E-PBF [15], is, therefore, a viable alternative.

E-PBF or Selective Electron Beam Melting (SEBM) is a powder bed based AM technology for the production of complex metallic components based on selectively melting the powder in a layer-wise manner which is similar to L-PBF [15]. The repeated heating steps result in the reduction of thermal stresses by holding the powder bed at elevated temperature up to about 1100 °C. Additionally, the electron beam is capable of high energy densities and build rates (e.g. 55–80 cm³/h for Ti-6Al-4 V [16]).
In this paper, the SEBM processing and heat treatment of the alloy 42CrMo4 and subsequent mechanical properties are investigated.

2 Materials and methods

2.1 Powder and process

Gas atomized 42CrMo4 powder with an approximate particle size between 53 and 150 µm was supplied by M4P, Germany. Flowability was characterized for 50 g of as-received and processed powders by means of a calibrated funnel with 2.54 mm diameter (Hall flowmeter, DIN ISO 4490). The measurement of the particle size distribution was assessed according to ISO 13320 (Table 1).

Table 1 Powder size distribution of the powder in different states

| Number of builds | D (10%) | D (50%) | D (90%) |
|------------------|---------|---------|---------|
| 0 (µm)           | 70.4    | 97.1    | 154.5   |
| 11 (µm)          | 75.2    | 104.1   | 164.3   |

Table 2 Powder flowability parameters of the as-received and processed powder

| No. of builds | Hall flow (50 g) | Density (g/cm³) |
|---------------|------------------|-----------------|
|               |                  | Apparent | Tapped | Pycnometer |
| 0             | 14.7             | 4.51      | 5.07    | 7.78       |
| 11            | 14.5             | 4.54      | 5.07    | 7.79       |

Apparent and tap densities were measured by the funnel method (DIN ISO 3923 and DIN ISO 3953) according to Table 2. The chemical composition was determined using a Thermo Scientific 6300 DUO ICP-OES and a LECO TCH600 and CS 230 as given in Table 3.

Table 3 Nominal chemical composition of the powder

| Element | O | C | Si | Mn | Cr | Mo | Fe |
|---------|---|---|----|----|----|----|----|
| wt-%    | 0.02 | 0.40 | 0.1 | 0.9 | 1.0 | 0.2 | Bal. |

3 Results and discussion

3.1 Powder analysis

The 42CrMo4 powder was analyzed regarding its composition, flowability and shape before and after several build jobs. While the composition did not reveal any changes and matches with the manufacturer’s data, the flowability seemed to be slightly improved (Table 2).

Figure 1 shows the micrographs of the powders before and after processing by SEBM. The nearly spherical particles shape and their smooth surfaces correspond to the good flow ability. Nevertheless, there are some hollow spheres...
and elongated particles, which can influence the build quality, as well as some satellites that still exist in the recycled powders. The etched cross-sections exhibit a microstructural change, which is related to a heat treatment in the course of the increased process temperatures. After 11 build jobs the medium particle size increased \( (D_{11 \text{ Jobs}}) = 104.1 \, \mu\text{m}) \), whereas the amount of finer particles was reduced. The comparison of both powder size distributions is given in Table 1 and Fig. 2.

While the impurity levels did not change in case of oxygen and nitrogen, a slight decrease of 50 ppm in carbon was measured.

### 3.2 Microstructure

The assessment of the process development was determined based on metallographic cross-sections and microstructural characterization.

Depending on the range of process parameters, densities of up to 99.90% could be obtained for energy densities of at least 3 J/mm². Figure 3 shows that for beam powers of at least 15 mA the majority of the samples showed crack formation oriented along the grain boundaries of elongated grains in build direction.

In case of 3 J/mm² samples with porosities of less than 0.1% without any sign of crack formation could be obtained.

Depending on the cooling rates in the SEBM machine and the hardness achieved, the microstructure (Fig. 4) can be attributed to ferrite (light) and pearlite (dark) in accordance with the time temperature transformation diagram in [1]. Ferrite was built on former austenitic grain boundaries.

Caused by the change in scan length when melting vertically oriented cylindrical samples and due to the faster cooling at the outer positions near the powder bed, the edges revealed finer grains than the center of the specimens which is shown in Fig. 5. Also a slight increase in porosity was detected over the cross-section of the samples. For the specimen in Fig. 5 a porosity of 0.03% in the middle and 0.25% in the fine grained outer ring was measured, respectively.

With the parameter set of Fig. 5 a design demonstrator was built up (Fig. 6). Pre- and post-heating parameters were slightly adapted to account for the variable sample geometry.

The design demonstrator was analyzed by means of 3D measurement. Minimum feature sizes like walls or holes of 0.8 mm with an average deviation of ± 0.4 mm were determined. However, vertical overhangs led to greater distortions, which underlined the need for support structures.

### 3.3 Mechanical properties

Mechanical properties were analyzed using samples in the as-built as well as heat-treated state. The hardness measurements resulted in a microhardness of 287 ± 5 HV1 (Fig. 7), which is slightly above the hardness in the soft annealed state [1]. This can be attributed to the in situ heat treatment...
at 850 °C during SEBM and conforms to the pearlitic phases from the micrographs (Fig. 4).

The subsequent heat treatment of the specimens was done to raise the hardness up to the target value of 370 HV. A first heat treatment resulted in slightly lower values due to diverging tempering times. A second heat treatment was done to obtain the targeted hardness. Ultimate tensile strength and elongation at break from both treatments compared to the as-built state are given in Figs. 8 and 9, respectively.

The values are in good agreement with the target values according to the data sheet [1]. Even in as-built state the deviations are rather small, which indicates a stable process across the build platform. No further enhancement of tensile strength and a slight increase in elongation from QT- to HIP + QT-state are in agreement with the high initial density of the samples.

Fig. 3 Optical micrographs of SEBM processed 42CrMo4 powder with the following parameters: a 2 J/mm², 300 W, b 2 J/mm², 900 W, c 3 J/mm², 600 W (build direction is vertical)

Fig. 4 Microstructure perpendicular to the built direction with ferrite and pearlite phases

Fig. 5 Micrographs a and b in and c perpendicular to build direction processed with 4000 mm/s and 600 W beam current. Cross-section a and b were obtained from the middle and edge of the sample, respectively
4 Summary and conclusions

Selective Electron Beam Melting of the presented quenching and tempering steel 42CrMo4 was successfully demonstrated for the first time. Therefore, test samples for microstructural analyses as well as a demonstrator were processed.

Due to the susceptibility of this steel to crack formation, maximum beam powers of 600 W and a minimum area energy of 3 J/mm² are suggested.

Mechanical properties are comparable to those of conventionally manufactured 42CrMo4.

Further investigations have to be done in case of differing scan lengths, implementation of support structures and their process parameters. The influence of sample orientation has to be completed additionally by measurement of horizontal specimens.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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