Processing of High-Carbon Steel by Selective Electron Beam Melting

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In addition to the production of lost moulds, additive manufacturing (AM) is increasingly used for the direct manufacture of tools, inserts, or parts thereof. Depending on the material and tool geometry, the combination of additive and conventional technologies (hybrid production) are advantageous. Commercially available AM tool inserts have their limits on the kinds of the materials that can be used. High-carbon, particle-reinforced, or crack-prone materials are indispensable for many areas of tool making but so far can hardly be processed using the common laser-based AM methods, as rapid solidification in these brittle materials results in high residual stresses, which may lead to crack formation. In contrast, selective electron beam melting (SEBM) is working under elevated temperatures of up to 1100 °C and, thus, minimizes thermal stresses. This study shows how such materials can be processed by SEBM. Results are presented for the first-time production of high-carbon iron–chromium alloy. Herein, powder properties and their reusability are focused upon, as well as process parameters and their influence on part quality. Investigations on density, microstructure, and hardness are shown to illustrate the potential of the SEBM process. Final heat treatments reveal that a further increase in hardness is possible in this alloy.

1. Introduction

Nowadays, the production of complex metallic structures can be carried out using powder bed-based additive manufacturing (AM), in which powder is selectively melted layer by layer. One of the most common AM technologies is laser beam melting (LBM).

In addition to classic applications for AM like the aviation or medical sector, the secondary service market, including AM-processed tool segments, is still expanding.[5] AM-based conformal cooling promises a faster product development and a higher degree of freedom compared with conventional cooling for plastic molding. This results in shorter cycle times during plastic part production and higher part quality.[3–4]

Moreover, recycling tools are made of highly wear-resistant materials, such as FeCr–10V, which will be the topic of the current study. Those materials are difficult to machine and, therefore, seem to be suitable for AM production. These highly vanadium carbide (VC)-containing materials can currently be applied only by powder spraying and act as wear protection layers. Due to the limited layer thickness on cutting tools, however, these coatings have to be renewed regularly, which leads to expensive downtimes in production.

Nevertheless, the limited material diversity is still an obstacle to the industrial implementation of AM processes in the tooling sector.

Up to now, expensive precipitation-hardenable materials such as low-carbon maraging steel 1.2709, which is already in industrial use, have therefore been used.[5] However, the production of larger tool inserts requires hybrid production, where only the complex parts of conformal cooling or the difficult-to-machine free-form surfaces are sensibly produced by AM, whereas the larger part is still conventionally manufactured. This saves costs while, at the same time, improving performance. In addition, the combination of 1.2709 with commonly used martensitic steels, which promise higher hardness, can lead to rapid tool failure, as cracking can occur in the often brittle interfacial area.

Materials that are difficult to weld or are susceptible to cracking like the former mentioned martensitic steels or FeCr–10V can currently only be produced to a limited extent or not at all with LBM. Due to the high-temperature gradients resulting from rapid cooling down to room temperature, cold cracks are formed in martensitic materials, for example.

Recent investigations into the use of heaters in the LBM process have now made it possible to process martensitic materials with increased carbon content.[7–11] With regard to the achievable dimensional accuracy and the freedom from cracks even
with complex structures, however, there is still not much literature. As usually only the construction platform is heated, the probability for crack formation is still feasible at a higher distance from the construction platform, i.e., at higher construction heights.

In contrast, selective electron beam melting (SEBM) may be suited for the processing of such materials susceptible to cracking, as each powder layer is subjected to a preheating step, thus preventing the formation of martensite and reducing cooling-induced cracking.\[12\]

In addition, thermal stresses are relieved by the increased temperatures, which in turn result in lower warpage. Moreover, the electron beam is capable of high energy densities and build rates, which even makes it possible to tailor the microstructure (e.g., $55 - 80 \, \text{cm}^3/\text{h}$ for Ti–6Al–4V\[13,14\]).

The aim of this study was to build up a cutting plate made of the material FeCr–10V using SEBM. For this purpose, a process window was derived, and accompanying investigations on powder, microstructure, and heat treatment were conducted.

### Table 1. Particle size distribution of the as-received and processed powder.

| Process step | $D$ (10%) [$\mu$m] | $D$ (50%) [$\mu$m] | $D$ (90%) [$\mu$m] |
|--------------|---------------------|---------------------|---------------------|
| As received  | 67.09               | 93.58               | 154.93              |
| Processed (six jobs) | 62.56               | 89.88               | 151.14              |

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

| Process step | Hall Flow [50 g] | Density [$\text{g cm}^{-3}$] |
|--------------|------------------|----------------------------|
|              |                  | Apparent Tapped Pycnometer |
| As-received  | 16.2             | 4.12 4.81 7.46            |
| Processed (six jobs) | 15.8             | 4.18 4.79 7.45          |

### Table 3. Contents of the main elements in the as-received FeCr–10V powder.

| Element | Fe | Cr | V  | W  | Mo | Si | Mn | C  |
|---------|----|----|----|----|----|----|----|----|
| wt%     | 76.5| 7.0| 10.5| 1.0| 1.5| 1.5| 0.6| 2.4|

The powder showed a particle size distribution between 50 and 150 μm and was produced by gas atomization. Powder parameters were being characterized to inspect the processability. The same powder was used throughout the experiments. After six jobs, the powder was characterized again to determine the changes in powder properties during the process.

Powder analysis was conducted using Hall Flowmeter (ISO 4490) and particle size distribution (DIN ISO 13320), as well as powder, tapped, and apparent densities have been assessed, as shown in Table 1 and 2. The chemical composition of powder and specimens was measured by inductively coupled plasma optical emission spectrometry and infrared absorption and thermal conductivity (LECO analysis) and is shown in Table 3. The microstructures of powder were finally characterized by optical analysis using a light microscope and are shown in Figure 1.

### 2. Processing

#### 2.1. Powder Analysis

The cross snake scan strategy. The electron beam moves from one side of the scanning area to the other and back again. After every layer the scanning direction is changed to minimize the influence of orientation on the microstructure.

### 2.2. Process Window

For all experiments, an SEBM machine (model Arcam A2X) with an accelerating voltage of 60 kV and a build size of 150 × 150 × 10 mm$^3$ was used. A layer thickness of 70 μm was held...
constant during the experiments and was chosen to achieve a maximum part quality. All experiments were conducted with a cross snake scan strategy in which the electron beam repeatedly moves back and forth across the scanning surface, whereas the scanning direction alternates by 90° with each layer (Figure 2).

To figure out the process window, some parameters were varied to examine their potential influence on part quality. For that purpose, 25 cubes (edge length: 10 mm) were built up on one building panel while the following parameter range was examined: 1) hatch distance between 0.05 and 0.2 mm, 2) scan speed between 1000 and 10 000 mm s\(^{-1}\); 3) and beam power between 200 and 1500 W.

After the SEBM process, the samples were solution treated and quenched for hardening and subsequent tempering to improve the hardness and, thus, wear resistance.

2.3. Analysis of the SEBM-Processed Specimens

Optical analysis was used for porosity measurement of SEBM-processed cubes. The cubes were cut in the middle so that the porosity caused by the manufacture process could be evaluated top down.

Furthermore, the microstructure was tested by scanning electron microscopy (SEM) and an energy-dispersive X-ray spectroscopy (EDX) scan was utilized to find out the distribution of the different carbides.

The hardness of the samples was measured by Vickers test and adjusted between 600 and 660 HV by annealing the samples at different temperatures, which are shown in Table 4. For that purpose, the cubic samples were cut in half and the hardness measurement was conducted diagonally over the sample with five indents each.

3. Results and Discussion

Regarding the picture of the powder which is shown in Figure 1, it has to be mentioned that after several jobs, the homogeneous distribution of the carbides decreases, so there are some regions in the structure that show a high content of carbides besides regions which are poor in carbides. However, neither the flow-ability nor the processability regarding the melt quality has changed significantly.

The quality of the SEBM plates ranged from highly porous samples to those with swelling phenomena due to excessive energy input (Figure 3). In general, high velocities led to a less-stable process. The investigations of the process window led to parameters with an area energy of about 4 J mm\(^{-2}\). The lowest porosity measured was 0.2% for a power of 600 W and is shown in Figure 4 next to the microstructure.

The rough surfaces of the samples, which are consequences of both the coarse starting powders and the process parameters, appear insufficient for direct use without post processing.

| Sample | Temperature [°C] | Hold time [h] | Hardness values [HV10] |
|--------|-----------------|--------------|------------------------|
| As built | – | – | 537 ± 32 |
| 0 (hardening) | 1140 | 1 | 814 ± 17 |
| 1 | 550 | 2 | 796 ± 10 |
| 2 | 570 | 2 | 730 ± 8 |
| 3 | 570 | 4 | 667 ± 13 |
| 4 | 580 | 2 | 649 ± 3 |

Figure 3. Surfaces of differently processed cubes: a) 1.2 J mm\(^{-2}\) (10 000 mm s\(^{-1}\)), b) 4 J mm\(^{-2}\) (3000 mm s\(^{-1}\)), c) 4 J mm\(^{-2}\) (2000 mm s\(^{-1}\)).

Figure 4. Porosity and microstructure using light microscope.
The surfaces of commercially available steels produced with LBM are usually much smoother, even though the processing of functional surfaces is also required here. In the present application of cutting plates, machining of the outer surfaces is not necessary, as the cutting edges sharpen themselves in the process. Accordingly, the main focus of the work was primarily on the freedom from cracks, density, and hardness of the specimens. Figure 5 shows a picture made by a scanning electron microscope. The composition was characterized by EDX. The overall composition did not show any significant changes compared with the starting powder (Table 3). Carbon content was measured by LECO analysis and resulted in about 2.3 wt%.

In Figure 6, the distributions of iron, chromium, and vanadium carbides are shown in different colors. The carbides are small and homogeneously distributed in the microstructure with a particle size of less than 2 μm. Apart from vanadium carbides, some chromium- and molybdenum-rich areas could be detected, which indicates that a full-phase transformation, as is to be expected conventionally, has not yet been completed.

The hardness measured on the as-built samples was in average 537 ± 32 HV and, thus, confirms the former assumption. After the hardening process the samples show a hardness of about 814 ± 17 HV, which demonstrates a significant hardening effect (Figure 7). There was no difference between the hardness in the middle and the hardness close to the surface of each sample. However, the standard deviation decreased due to the heat treatment compared with the as-build samples (Table 4). The target hardness of about 649 ± 3 HV could best be achieved with tempering tests at 580°C.

### 4. Conclusion

The processability of the material FeCr–10V using the SEBM method was shown. The highest densities of ≈99.8% and a simultaneously stable process could be found in the range of 4 J mm⁻². This proves that dense and crack-free martensitic steels with carbon contents above 2 wt% can be realized via AM methods.

The obtained microstructures showed a homogeneous distribution of mainly small vanadium carbides. For these parameters additional heat treatment tests were carried out because the as-built hardnesses were well below the target values of about 630 HV. These tests showed that a significant increase in hardness was still possible and that the samples could be further homogenized at the same time. In the future, tests to determine wear resistance will show which hardness range will actually be the best for the AM-processed FeCr–10V.

Finally, powder analyses led to the conclusion that powders could be reused even after repeated processing in the SEBM machine. There were no significant changes in flowability or composition. However, the influence of the microstructural change should be further evaluated in the future.

On the basis of these investigations, cutting plates were constructed both monolithically and in hybrid design, which are to be tested in subsequent investigations for their dimensional accuracy and compound behavior.
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Conflict of Interest
The authors declare no conflict of interest.

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