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ALLIANCE DEEP DIVE | 2021

EXCLUSIVE

POST-PROCESSING OF METAL FUSED DEPOSITION MODELING PARTS

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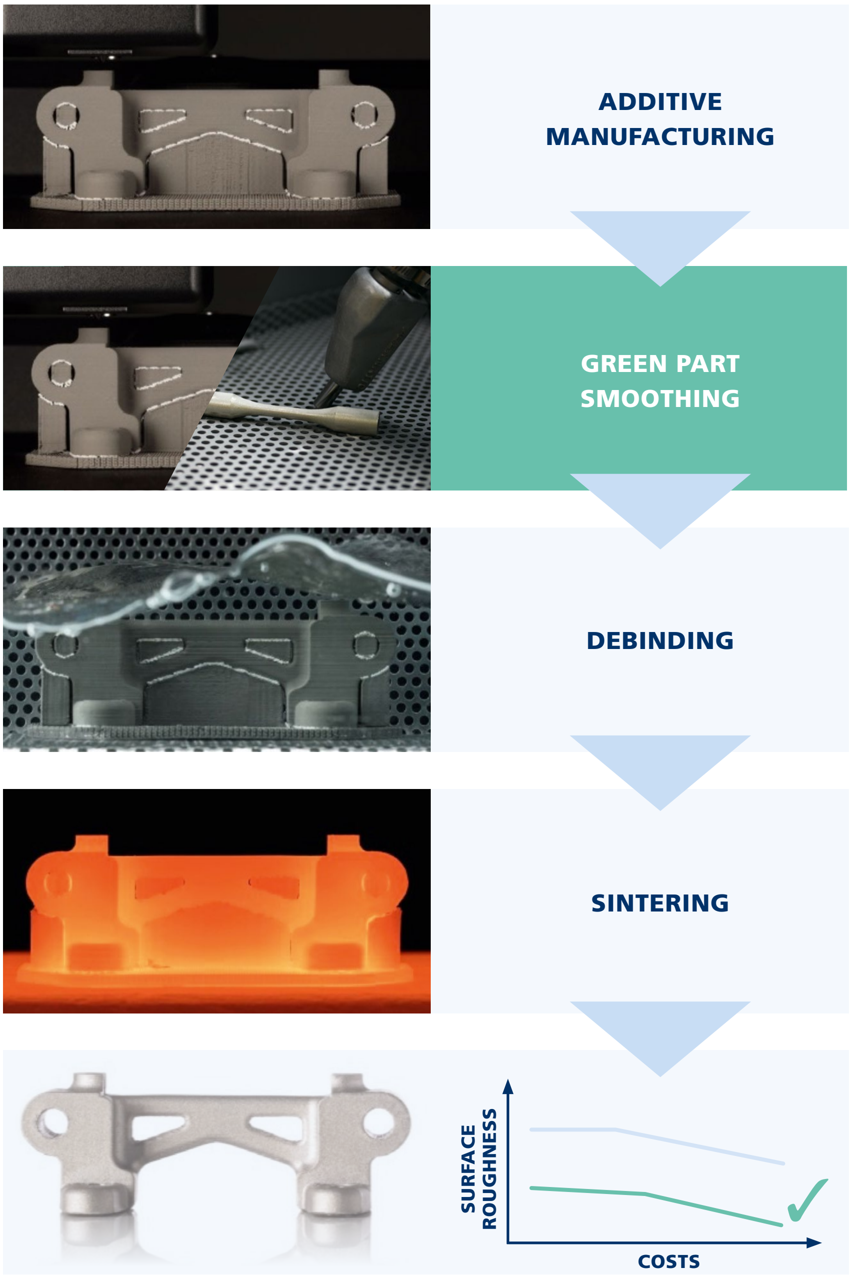
1_ABSTRACT

POST-PROCESSING OF METAL FUSED DEPOSITION MODELING PARTS



2_CONTENT

3_ACKNOWLEDGEMENT

Deep Dives are reports intended exclusively for the members of the Additive Alliance®. They provide latest insights into the science behind additive manufacturing (AM). Our gratitude goes to the following members. This Deep Dive could not have been prepared without their financial support.

3D SYSTEMS	aalberts surface technologies	Additive Industries
AIRBUS	ALTAIR	BeAM an AddUp company
BIONIC PRODUCTION	DB	DMG MORI
eos	FANUC	FFT
GE Additive	HHLA HAMBURGER HAFEN UND LOGISTIK AG	HEXAGON simufact
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amt

Additive Manufacturing Technologies (AMT) assisted us with post-processing of test specimens using their chemical vapor smoothing process.

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4_ABOUT THE AUTHORS

The authors of this Deep Dive are Lennart Waalkes and Kevin Janzen. Their aim is to advance the industrial implementation of sinter-based AM technologies.

Both authors have been working in the field for several years and have conducted and accompanied various research projects. Their goal with the Deep Dive was to generate findings that would remove previous obstacles and contribute to the further development of sinter-based material extrusion such as metal FDM (fused deposition modeling) as a cost-effective and reliable production technology, looking at the entire process chain.

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5_MOTIVATION

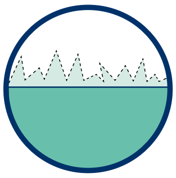
Sinter-based additive manufacturing processes such as metal FDM offer great cost cutting potential compared to established metal AM processes such as laser melting, especially due to low-cost equipment technology [1]. This applies in particular to low-complexity components that are manufactured in small quantities. The greatest drawback and showstopper for the technology consists in significantly lower component resolution and poor surface quality. The latter is caused primarily by the staircase effect typical of FDM, which occurs on all vertical walls of the components and makes them appear very rough [2]. Post-processing methods to improve surface quality after the process increase the lead time as well as the component costs.

This Deep Dive therefore investigates a new metal FDM process chain for parts with improved surface quality. It exploits the fact that during production, the components pass through a green stage with significantly reduced mechanical properties compared to the metallic end product. The hypothesis underlying the Deep Dive is therefore that lead times and thus costs can be reduced because shorter processing times in the green stage are sufficient to produce a required surface quality. In addition, the plastic properties of the green parts permit chemical finishing processes that are not applicable to the post-processing of metal components.

6_APPROACH OF THE DEEP DIVE

6.1_INVESTIGATED PROPERTIES

Sinter-based AM processes are suitable for a wide range of applications in different industries. Surface quality requirements vary greatly depending on industry and application. Meeting these requirements necessitates not only knowing the achievable surface quality of the finishing methods in detail. Selecting the right method for surface smoothing must also give due consideration to possible erosion, edge rounding and, in extreme cases, destruction of the component by the process. The properties investigated in this Deep Dive are presented and explained in the following.

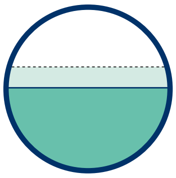


6.1.1_Surface roughness

Surface roughness Sa extends the line roughness parameter Ra (arithmetic mean) to the surface. It describes the difference in height for each point compared to the arithmetic mean of the surface. This parameter is generally used to assess surface roughness and provides a more accurate picture than the previously more commonly used line roughness Ra.

Surface roughness is measured optically with a 3D laser scanning confocal microscope VK-8700 (Keyence). The 3D laser scanning confocal microscope generates a three dimensional scan of the surface by scanning the surface pointwise in all three spatial directions. Three measuring points are evaluated on each surface. The measuring point is divided into six segments with a size of 450 x 450 µm. The given surface roughness is the average value of all 18 segments of the surface. The surface roughness parameter (Sa) is calculated in accordance with DIN EN ISO 25178 using an S-L-surface (S-filter: 2 µm; L-filter: 0.5 mm).

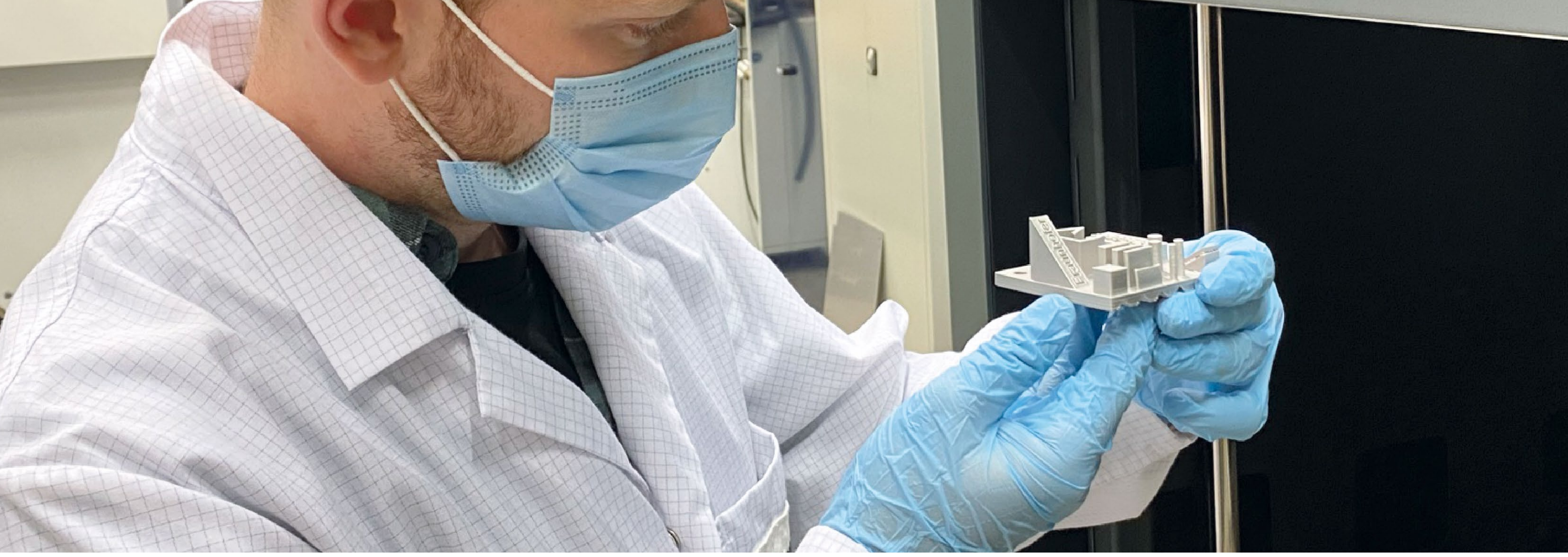
Surface quality is the central target value of the Deep Dive and is the quantity whose improvement is targeted.



6.1.2_Erosion rate

In the vast majority of surface smoothing processes, surfaces are leveled by removing material. In order to maintain the original part geometry, it is therefore important to know how much material is eroded. Preference is given to surface finishing processes with low material erosion that often make it easier to produce dimensionally accurate components.

Two different approaches are taken to evaluate the erosion rate. Firstly, images of the walls are evaluated visually to observe any damage such as deformation or removal of material from the walls. Secondly, the digital microscope VHX-5000 (Keyence) is used to measure wall thickness at three different points of the wall. The erosion rate is quantified by comparing the average wall thickness with the reference test specimen.



6.1.3_Edge rounding

Many applications and also aesthetic reasons demand clearly defined component edges. However, the removal of material during surface smoothing processes often causes rounding of the outer edges.

To evaluate edge rounding, the edges of the test specimens are recorded with a digital microscope VHX-5000 (Keyence). A focus shift improves the measurement by generating a deeply focused image of the edges. The radius is measured to compare the post-processed test specimen with the reference.

6.1.4_Readability

One attractive advantage of additive manufacturing processes is the ability to introduce inscriptions directly in the original shaping process. However, material removal during the finishing process can lead to rounding and ultimately make the inscription unreadable.
To assess readability, the test specimen has engraved and embossed lettering. A digital microscope VHX-5000 (Keyence) is used to generate a deeply focused image.

6.1.5_Green part fragility

A special characteristic of the investigated test bodies is that these are not finished components: instead, they consist of metal particles bound in a plastic matrix. They therefore have a significantly reduced strength compared to dense metal components. Surface processing can thus destroy individual features or even the entire component comparatively quickly. For this reason, the test bodies are also simply checked for completeness. In some cases they contain filigree structures such as rods, which are intended to show how non-destructive the surface smoothing processes are.

6.2_TEST SPECIMEN

In order to investigate the predefined target properties of the post-processing methods, a test specimen was developed with all the necessary test surfaces and geometries.
Designing individualized multi-property test specimens entails a trade-off between the required features and overall complexity. The objective is to integrate as many investigable features as possible while still allowing the entire specimen to be analyzed with a reasonable level of effort. On exceeding the point where effective testing of features is still possible, the specimen has to be split into multiple bodies. For this Deep Dive, a single specimen was developed that contains all relevant features. The features investigated using the test specimen are presented in 6.1.

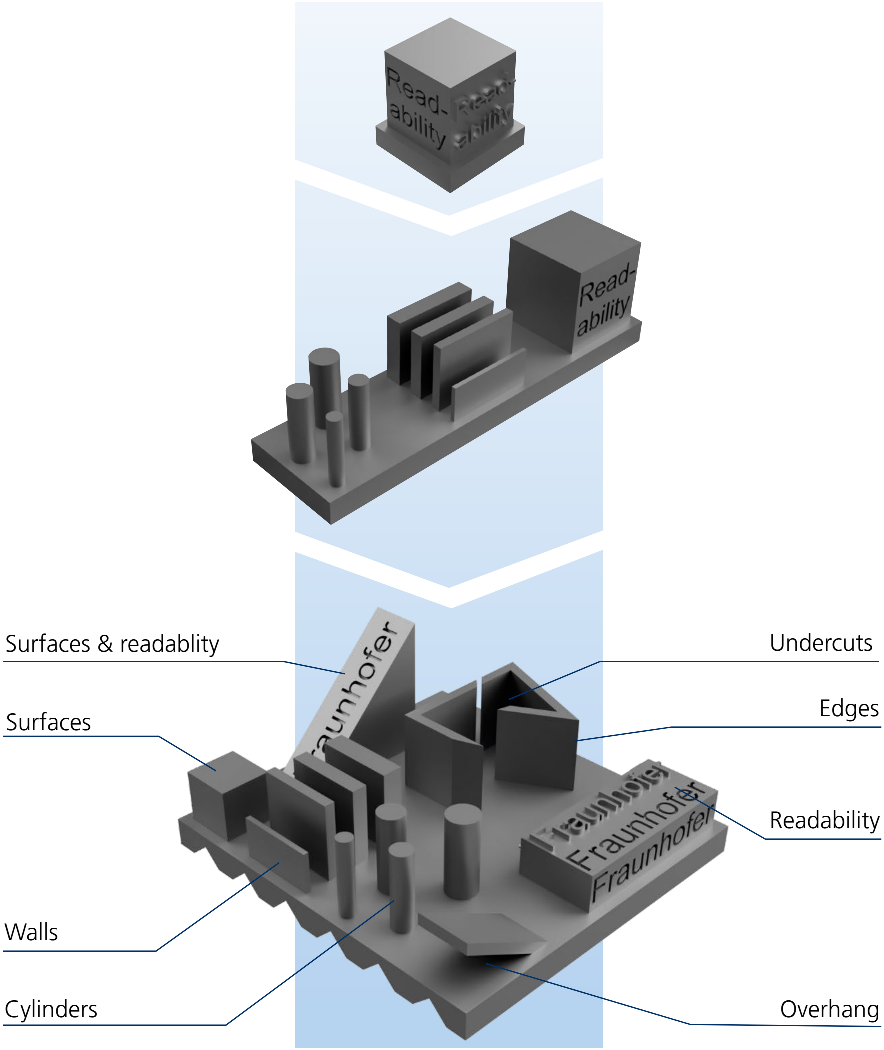
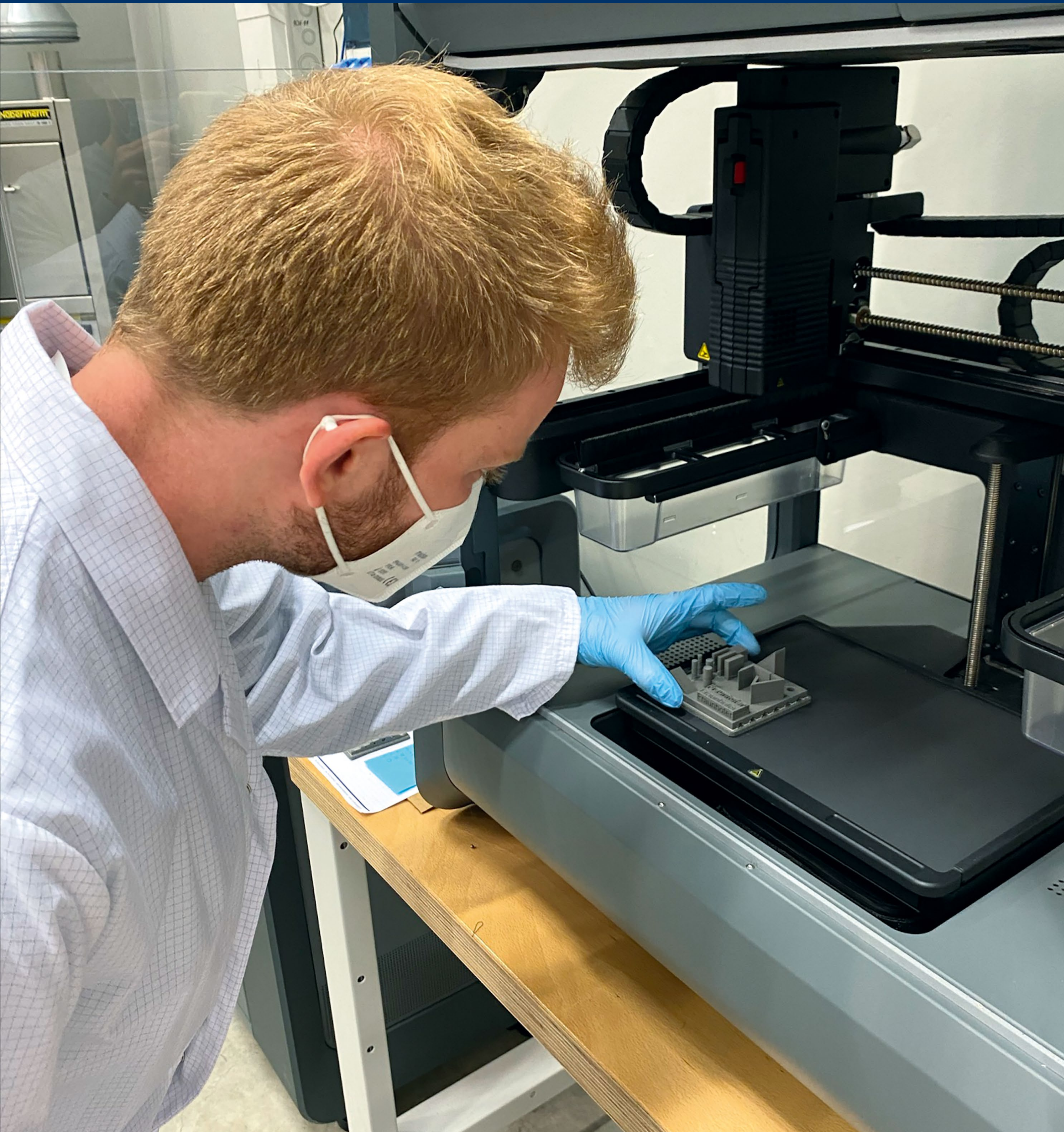


Figure 1: Increasing the complexity and investigable features to develop the test body



6.3_MANUFACTURING THE SPECIMEN

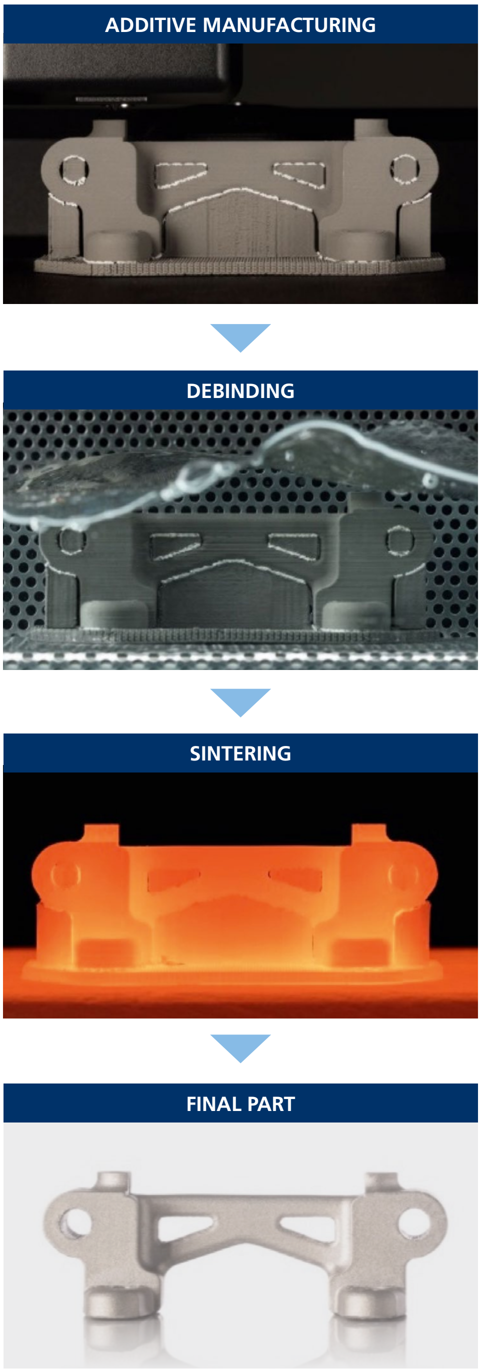


Figure 2: Bound Metal Deposition^{TM} (BMD) process chain [4]

Metal FDM is a material extrusion-based additive manufacturing process for metal components that produces green parts by extruding a thermoplastic base material (binder) filled with metal powder. A subsequent step, known as debinding, removes the first binder component (typically paraffin wax).
This process step consists of thermal debinding, catalytic debinding or (as in our case) solvent-based debinding. The workpiece at this point is called a brown part: the metal particles are still in their original position and are only held together by a so-called polymer backbone.
To create metallic bonds between the particles and produce a dense component, the brown part now goes through the third and final step: sintering. For this purpose, it is slowly heated in a furnace until it is close to the melting temperature and the metal particles sinter together [3].

This Deep Dive uses the Studio System™ by Desktop Metal as an example. The special feature of this system lies in the shape of the base material and is also reflected in the manufacturer's process name: Bound Metal Deposition™ (BMD). The material, consisting of metal powder, wax and the polymer backbone, is present here in rod form. These rods are heated and extruded onto the build plate, forming one part layer by layer. After printing, the binder is removed in the debinding process and then sintered, compacting the metal particles into the final part [4].

6.4_INVESTIGATED MATERIAL

Feedstocks for metal FDM consist of a polymer mixture, sinterable powder and additives. This applies in principle to all metal FDM feedstocks. In the final component, the same or similar binder systems are often used even with different alloys so that the investigations of this Deep Dive can also be transferred to other material systems (especially within the material range of a particular manufacturer). Specifically, this Deep Dive uses Desktop Metal's 17-4PH material, which, along with 316L stainless steel, is probably the material that is most commonly processed on Desktop Metal systems. 17-4 PH is a martensitic precipitation hardened stainless steel. It is known for its corrosion resistance and high strength and hardness, especially when heat treated. 17-4 can be heat treated to a variety of hardness and toughness levels, allowing users to customize the alloy's properties after sintering for a wide range of applications such as manufacturing machinery, valves, fasteners, jigs and fixtures.

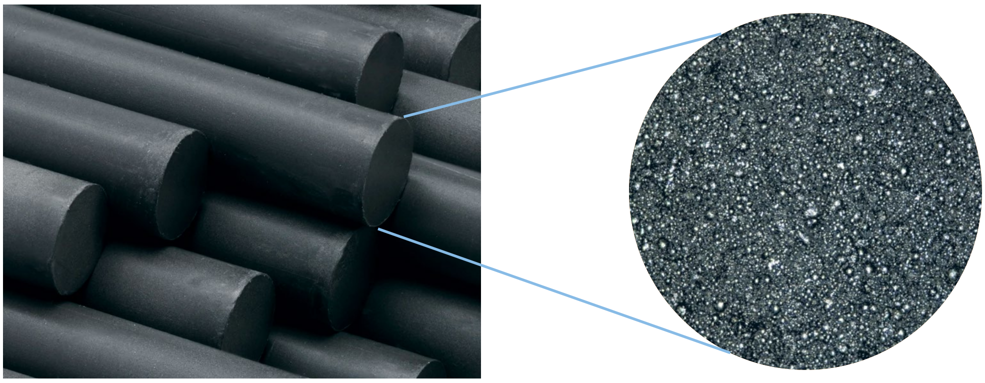


Figure 3: Microstructure of the feedstock system consisting of 17-4PH metal particles and binder matrix

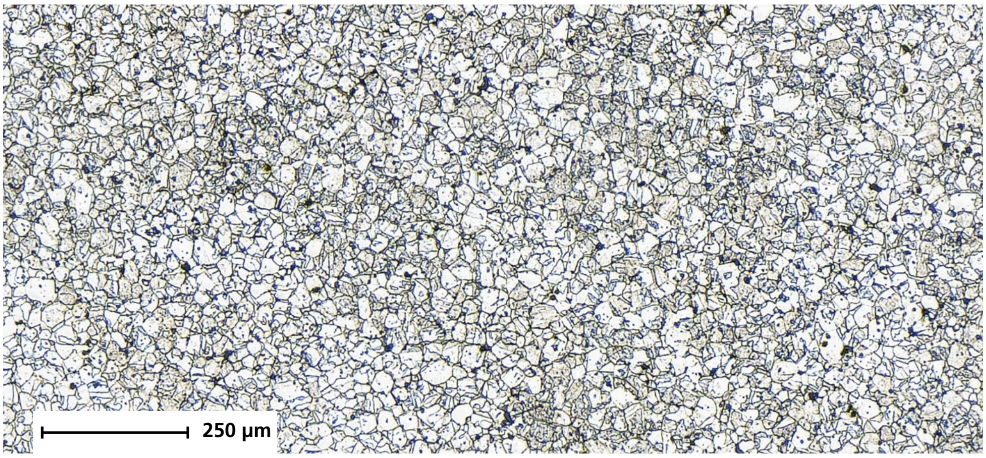


Figure 4: 17-4PH microstructure after sintering

7_SAMPLE ANALYSIS

This Deep Dive focused primarily on surface smoothing processes that are either typically specific to plastic components (but not metals) or that promise shorter and thus more effective machining due to the lower mechanical strength of green parts. The background to this is the hypothesis that green bodies are similar in their properties to common polymers. Applying the processes already in the green stage should thus open up new, cost- and time-saving post-processing methods for metal components. Three different blasting methods and a chemical smoothing process were investigated on the basis of this idea.

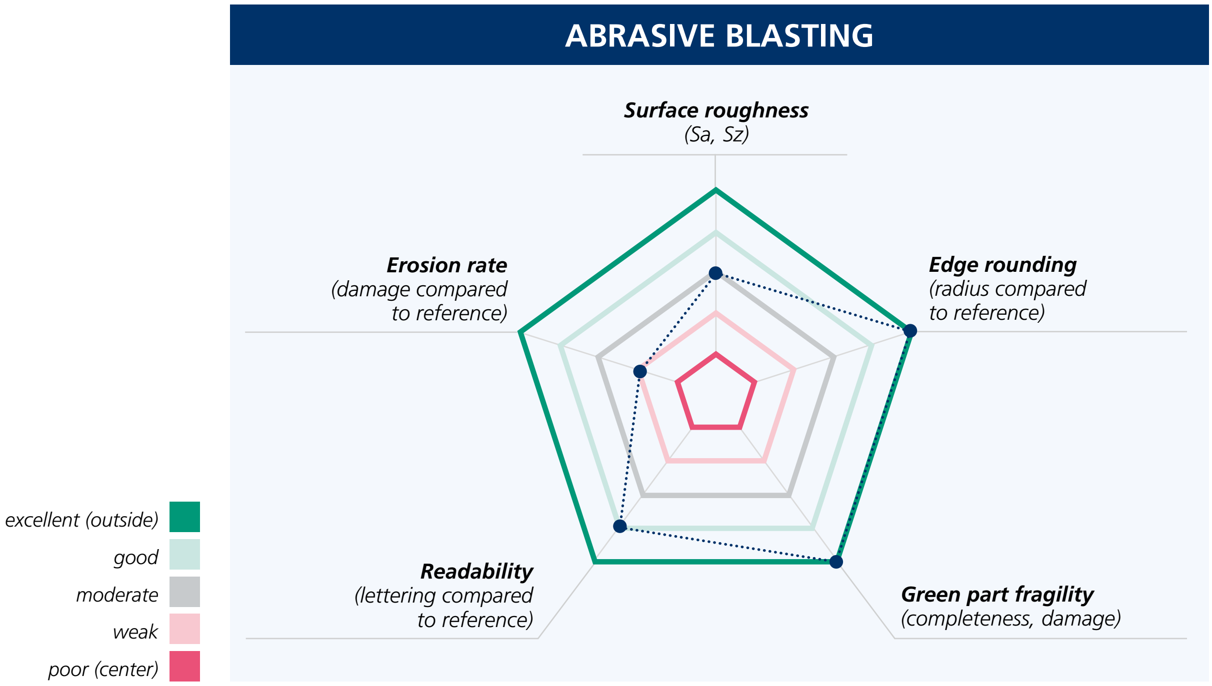
7.1_BLASTING

Blasting is a common surface smoothing process in which an abrasive is thrown against a surface under high pressure. It belongs to the machining processes with indeterminate cutting edge geometry. The most commonly used blasting media are sand and corundum. Depending on the abrasive, this process aims to smooth a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. Blasting processes can in principle be adapted to all conceivable materials by selecting a suitable blasting medium in combination with the right pressure and a suitable processing time.

All the blasting processes investigated in this Deep Dive smoothed the component surface. While the expected erosion also occurred, this was limited to surfaces only and did not contribute to any measurable edge rounding. Also, all specimens were processed without features being damaged or destroyed.

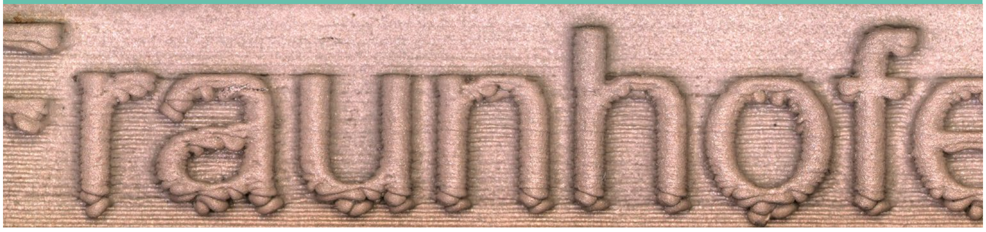
7.1.1_Abrasive blasting

The media used for abrasive blasting was a high-grade corundum with a particle size of 53 to 90 µm. Non-destructive processing of the entire specimen was possible without any features from the component platform being torn or damaged. Furthermore, the optical microscopy examinations already revealed a smoothing of the staircase effect. This was also confirmed with the 3D laser microscope. The average Sa value on the vertical surfaces of the specimen was reduced from approx. 14 µm to 5.1 µm. The readability of the embossed letters did not deteriorate as a result of the process, but this must be seen in contrast to the engraved lettering, with a slightly visible loss in sharpness compared to the reference.



REFERENCE: VERTICAL SURFACE

ABRASIVE BLASTED: VERTICAL SURFACE



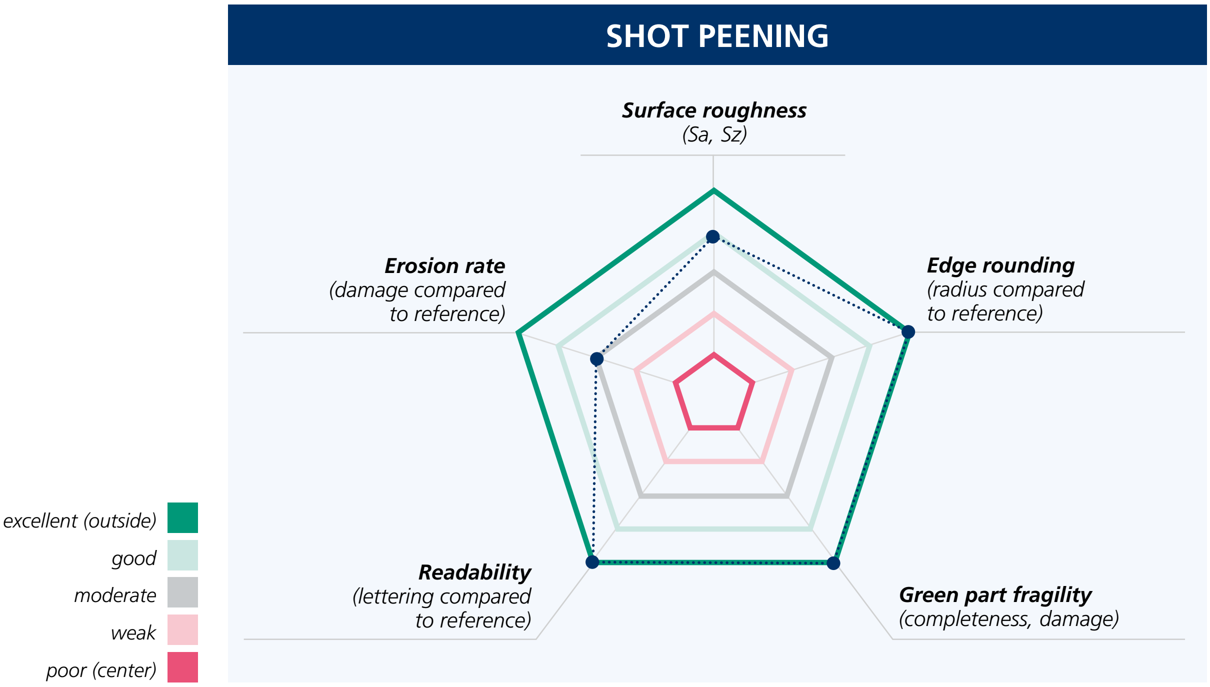
REFERENCE: ANGLED SURFACE

ABRASIVE BLASTED: ANGLED SURFACE

Figure 5: From top to bottom: vertical surface with embossed writing on the reference specimen, abrasive blasted specimen, angled surface with engraved writing on the reference specimen, abrasive blasted specimen

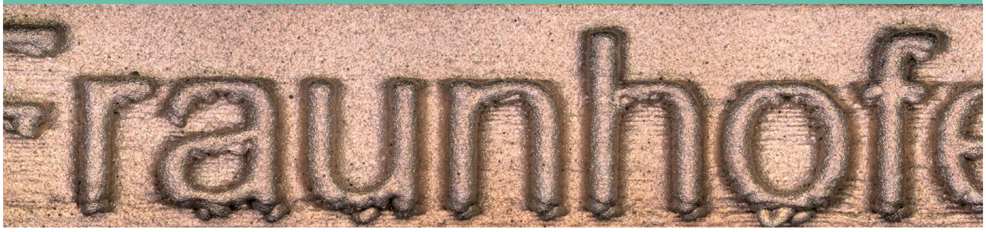
7.1.2_Shot peening

Ceramic beads with a size of 125 to 250 µm were used for shot peening. Again, the entire sample was processed without any features from the part platform being torn or damaged. Smoothing of the staircase effect was even slightly better than with abrasive blasting.
The average Sa value on the vertical surfaces of the sample was reduced this time from about 14 µm to 4.2 µm. The readability of both embossed and engraved letters did not deteriorate as a result of the process.



REFERENCE: VERTICAL SURFACE

SHOT PEENED: VERTICAL SURFACE



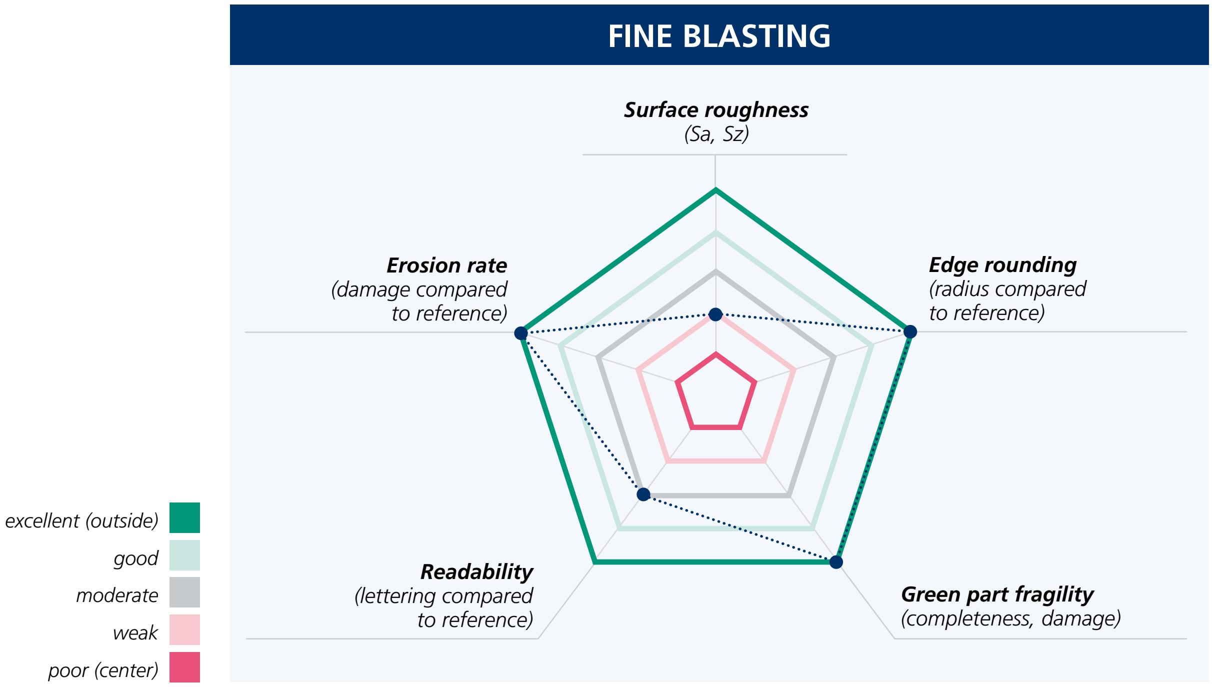
REFERENCE: ANGLED SURFACE

SHOT PEENED: ANGLED SURFACE

Figure 6: From top to bottom: vertical surface with embossed writing on the reference specimen, shot peened specimen, angled surface with engraved writing on the reference specimen, shot peened specimen

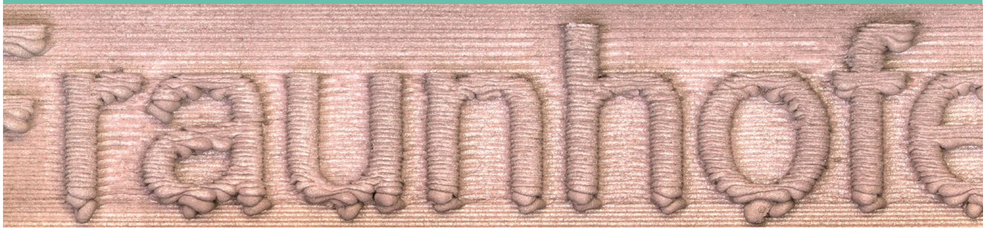
7.1.3_Fine blasting

A high-grade corundum was used for fine blasting (as for abrasive blasting). The particle size here was around 25 µm, which is typical for fine blasting processes. Fine blasting also allowed damage-free processing of the specimen. Only slight smoothing of the specimen was observed compared to the two other blasting methods. The average Sa value on the vertical surfaces of the specimen was reduced this time from about 14 µm to 8.6 µm. There was comparatively extensive deterioration to the readability of the engraved lettering.



REFERENCE: VERTICAL SURFACE

FINE BLASTED: VERTICAL SURFACE



REFERENCE: ANGLED SURFACE

FINE BLASTED: ANGLED SURFACE

Figure 7: From top to bottom: vertical surface with embossed writing on the reference specimen, fine blasted specimen, angled surface with engraved writing on the reference specimen, fine blasted specimen

7.2_CHEMICAL VAPOR SMOOTHING

The chemical vapor smoothing process used in this Deep Dive is a patented method by Additive Manufacturing Technologies (AMT) for smoothing plastic components. The process was integrated in the investigation on the basis of the above-mentioned hypothesis that green bodies have similar properties to plastic components so that similar processing should be possible. To this end, the components are placed in a closed chamber and heated under vacuum. A solvent is then vaporized and also fed into the process chamber, where it condenses on the surfaces of the workpieces. In the final step, the process chamber is placed under vacuum again to discharge the process vapor and dry the components [5].

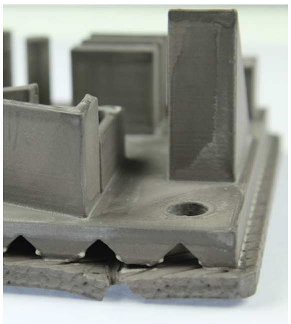
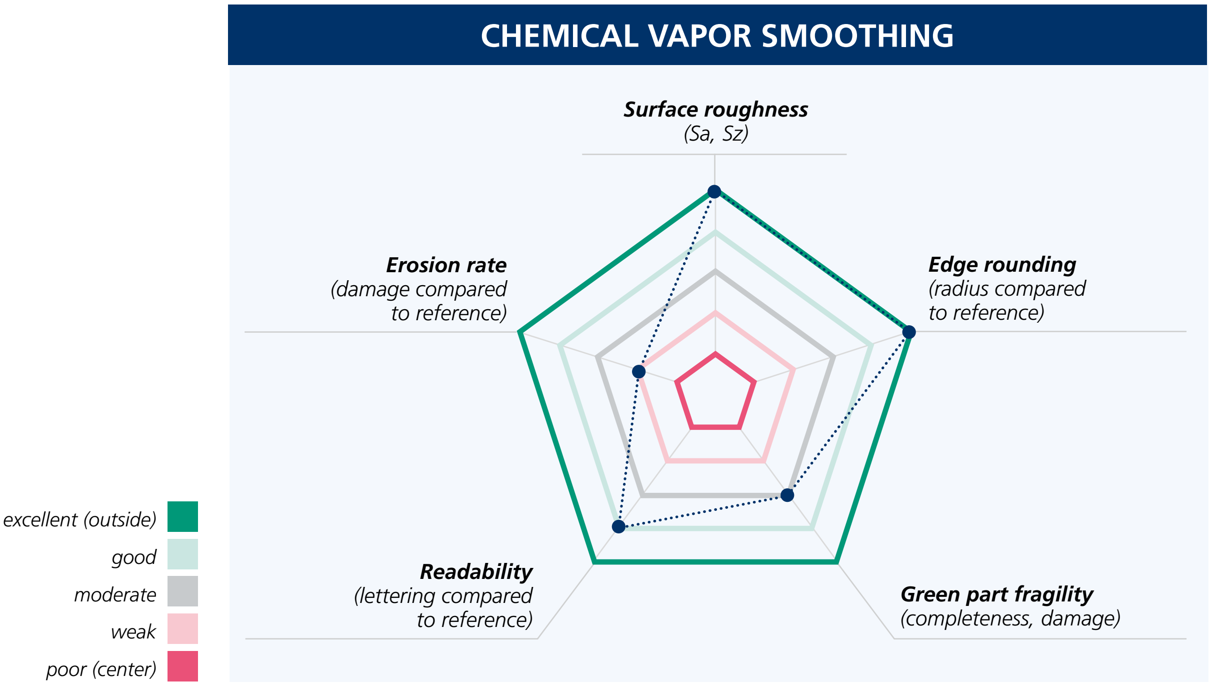


Figure 8: Support platform damaged by the chemical vapor smoothing process

Chemical vapor smoothing produced the highest surface quality during the investigations of this Deep Dive. The Sa value of the vertical walls was reduced from 14 to 3.9 µm compared to the reference sample. As with the blasting processes, no measurable edge rounding of the specimens was observed. Nevertheless, there was comparatively strong erosion of the surfaces. In addition, slight damage was caused to the support platform (see Figure 8). According to AMT, minor adjustments to component handling could prevent this in future.



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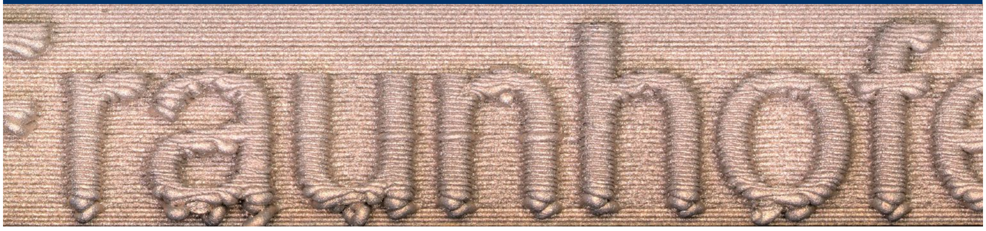
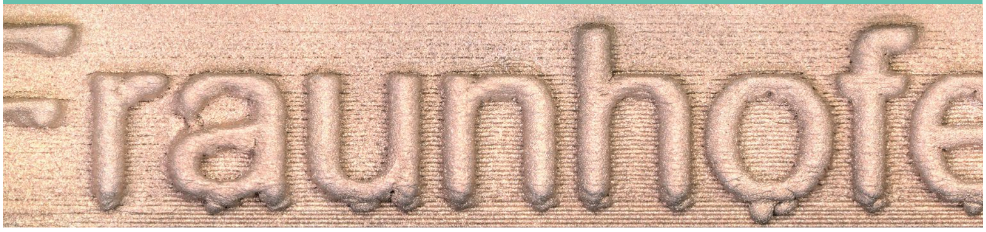


VAPOR SMOOTHED: VERTICAL SURFACE



REFERENCE: ANGLED SURFACE

VAPOR SMOOTHED: ANGLED SURFACE

Figure 9: From top to bottom: vertical surface with embossed writing on the reference specimen, vapor smoothed specimen, angled surface with engraved writing on the reference specimen, vapor smoothed specimen

8_SUMMARY & CONCLUSION

This Deep Dive investigated new possible surface smoothing techniques for components of sinter-based 3D printing processes, in particular metal FDM. The basic idea resulted from the hypothesis that the plastic-like material properties of the components in the green body stage can be exploited in the interests of short processing times or even completely new methods. The investigations delivered promising results which will be discussed and evaluated in the following.

8.1_ECONOMIC EVALUATION

As mentioned at the outset, this Deep Dive was devoted to discussing the following key questions:

1. **Can chemical vapor smoothing be used to process green bodies?**
2. **Can the presented blasting processes be used to achieve higher surface qualities with shorter processing times, i.e. lower costs?**

While a positive answer to the first question was already obtained in 7.2, answering the second question entails the post processing of initially unprocessed reference specimens after sintering. It is not possible to compare chemical vapor smoothing in this way because the process is not applicable to metal components. Shot peening was the only process to be selected on the basis of the most promising results. In addition, the treatment was only applied to surfaces lying in the direction of build-up and therefore exhibiting the staircase effect typical of the process. Longer processing times were also tested on the sintered part to ascertain the improvement in achievable surface finish when processing the green part compared to the sintered part.

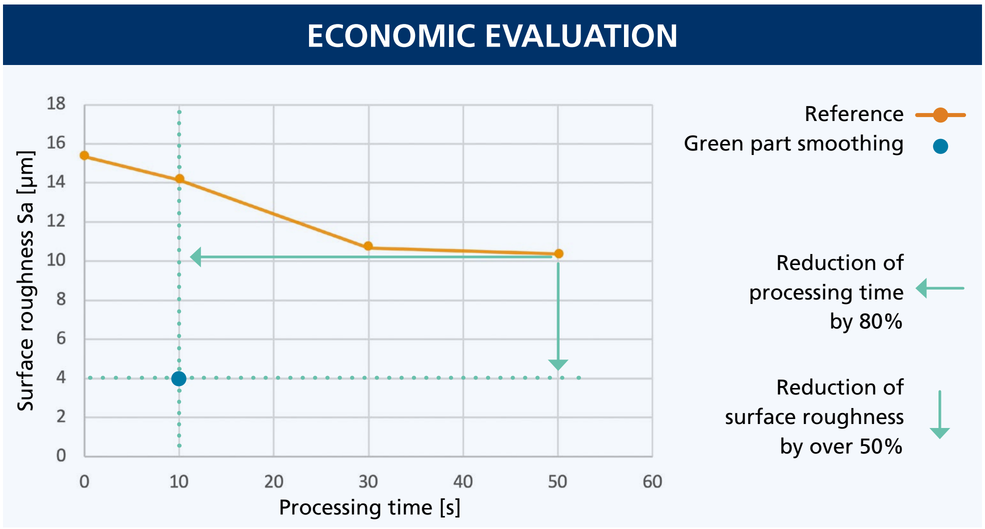


Figure 10: Comparison of machining times and achieved surface quality of green body smoothing and processing of the final component.

It was shown that a significantly higher surface quality was achieved with considerably shorter machining times. This reduces post-processing costs by up to 80 percent while improving the achievable surface quality, which could enhance the economic appeal of the technology in the future.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8.2_CONCLUSION

Metal FDM is a cost-effective, flexible manufacturing process whose main drawback is the comparatively poor surface quality. The results of this Deep Dive should therefore help to open up new use cases that require higher surface qualities. It can be said in advance that basically all the analyzed methods worked to varying degrees and were able to produce a higher surface quality (compared with the reference sample).

ABRASIVE BLASTING

✓
- **Good improvement of the surface finish**
- **No damage to the green part**

✗
- **High erosion rate**

SHOT PEENING

✓
- **Very good improvement of the surface finish**
- **No damage to the green part**

✗
- **Noticeable erosion rate**

FINE BLASTING

✓
- **Very low erosion rate**
- **No damage to the green part**

✗
- **Low improvement of the surface finish**

CHEMICAL VAPOR SMOOTHING

✓	✗
Very good improvement of the surface finish **Slight damage to the green part**	**High erosion rate**

In the light of the investigations, the shot peening and chemical vapor smoothing processes appear to be particularly suitable. Both processes showed very good results in surface smoothing which was achieved to a large extent without destroying the components. Further investigations could adapt both processes more specifically to the processing of green bodies. Chemical vapor smoothing is already a largely automated process that does not require much manual effort. There is still potential here for further process optimization or automation of the blasting processes, with more reductions in component costs.

Furthermore, chemical vapor smoothing provides a uniform result typical of the process, whereas the manual blasting processes tend to be non-uniform. Microstructure investigations looking at impurities and influences on the sintering process would be useful for further qualification of chemical vapor smoothing in terms of treating green bodies.

The Deep Dive showed that green body smoothing basically achieves good to very good results in terms of surface quality and processing time. Further investigations should continue to optimize the processes while eliminating possible drawbacks with regard to the mechanical and physical properties of the components.

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10_IMPRINT

Imprint

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p. 3, 14 (process steps), 15 (rods top left) desktopmetal.com

Status of the Deep Dive, October 2021.