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LBM Additive Manufacturing

Defect Catalogue

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Contents

Figures

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Laser beam melting (LBM) is a complex technology and the resulting component quality is dependent on various parameters. The aim of this study was, on the one hand, to give an overview of potential process deviations during the LBM process and of possible component defects that may result from these, and on the other hand, to evaluate the most critical errors of the LBM process. A closer look was taken at resulting building defects and their consequences on component quality. The results should give an indication of how much they affect part quality.

1 Identification of process deviations in LBM

In order to identify possible faults during LBM, a closer look was taken at the main error sources, machine, material, process and human. An overview is shown in Figure 1.

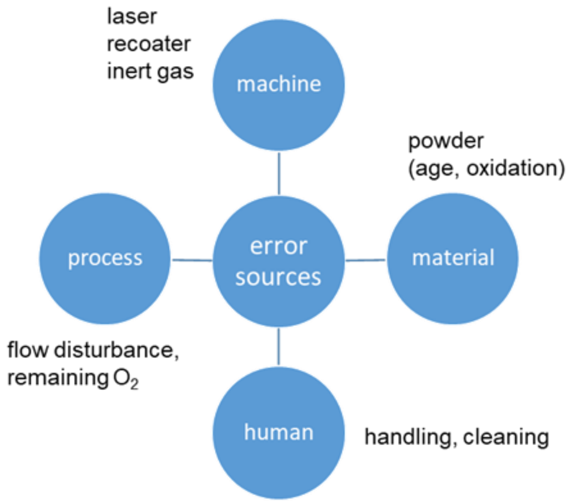


Figure 1: Error sources

Since some errors are very rare (e.g. remaining oxygen and laser power or wavelength too high / too low, bad focusing or x/y-position, galvanometer scanner system too fast / too slow), only those with a higher and middle chance of occurrence were taken into account. This analysis is based on the first model of the EOS M280 machine generation from 2011, which is located at FOTEC.

Figure 2 shows common errors on the machine. Those with a higher chance of occurring are marked in red and those with a middle chance of occurrence in orange. As stated before, rare errors (low chance of occurrence) will not be referred to hereafter.

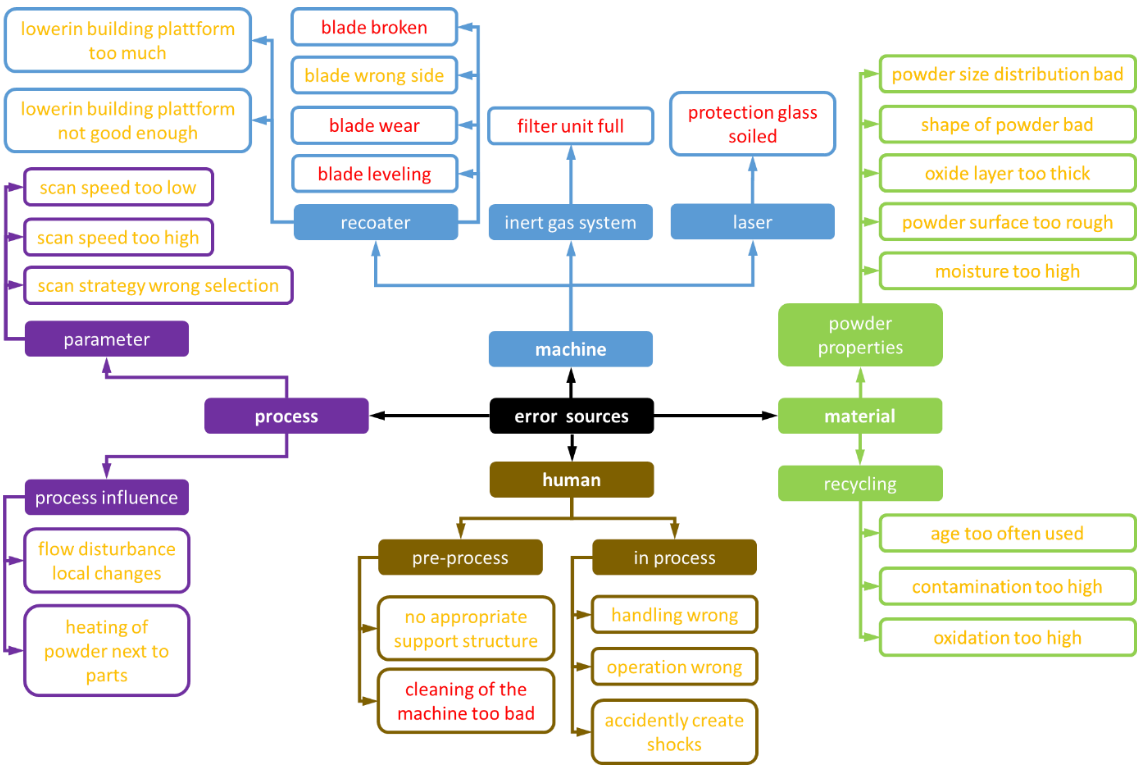


Figure 2: Error sources – detailed

By implementing process monitoring (layer- and melt pool-monitoring systems), some of the errors can generally be detected mid-process. The recoater-based errors shown in Figure 2 can be detected by powder bed layer monitoring, the parameter-based errors (also Figure 2) by melt pool monitoring.

Aside from these, there are several machine and process errors which cannot be detected automatically in process at the current state of the art. However, all human and material errors could be nearly eliminated through appropriate pre-processing, well-trained staff and elaborated workflows to ensure continuous material quality from start to finish.

Nevertheless, despite all these measures, errors can still arise, e.g. due to inadequate process stability. Component defects and building defects could result. The following section outlines the most common general component and material defects. Thereafter, the most frequent building defects and their consequence on component quality are discussed.

2 Component and material defects

The most common error types monitored in the LBM process are geometrical deviations, unsatisfactory surface quality, bonding errors and porosity.

2.1 Geometrical deviations

During the layer-wise solidification of the feedstock material in the LBM process, thermally induced residual stresses arise. These residual stresses can lead to deviations from the nominal geometry due to shrinkage and distortion. To prevent distortion or even detachment of the component from the building plate, as shown in Figure 3, the building plate can be preheated in order to reduce the temperature gradient.

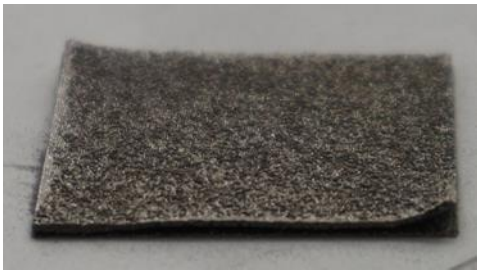


Figure 3: Detachment of the component from the building plate (mid-process)

Besides reducing distortion, preheating also prevents stress-induced micro-cracks in the component. In addition, improved heat dissipation from the component into the building plate can be attained by the use of suitable supporting structures. In case of poor adaptation of these supporting structures to the geometry of the component, the component may be bent upwards, resulting in curvature. If this happens during the LBM process, there is a risk that the coater will collide with the component. This can cause a process breakdown, or even damage to the coater unit.

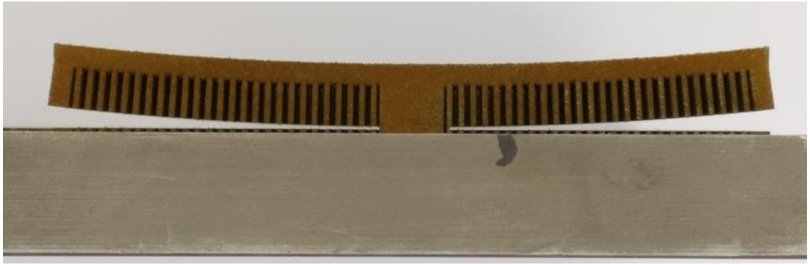


Figure 4: Residual stresses become apparent during separation from the building plate (post-process)

To prevent post-process distortion as indicated in Figure 4, it is recommended that the component is separated from the building plate after the appropriate post-heat treatment.

During LBM it is also possible that entire layers become detached from the solid material. This macroscopic defect is referred to as delamination (Figure 5). Insufficient layer bonding can occur due to lack of energy input, incomplete particle melting or contaminations in the feedstock material. Delaminations cannot be eliminated using post-heat treatment.

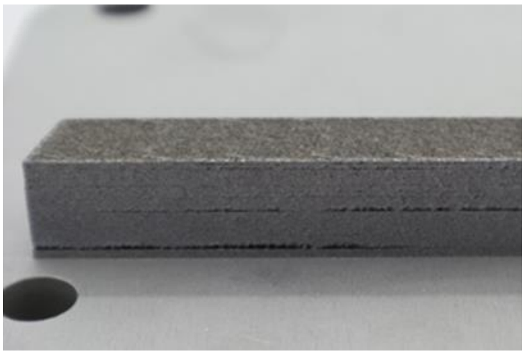


Figure 5: Macroscopic delamination

2.2 Surface quality

On the one hand, the surface quality of components manufactured using LBM depends on the appropriate processing parameters. On the other hand, the alignment of the geometry in the building space also affects surface quality. In particular, surfaces manufactured parallel or perpendicular to the construction panel are generally of better quality than overhanging surfaces. Overhanging surfaces have a lower roughness because more powder particles adhere to these surfaces.

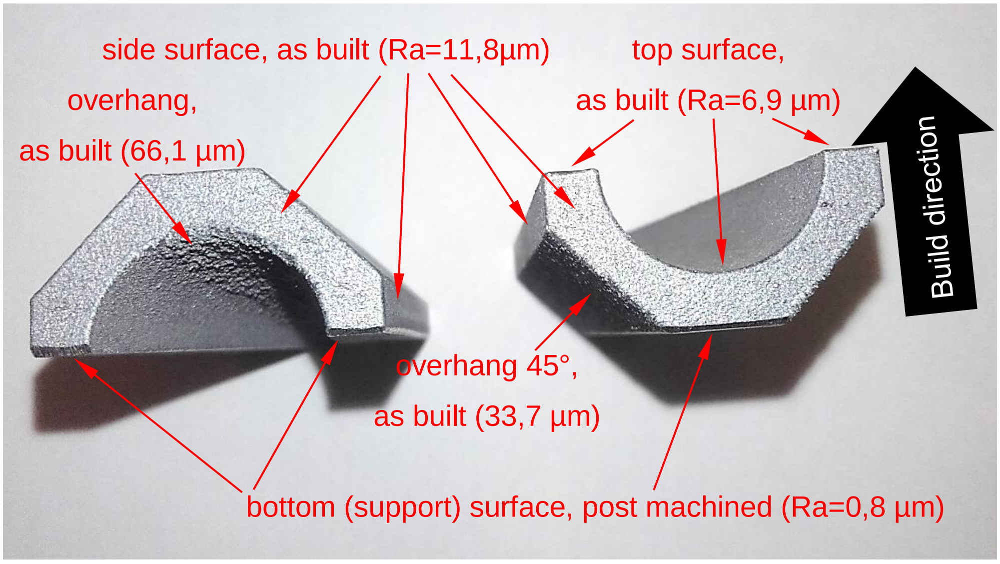


Figure 6: Roughness (AlSi10Mg) influenced by build direction

In order to be able to use LBM-manufactured components industrially, it is often necessary to reduce surface roughness by using suitable finishing processes.

2.3 Porosity

Porosity inevitably occurs in the LBM process. Thus densities of one hundred percent can be hardly achieved. A distinction is made between circular pores, usually gas pores, and irregularly shaped pores, referred to as bonding defects. Both types of defect can be seen in the exemplary micro-section in Figure 7, which was deliberately produced with insufficient energy input. Gas pores are formed either by trapping gases from the atmosphere or through the evaporation of certain alloy elements. Gas pores are circular and often form due to the high energy input into the material. Their distribution in components is random. Lack-of-fusion defects result from insufficient melting of the feedstock material. With materials that are easily oxidised, oxides can reduce the melt flow, resulting in poor coverage and thus to lack-of-fusion defects.

Figure 7: Micro-section of AlSi10Mg test sample with insufficient energy input, resulting in porosity (circular and irregular pores)

2.4 Spatter inclusion

The formation of spatter particles during the LBM process is an inherent effect. In general, increasing the laser energy input increases the intensity of spatter formation. The inert gas flow across the powder bed surface is designed to remove the spatter particles from the construction area so that spatter into the component and the powder bed is avoided. Depending on where the particles are deposited, two consequences can occur. Firstly, spatter deposits on the component cross-section within a layer can lead to micro-structural defects. Secondly, the pick-up of spatter particles in the powder bed gradually changes the powder properties when the powder is reused.

2.4.1 Micro-structural defects due to partially melted spatter

Spatter inclusion can dramatically affect mechanical component quality, as tests with Ti6Al4V have shown (see section 0). By blocking the inert gas flow, weld spatters were inevitably included, which can of course occur during long building jobs (see section 3.3). This can be for one of two reasons or a combination of both.

Firstly, due to differences in particle size and shape compared to LBM powder, weld spatter can lead to inhomogeneous melting and thus to spatter inclusions, or even pores (see Figure 16 to Figure 21). Secondly, blockage of the local inert gas flow can lead to local flow disturbances and thus to an improper welding atmosphere.

2.4.2 Spatter pick-up in reused powder

Spatter particles produced during LBM processing of Ti6Al4V have shown an 8% increase in oxygen content and a 67% increase in nitrogen content. A large part of the deposited spatter particles is recycled and transferred to the reusable powder for later building jobs. In this special case, 82% of the isolated spatter particles passed the 75 µm mesh during the subsequent sieving process. This effect leads to a gradual increase of oxygen and nitrogen in the powder, which might exceed the specified limits and/or impair the mechanical properties of the component.

3 Building defects

As previously mentioned, building defects can of course occur despite concerted efforts to avoid errors through process monitoring, appropriate pre-processing, well-trained staff and sophisticated workflows. Based on the current analysis of the M280 model at FOTEC, building defects typically cause the building process to stop automatically. This results either in rejects or in intact components. Sometimes it makes sense to stop the process manually to prevent the inclusion of weld spatter caused by inert gas flow disturbance, which does not normally stop the building process automatically. The following defects are also mentioned in this study:

- construction stop with reject components – automatic stop in case of recoater collision resulting in bent samples
- construction stop with intact parts – automatic stop in case of recoater collision, with samples remaining intact and building job able to be continued
- weld spatter inclusion – by blocked inert gas flow nozzles

3.1 Building stop with reject components

In the worst case scenario, the build job must be rejected because components are bent. This can be caused by a collision of the recoater with component layers that have been bent due to previous exposures on account of thermal stresses caused by weak geometrical stability of the component areas, or alternatively, by omitting or installing inadequate supports. A weak support strategy can lead to a break in the interface between the support and the component, or between the support and building platform. Of course, if the geometrical stability of the component is weak, a break in the weakest part of the component may occur.

Figure 8: Break in the interface between support and component due to weak support strategy

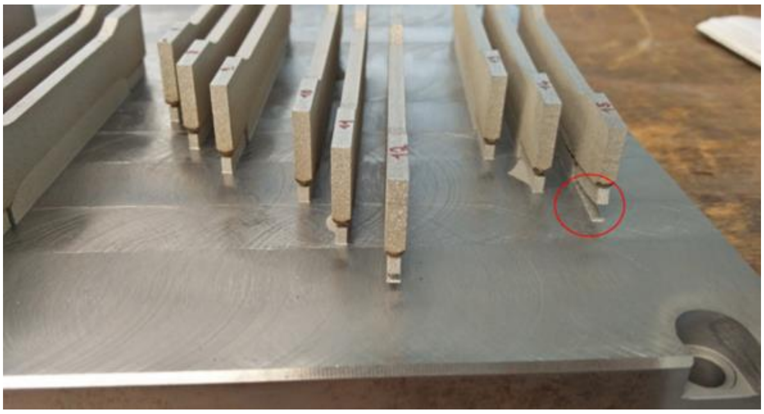


Figure 9: Break in the interface between support and building platform due to weak support strategy

3.2 Building stop with intact components

If the recoater collides with the components but these do not bend, construction can normally continue. Continuation can either be in the same layer of the recoater crash or in one or two layers above it to avoid another recoater collision.

After the building job is continued, traces of this event are usually visible on the component if the pause lasts longer than a few hours.

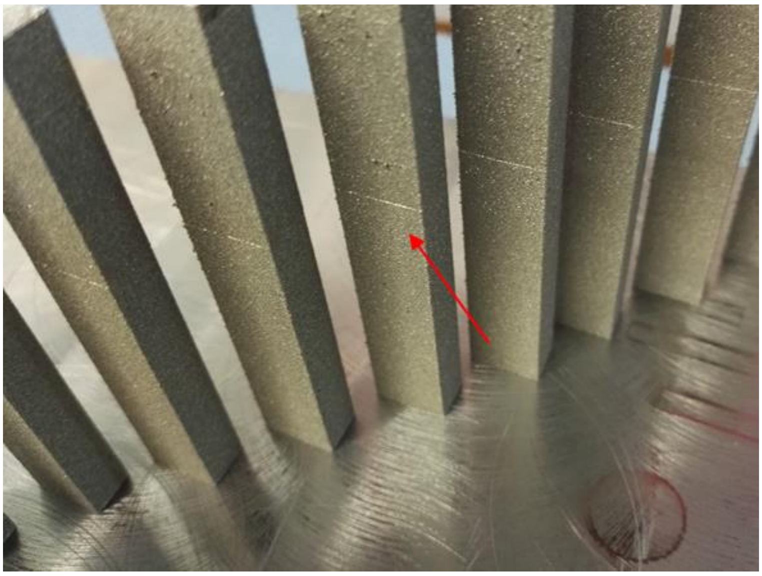


Figure 10: Marks caused by pausing a building job

Up until now it was unclear whether the components described above had the same mechanical stability as parts that are produced without errors. The results obtained in this study and outlined below partly answer this question.

3.3 Weld spatter inclusion

With longer construction jobs, depending on material, component height and component volume, the inert gas nozzles sometimes get blocked with welding spatter and loose powder. If this happens, stay on the exposed layers of the components. This allows them to be integrated into the remaining component layers during recoating and exposure and avoids a potential component defect.

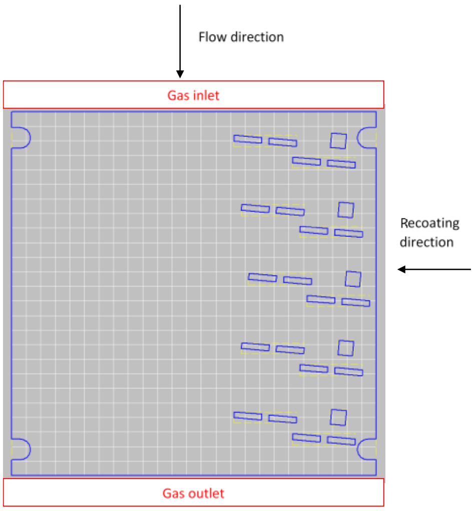
Any remaining weld spatters do not necessarily cause the recoater to collide with the components and to cause the aforementioned damage. It is therefore a practicable procedure to stop the construction process manually every so often for a short period of short time to clean the inert gas nozzles, so as to be able to continue building and to prevent welding spatters from becoming trapped.

Such a manual stop more or less results in the same component properties as the pausing of a job. Nevertheless, the ways in which the integration of weld spatters through blocked inert gas nozzles affects component properties was also investigated in detail.

4 Effects of pausing building jobs

The effect of a longer pause (leading to markings as in Figure 10) on the mechanical properties was investigated with Ti64 (Ti6Al4V) tensile samples. In order to simulate a building pause, the construction process was manually stopped at a building height of 64 mm (incl. 4 mm support height), i.e. in the middle of the components which were vertically aligned tensile samples of 120 mm length. The delay between stopping and continuing the construction process was ten hours. The samples were heat treated (800°C/4h) after 3D printing.

In the first test, building was continued in the same layer where it had been manually stopped. In the second test, building was continued three layers above (90 µm) to simulate a recoater collision where the actual stop height cannot be determined. In order to evaluate the differences to an error-free building job, a reference component with the same component alignment was 3D printed without interrupting the process.



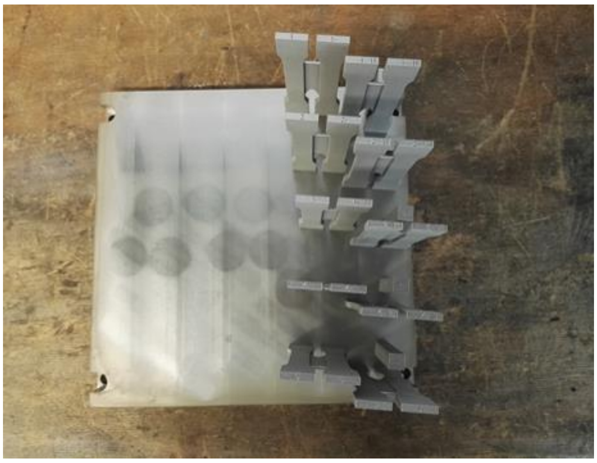


Figure 11: Building job - investigation of the effects of interruptions; 2D view with recoating/gas flow directions and gas inlet and outlet (left) and built job (right)

The result of the tensile tests (according to ASTM E-8) is shown in the following diagram (see Figure 12). Compared to the reference component, there are almost no differences in Young's modulus (E), yield strength (Rp), ultimate strength (Rm) and elongation at break (A). The only striking difference is the standard deviation of elongation at break. Here, the average value is below the reference value. The standard deviations for an interrupted building job are also twice as high as the reference value.

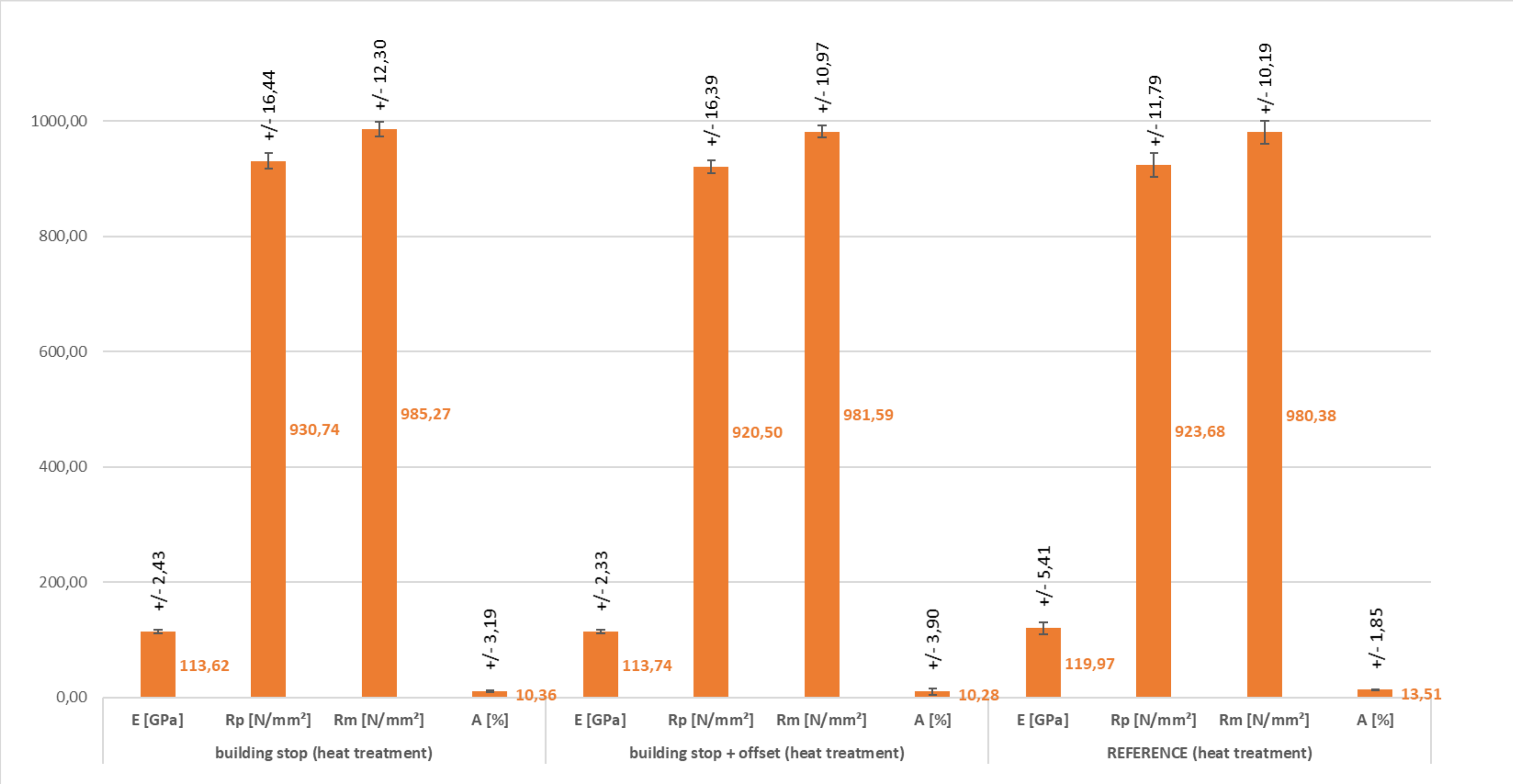


Figure 12: Tensile test diagram – effect of pausing building jobs Impact of blocked inert gas flowImpact of blocked inert gas flow

To investigate the effects of inert gas flow blockage and inclusion of weld spatter Ti64 (Ti6Al4V) tensile samples were built. They were aligned horizontally to the building platform. After 3D printing, they were also heat-treated (800°C/4h). A blockage of the inert gas flow was simulated by covering the gas outlet with adhesive tape on the right half.

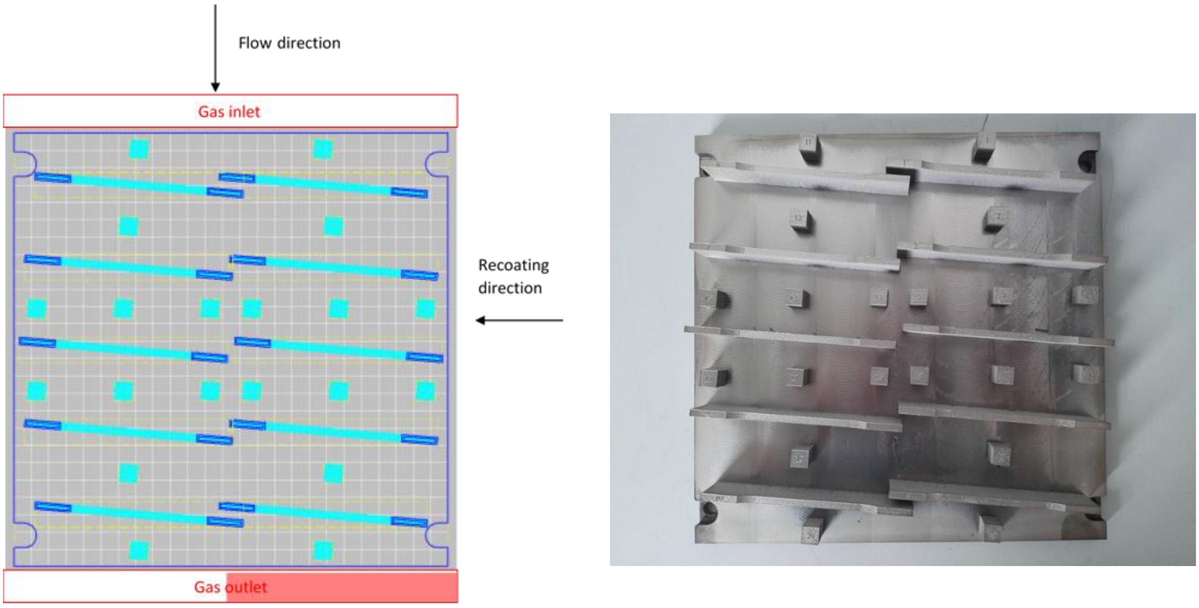


Figure 13: Building job – investigating blocked inert gas flow; 2D view with recoating/gas flow directions and gas inlet and outlet (left); built job (right)

Figure 14: Inert gas flow direction and area of blocked gas outlet nozzle

The tensile test results (according to ASTM E-8) of the blocked nozzle samples actually show some differences to the open nozzle samples.

The yield strength (Rp), ultimate strength (Rm) and elongation at break are lower than the values of the open nozzle samples. When comparing the standard deviation, the only significantly higher value for the blocked nozzle samples is represented in elongation at break.

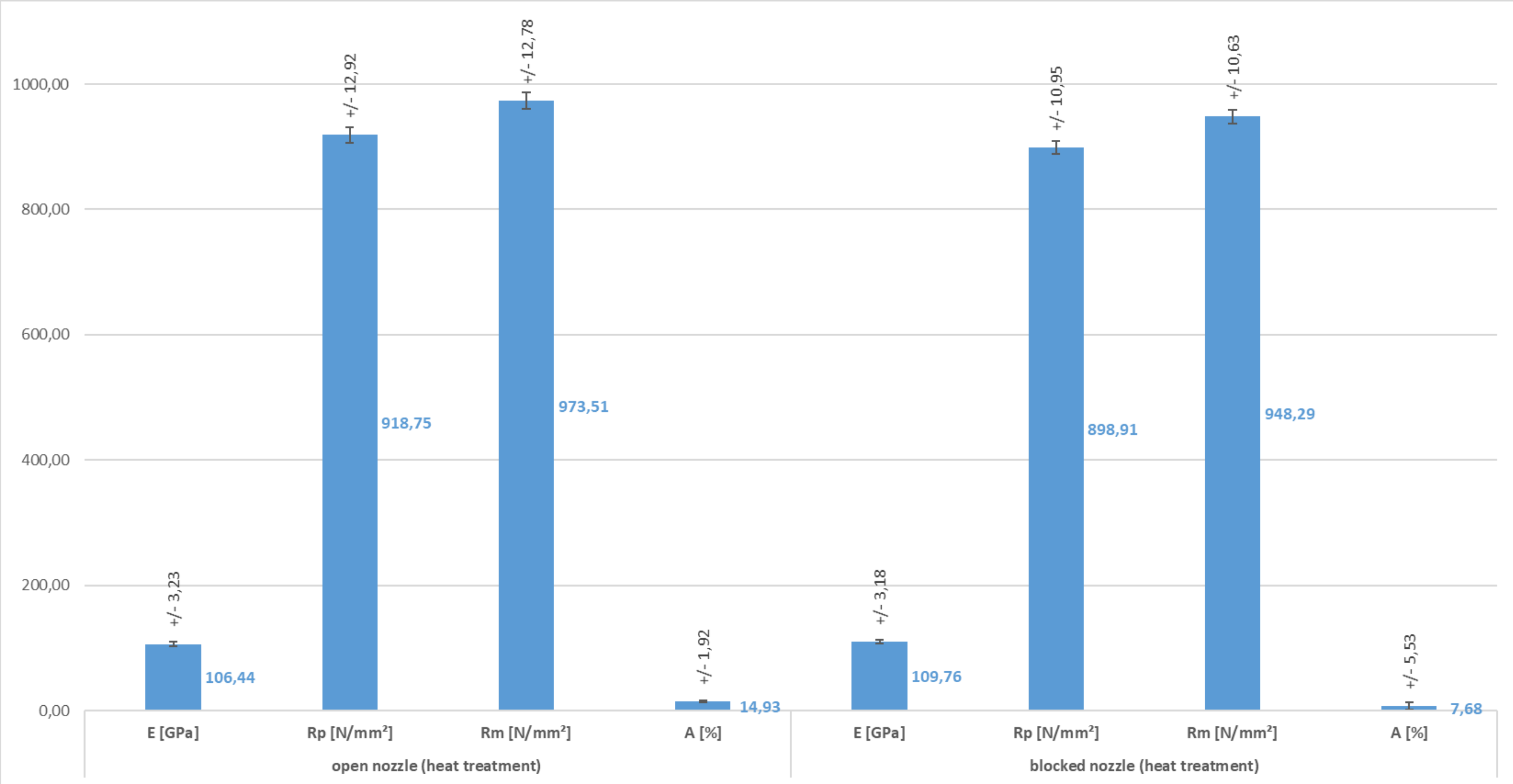


Figure 15: Tensile test diagram – impact of blocked inert gas flowCompared to the fractured surface of the tensile samples (see pictures below), there is also a difference. While the samples in the area of the blocked nozzle (right side of building platform, Figure 13) showed

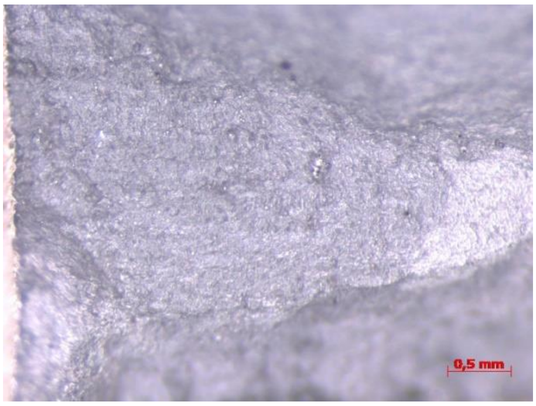


Figure 16: Sample 6 (open nozzle, near gas inlet)

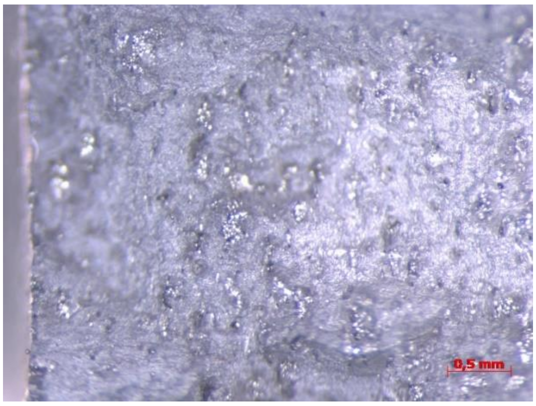


Figure 17: Sample 1 (blocked nozzle, near gas inlet)

Figure 18: Sample 8 (open nozzle, middle of gas inlet and outlet)

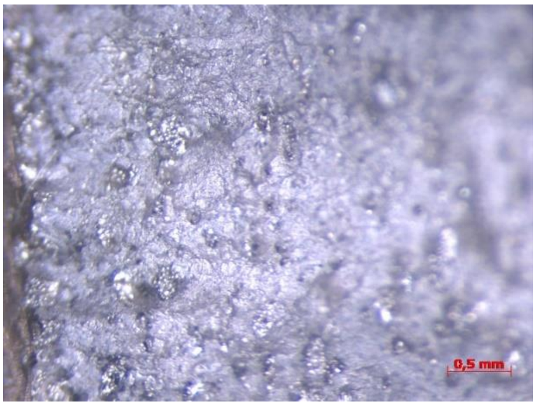


Figure 19: Sample 3 (blocked nozzle, middle of gas inlet and outlet)

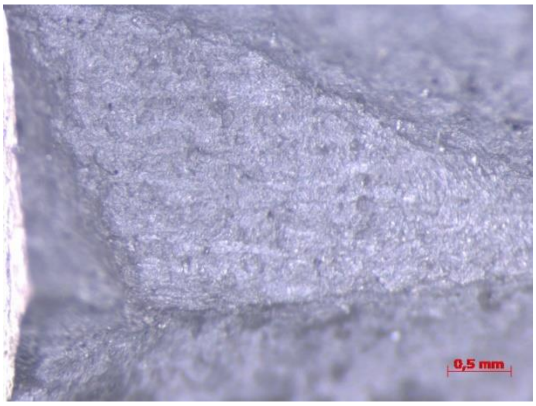


Figure 20: Sample 10 (open nozzle, near gas outlet)

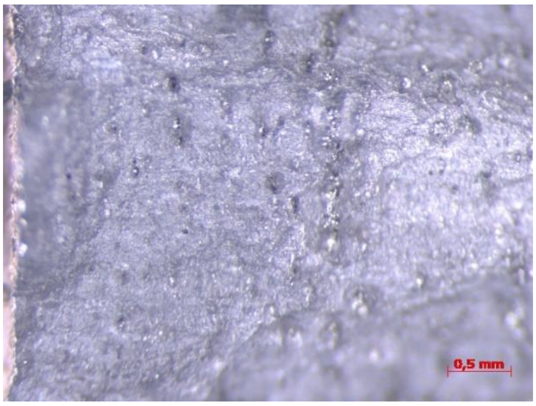


Figure 21: Sample 5 (blocked nozzle, near gas outlet)

The CT analysis again showed these errors in the samples. Sample 2 from the right side and sample 7 from the left side of the building platform are compared in two layers (visual defect area in layers 153 and 297 from the top). Almost every layer of sample 2 showed weld spatter defects, while sample 7 showed no defects.

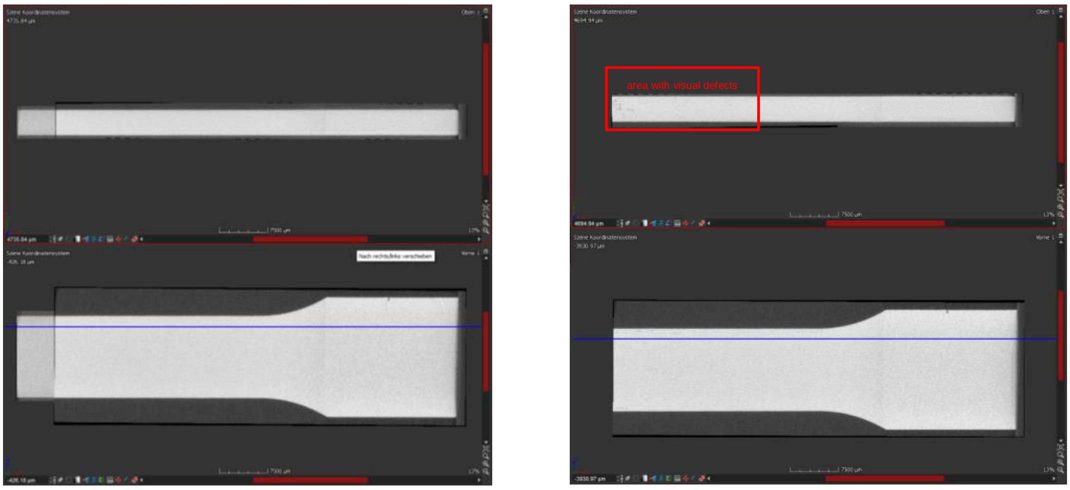


Figure 22: Layer 153 from top surface sample 7 (left), sample 2 (right)

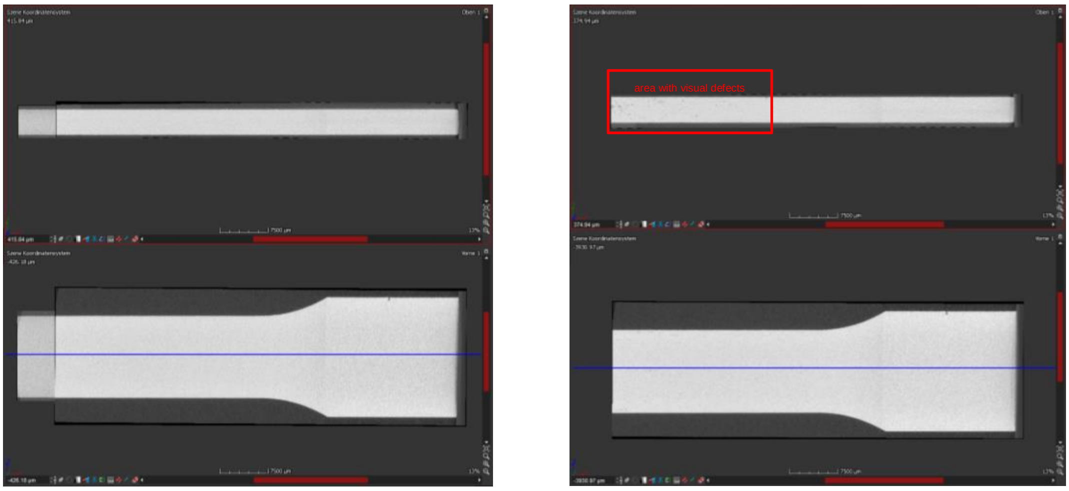


Figure 23: Layer 297 from top surface sample 7 (left), sample 2 (right)

FOTEC's layer monitoring system identified the weld spatter errors as well. Melt pool layer monitoring measures the emitted light every 20 µm x 20 µm over the entire building platform and calculates an average value from the values for a point of 100 µm x 100 µm. It clearly shows the defects (brighter areas) on the right side of the building platform. Here, too, the layers from the CT analysis from Figure 22 and Figure 23 before the CT analysis are shown in the subsequent figures.

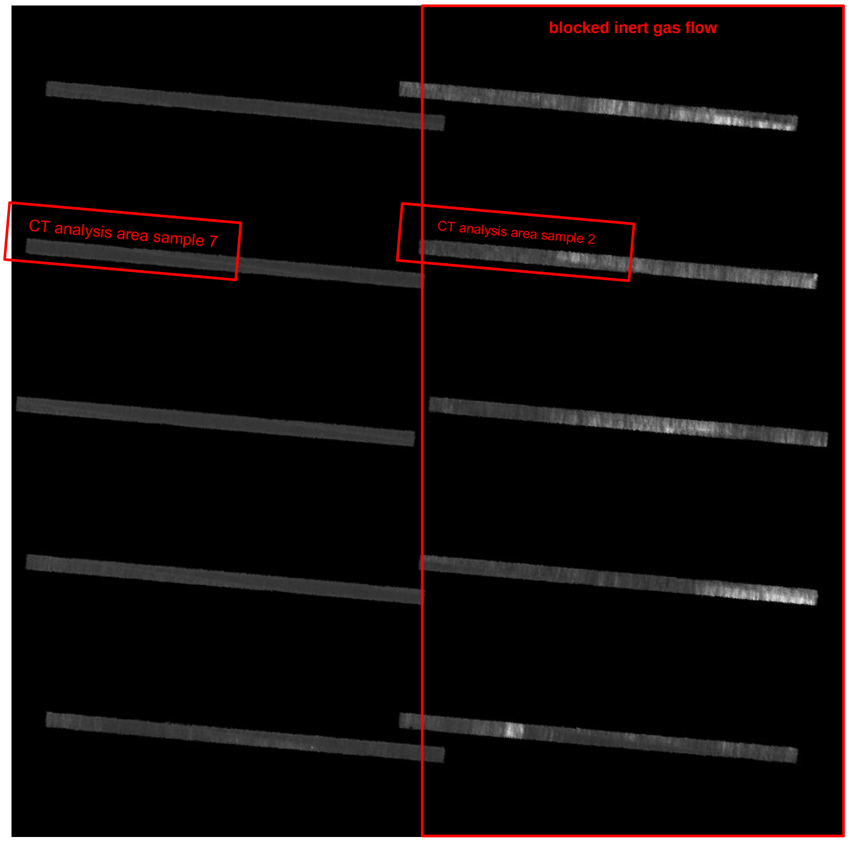


Figure 24: Melt pool monitoring at FOTEC (Layer 153 from top surface)

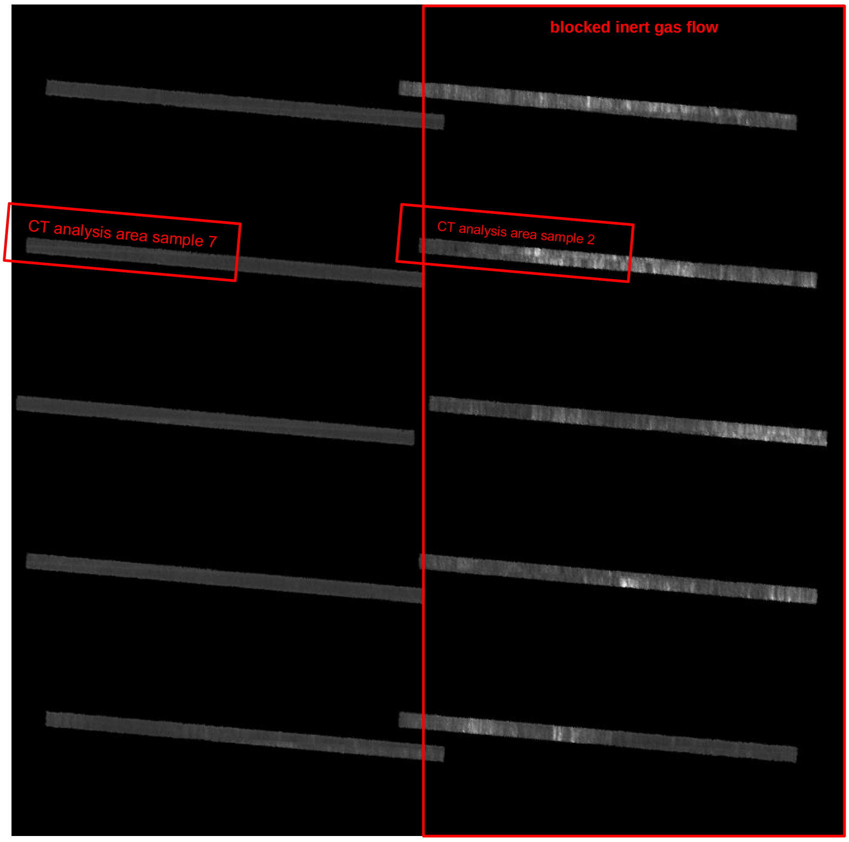


Figure 25: Melt pool monitoring at FOTEC (Layer 297 from top surface)

Therefore, melt pool monitoring could be used to detect weld spatter inclusion faults during building jobs. Through implementation of a limit of reflected laser power scrap parts / regions could be identified and documented.

5 Interpretation

In this study, common error and process deviations during LBM were presented in section 1 and 2. In order to avoid these errors to a large extent, appropriate pre-processing, trained personnel and elaborated workflows are helpful. Nevertheless, the following building defects can occur:

- building stop with reject components – automatic stop in case of a recoater collision which results in bent components
- building stop with intact parts – automatic stop in case of recoater collision, with components remaining intact and building being able to continue
- weld spatter inclusion – through blocked inert gas flow nozzles

To assess these building defects, tensile samples were 3D printed and tests with the three defects were provoked and observed parallel to process monitoring. The samples were examined (according to ASTM E-8) and the following results were obtained:

- A pause or building stop, even after about ten hours, is relatively uncritical due to minor differences in tension parameters. Only if the component quality is critical for elongation at break does it need to be taken care of. In these cases, the focus should be on optimising support and component alignment to prevent the recoater from colliding (see section 4).
- The gas nozzles must be regularly cleaned to minimise noticeable mechanical quality deterioration of the components due to weld spatter inclusion (see section 0).
- Using melt pool monitoring, parts / areas with weld spatter inclusions can be identified and documented (see section 0).