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# Case study on AM of an IN718 aircraft component using the LMD process

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**Abstract**

When manufacturing components from forged blanks of nickel-based super alloys, companies have to cope with rising prices, long delivery time as well as cost intense machining. In this case Additive Manufacturing (AM) can provide an alternative solution. To prove the feasibility of AM, an aircraft engine mounting component was successfully built up by Laser Material Deposition (LMD) from Inconel 718 powder. Due to the length of 500 mm and its complex structure, the pylon bracket component is demanding to build up by LMD. Investigations on process and build-up strategy development as well as analysis of deformation behaviour have been performed.



*Keywords:* "Additive Manufacturing ; 3D Laser Material Depositition ; near-net-shape ; Inconel 718 ; Aviation"

## 1. Introduction

Laser material deposition (LMD) is a free form additive manufacturing (AM) technology that can be used to produce functional, three-dimensional components. LMD provides significant benefits over conventional manufacturing due to a low heat input, near net-shape manufacturing and a high material efficiency [1].

Investigations have been carried out on an Inconel 718 engine mount component of a civil passenger jet by applying the LMD technology. To prove the concept, a demonstrator of an aircraft pylon bracket (Fig. 1) supplied by Airbus Group was built up and machined. The investigation is focused on build-up strategies, deposition rate and deformation. One of the technological challenges is to limit the distortion of the part and substrate material during the build process in order to successfully perform final machining and thereby achieve a valid component. This aspect at the same time has a strong economic impact as this allows near-net-shape manufacturing and a high resource efficiency resulting in a low buy-to-fly ratio which represents the relation of the raw material weight to the weight of the final part. One target within the investigation is to obtain a buy-to-fly ratio improvement of 100%. Compared to a ratio of 4 for milling from a forged blank, the goal is to achieve a buy-to-fly ratio of 2 or less.

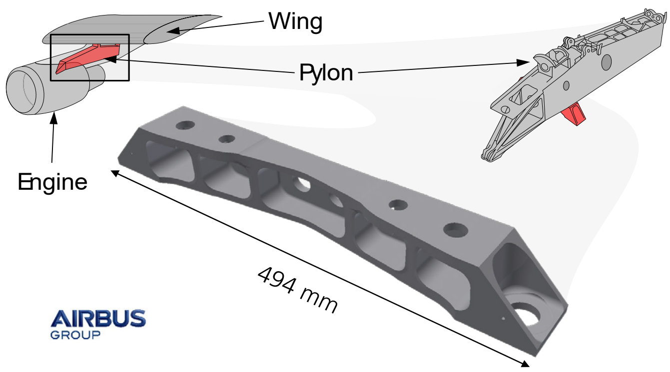


Fig. 1. Pylon bracket demonstrator component APOD11

Due to its size of 500 mm the investigated component exceeds the limits of standard powder bed machines and therefore is better suited for direct laser deposition (DED)


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processes [2]. Larger AM DED components have been manufactured using wire or powder as additive material for example on rocket engine components and aircraft frames mainly applying laser radiation or electric arc as energy source [3,4,5]. Compared to a full part build, a hybrid approach can be advantageous, as demonstrated in an application of building up turbine blades on a disk [5].

## 2. Experimental Investigation

Within the experimental investigation, aspects related to equipment, materials, process parameter development and deformation issues are addressed in respect to the planned demonstrator.

To reach the objective of an economic and efficient production, one of the key factors of the LMD process is the deposition rate which is the mass deposited per time. As the dimensions of the individual tracks influences the build-up rate and the dimensional accuracy, this is explicitly examined in chapter 2.3. As the final geometry of the demonstrator is achieved by milling, the LMD built up volume has to be larger to supply sufficient additional material for machining. The needed amount of additional material is strongly dependent on the distortion developed during the LMD. The lower the deformation, the less additional or excess material is necessary. Due to the importance of distortion, this topic is investigated in chapter 2.4.

### *2.1. IN718 Additive Material*

The applied additive material for the LMD process is metal powder from the alloy IN718 with a nominal powder particle size from 45 – 75 µm. IN718 is a niobium-modified nickel-based super alloy, which is widely used in the aero and space industry for critical rotating parts, airfoils and pressure vessels. It provides high tensile strength, creep-rupture strength, fatigue life and resistance to oxidation at temperatures up to 700°C. [6,7]

### *2.2. Experimental Setup*

During LMD, a melt pool is generated on the surface of the substrate material or a previous layer by laser radiation. Simultaneously, the IN718 powder is injected into the melt pool by a powder nozzle attached to the laser processing head. By moving the laser processing head relative to the substrate material, the material solidifies and generates a cladded track forming a metallurgical fused bond. By stacking tracks next to each other, deposition layers can be created and by stacking layers on top of each other, 3 dimensional structures can be produced.

The LMD setup for processing is displayed in Fig. 12. The laser radiation is emitted by a 3 kW Nd:YAG laser via a 600 µm fiber linked to a 200 mm collimation and a 200 mm focusing optic. The IN718 powder is transported to an ILT-Coax-40 powder nozzle from the powder feeder by Argon feeding gas via connected tubes and a powder splitter. The Laser optics and the powder nozzle are adjusted to each other and mounted to a NC-controlled 5-axis handling system. During LMD processing, local shielding is applied by an argon gas flow fed through the exit of the powder nozzle to prevent oxidation.

### *2.3. Deposition Rate Investigation*

As the LMD track dimension has a high dependency on the deposition rate, a variation of the track width has been analysed to determine the appropriate settings for the build-up of the demonstrator part. The processing velocity is a further factor with a strong influence on the deposition rate. Due to the limited LMD machine acceleration (inertia) and the demonstrator structure size, the processing velocity was fixed to 1500 mm/min to avoid inaccuracy and speed fluctuation. For deposition rate analysis, representative sections were extracted from the pylon bracket geometry as feature samples (Fig. 2). As marked in Fig. 2, a wall (1), a T-section (2) and a triangle (3) feature were designed for this purpose.

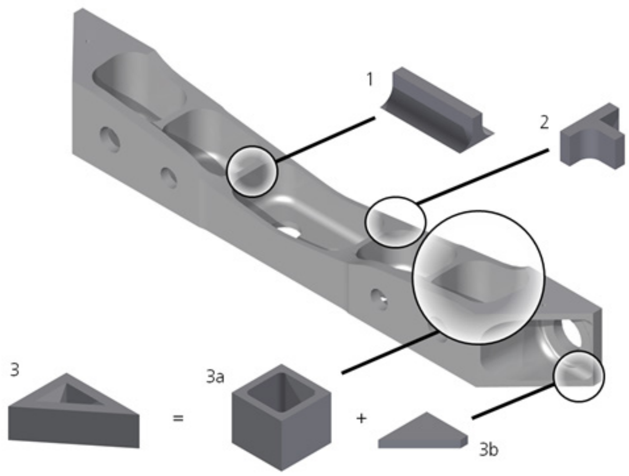


Fig. 2. Feature samples extracted from the pylon bracket geometry

Within the track size investigation, the track width was varied from 1 to 4 mm in 1 mm steps on all selected features. Exemplary the obtained samples of the triangle feature sample T1 to T4 (side length approx. 45 mm) are displayed in Fig. 3.

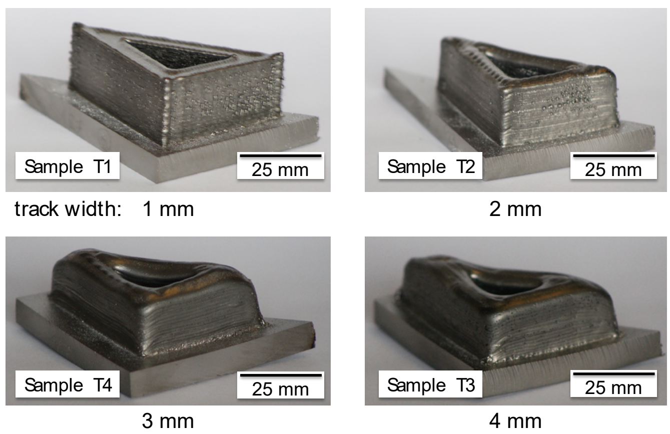


Fig. 3. Triangle feature samples T1 to T4 with track width variation (1-4 mm)

The achieved grade of resolution and accuracy distinguishes all feature samples and decreases with increasing track width. Regarding the detail resolution, the samples with 1 mm track width shows the best result.

The surface of the layers are filled up by a meander shaped pattern. The laser spot diameter has been set to the same value as the track width. The main applied process parameters used for all features are listed in table 1.

The LMD deposition rate relates to the build-up rate when processing (laser on time). As visible in table 1 the deposition rate is significantly dependent on the track size rising from 125 g/h to approx. 2 kg/h which relates to an increase by a factor of 15.

Table 1. Process parameter settings of track width variation

| Track width [mm] | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| processing velocity [m/min] | 1.5 | 1.5 | 1.5 | 1.5 |
| laser power [kW] | 0.5 | 1.2 | 2.6 | 3.3 |
| powder feed rate [g/h] | 180 | 600 | 1380 | 2040 |
| track offset [mm] | 0.5 | 1.0 | 1.5 | 2.0 |
| layer offset [mm] | 0.34 | 0.75 | 1.15 | 1.3 |
| LMD deposition rate [g/h] | 125 | 550 | 1270 | 1915 |

The pylon bracket as well as the features contain wall structures which heat up the part significantly during the build process. With wider tracks higher laser power settings are needed (table 1), increasing the heat input and part temperature even further. To avoid overheating and oxidation a temperature limit of 70°C before starting the next layer has been determined. The temperature on the surface of the top layer was measured by a thermocouple after each layer and if the temperature was above 70°C, a cooling break was inserted before continuing with the next layer. The duration of the build process for the feature samples was recorded and evaluated as displayed in Fig. 4 for the T-section. As the target volume is constant, the duration directly indicates the deposition rate.

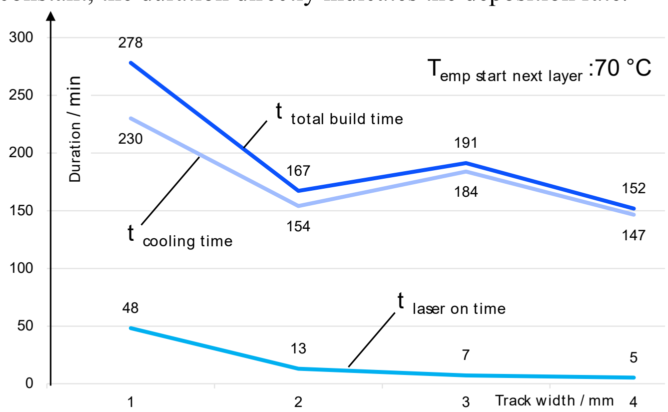


Fig. 4. Build duration of LMD feature T-section T1 – T4 with 70°C limit

The correlation of the three time curves of the T-section feature for track widths of 1 to 4 mm are presented in Fig. 4:

- Material depositing time only (laser on time)
- Time to cool down to 70°C
- Accumulated total build time

As expected, the process laser-on time decreases rapidly with larger track widths from 48 min for 1 mm to 5 min for 4 mm track width. With wider tracks, the total LMD track length is shorter, hence the laser-on time drops. Additionally the layer offset is larger too for wider tracks reducing the number of layers needed to build up the targeted height of 15 mm. Concluding the laser-on time, the deposition rate of the 4 mm tracks is 9 times higher than that of the 1mm tracks. If no cooling is considered, this would also be the total build time for the samples and an essential benefit. The situation changes dramatically if cooling of the top surface to 70°C is requested. The increased laser power (table 1) for wider tracks boosts the energy transferred to the sample, heating it up strongly and thus requiring a significant cooling time to reduce the temperature again. Due to this effect, the 3 and 4 mm wide tracks lose their advantage compared to the 2 mm tracks. The 1 mm setting offers the highest geometric resolution, but by far has the longest total build time and by this the lowest overall deposition rate and therefore is not considered for further trials.

Concluding the 2 mm track width parameter set obtains the second best deposition rate with cooling time of which is only 9% less than that of 4 mm track width. Further considering the achieved detail resolution and the wall structure of the pylon bracket the 2 mm track width is best suited compared to the 3 and 4 mm tracks. Therefore the 2 mm track width parameter set is selected for manufacturing the final demonstrator. The achieved metallographic result is documented by the displayed cross section in Fig. 5 revealing a porosity level below 100µm and no visible cracks or bonding defects.

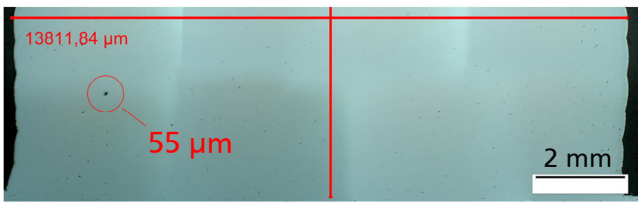


Fig. 5. Cross section analysis of the 2 mm track width parameter set

### *2.4. Deformation Analysis*

Regarding the sleek and 500 mm long shape of the pylon bracket, deformation is a critical issue and it is a challenge to obtain a buy-to-fly ratio $r_{btf}$ of 2 or less which can be calculated by:

$$r_{btf} = \frac{(V_{part} + V_{excees})}{V_{part} * \eta} \quad with\ V_{LMD} = V_{part} + V_{excees} \qquad (1)$$

By applying equation 1 the deformation limit for a given buy-to-fly ratio can be determined. With a ratio $r_{btf}$ of 2, the pylon bracket volume $V_{part}$ of 536 cm$^3$ and a powder efficiency η of 90% the excess volume is calculated to $V_{excess}$ = 429 cm$^3$ by equation 1. As the calculated excess volume is needed for machining and compensating deformations it is represented by an equidistant offset surface to the CAD geometry (Fig. 2). At a surface offset of 2.5 mm the offset volume matches the calculated excess volume $V_{excess}$ = 429 cm$^3$. As a consequence the offset surface also limits the distortion of the LMD part: If the distortion is larger than 2.5 mm then the CAD geometry does not fit inside the LMD part. The total LMD volume is determined to $V_{LMD}$ = 965 cm$^3$ (equation 1). The powder efficiency of 90% is calculated from table 1 for a track width of 2 mm considering a 2% loss for process start and stop. Regarding deformation two strategies were investigated:

- Preheating to reduce the stresses induced by the LMD process and by this lower the deformation
- Increased substrate stiffness to withstand the deformation caused by the induced stresses

In an experimental study, preheating of the substrate by laser radiation was tested to reduce the induced deformation. Two identical test geometries of 150 mm x 80 mm were generated on a 15 mm thick 1.4301 substrate material (Fig. 6): Sample LH_RT starting at room temperature (25°C) and sample LH_325 with preheating to 325°C. On sample LH_325 preheating was obtained by scanning the sample surface with a defocused laser beam prior each layer.

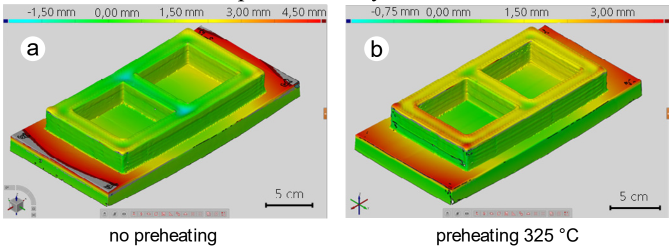


Fig. 6. Deformation analysis samples (a) LH_RT without preheating and (b) LH_325 with preheated substrate to 325°C

Due to preheating the laser power was reduced by 16%. The LMD processing of the test geometries was performed with the 2 mm track width parameter set from table 1.

A geometric analysis of the completed samples was performed with a GOM Atos Compact Scan inspection system. The deformation on the substrate surface without preheating summed up to be 4.5 mm (Fig. 6a) compared to a value of 3.4 mm (Fig. 6b) when preheated to 325°C. The deformation could be reduced by approx. 25%. Although preheating leads to a deformation reduction, this approach is not applicable for the demonstrator part due to the remaining deformation of 3.4 mm which exceeds the limit of 2.5 mm. A further disadvantage is the time consuming preheating.

Therefore an alternative strategy was studied on the APOD11-50-1 sample which is a half part of the final demonstrator. In order to reduce the deformation, a stiffener structure was added to the rear side of the 20 mm thick 1.4301 substrate by LMD (Fig. 7).

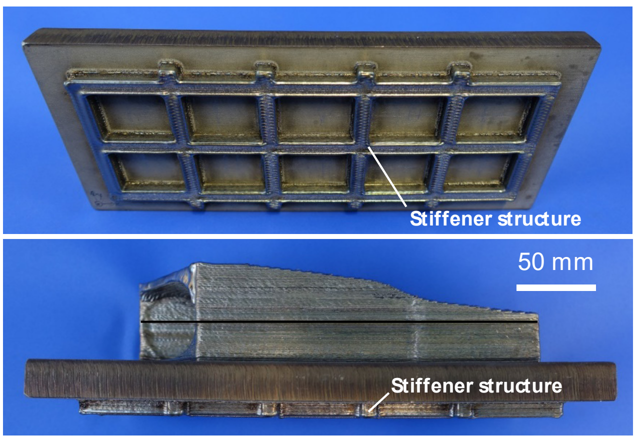


Fig. 7. Half part APOD11-50-1 with rear stiffener structure

As with the previous samples, the APOD11-50-1 sample was inspected with the GOM system, detecting a distortion of 2.75 mm along the substrate of the sample (Fig. 8).

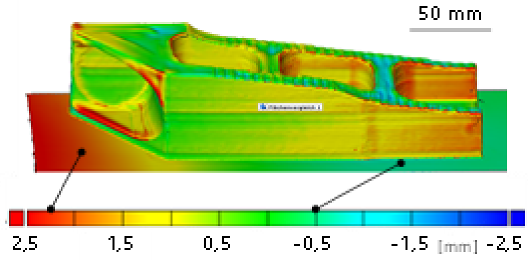


Fig. 8. Deformation analysis on the half part APOD11-50-1

In order to further improve the stiffness of the substrate and by this reduce deformation, a rigid platform was designed (Fig. 9). It is assembled as a welded construction from 20 mm thick 1.4301 sheet material (Fig. 9b) to support the demonstrator manufacturing by LMD.

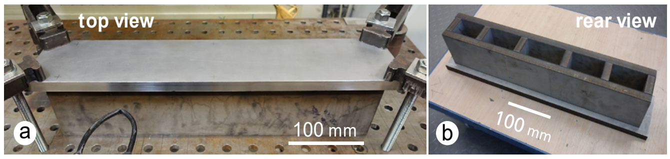


Fig. 9. LMD build platform for demonstrator

## 3. Manufacturing of the Demonstrator

The achieved results are taken into account when building the pylon bracket demonstrator including a geometry adaption step and a heat treatment and final machining. Due to the rigid platform a further deformation reduction is expected. To take advantage of the reduction the surface offset was lowered to further improve the buy-to-fly ratio. The planned surface offset consists of a 1 mm offset from the CAD geometry and 1 mm resulting from half of the 2 mm LMD track width. The total surface offset of 2 mm leads to a calculated LMD volume of 852 cm$^3$ and results in a fly-to-buy ratio of 1.77 (equation 1).

### *3.1. LMD Related Geometry Adaption*

In order to build up the demonstrator, LMD process related modifications have to be applied to the original part geometry (Fig. 10).

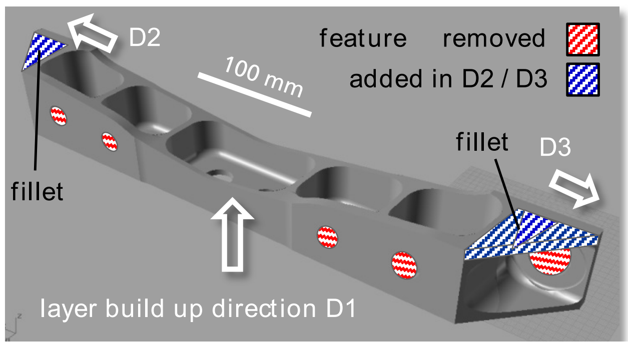


Fig. 10. Geometry adaption to achieve feasibility for LMD processing

Considering the selected main layer build-up direction, this applies to 2 types of features:

- The horizontal bore holes (marked in red in Fig. 10)
- The fillet sections on the left and right upper side of the demonstrator (marked in blue in Fig. 10)

As the horizontal bore holes cannot be generated by LMD, they are removed from the geometry and filled up. Instead, they will be manufactured in the final machining step. Due to missing support the fillet features are removed from the geometry and have to be added in a following step with a different part orientation.

### 3.2. LMD Build-up of Demonstrator

The demonstrator was manufactured in 2 sections consisting of the body with the build-up in direction D1 and the fillets added on the outer sides in the modified direction D2 and D3 (Fig. 10). For the demonstrator build-up, the 2 mm wide LMD tracks were applied using the settings in table 1.

The body was built on the designed platform which was clamped onto the machine table to add further stiffness to the setup (Fig. 11). The build direction is perpendicular to the platform top surface which is indicated by the white arrow.

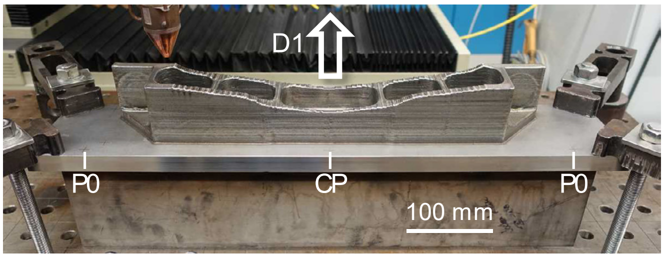


Fig. 11. LMD build-up of demonstrator body on platform

Based on the CAD-Dataset, the slicing of the LMD-layers and generating of the LMD tracks was performed with help of the ILT CAM planning tool LMDCAM. The body section was built up in 75 layers. To improve the cooling effect, water cooled copper pipes were fitted to the platform.

In the next build step, the fillets were added to the sides in the adapted build direction D2 (Fig. 10) and D3 (Fig. 12).

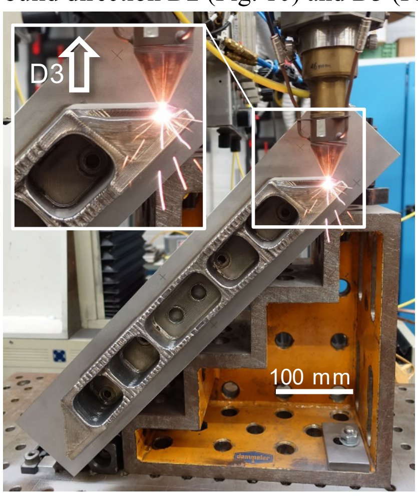


Fig. 12. LMD build-up of demonstrator of fillet 2 in direction D3

The body with the platform was aligned and clamped to a fixture to obtain the desired orientation with the Z-axis of the handling system perpendicular to the front edge of the fillet.

Fig. 13 displays the successfully completed pylon bracket on the platform after cleaning by sandblasting.

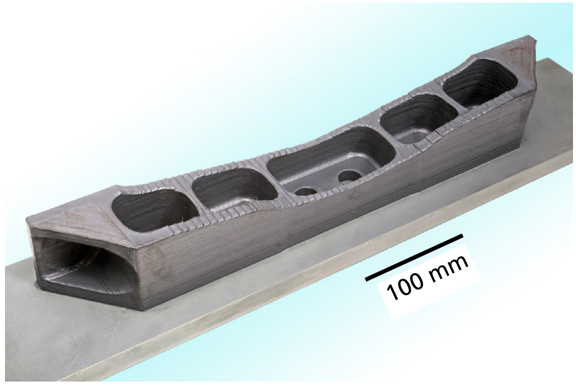


Fig. 13. LMD built pylon bracket demonstrator on the platform

The total LMD processing time for the demonstrator summed up to approx. 16.5 h. With the afforded cooling time of approx. 7.5 h, the total build time accumulated to 24 h. Before removal of the completed demonstrator from the platform a deflection of 1.25 mm was detected in the platform centre position CP (Fig. 11) in respect to the outer positions P0 which indicates a significant deformation reduction.

### 3.3. Post Processing and Analysis of Demonstrator

The final steps are to remove the demonstrator from the platform, to validate the build results and machine sections of the demonstrator to achieve the final part geometry.

As the LMD process induces stress in the deposited material a significant internal stress level accumulates during processing. When cutting off the LMD part from the platform, the “holding forces” of the platform are no longer present. The residual stresses present in the part can lead to a deformation. In order to eliminate or at least reduce the internal stress level, a heat treatment for stress relief has been included. The performed solution heat treatment of the LMD part and platform consisted of heating up to 980 °C at a rate of 5 K/min, holding this temperature for 1 h and cooling down to 200 °C at a rate of <2.5 K/min. Compared to an usual solution heat treatment with a harsh cooling phase, a low cooling rate was selected to avoid a new stress development. After heat treatment, the LMD demonstrator was trimmed off the platform by wire-cut electric discharge machining (EDM).

To analyse the LMD geometry, the demonstrator was scanned with the GOM Atos measurement system. The analysis of the measurement is displayed in Fig. 14. According to the colour grading, the offset from the CAD geometry ranges from 0.4 to 1.9 mm and this indicates the amount of excess material available for machining. The deformation of the LMD part causes the excess material thickness to vary.

Considering a calculated volume of 831.4 $cm^3$ from the scan data a buy-to-fly ratio of 1.72 is obtained (equation 1). Calculating the buy-to-fly value from the parts weight of 6.9 kg results in a ratio of 1.75 considering a density of 8.19 g/ $cm^3$ for IN718 confirming the planned value of 1.77 (chapter 3.3).

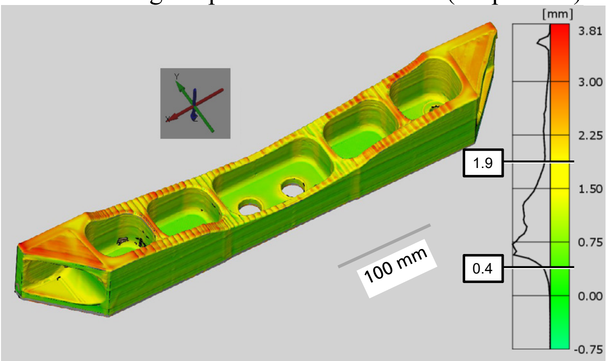


Fig. 14. Surface offset of the LMD demonstrator related to CAD-model

In order to determine the base deviation and the yield of the heat treatment the base surface was analysed. The examination reveals a low deviation of 0.4 mm as presented in Fig. 15.

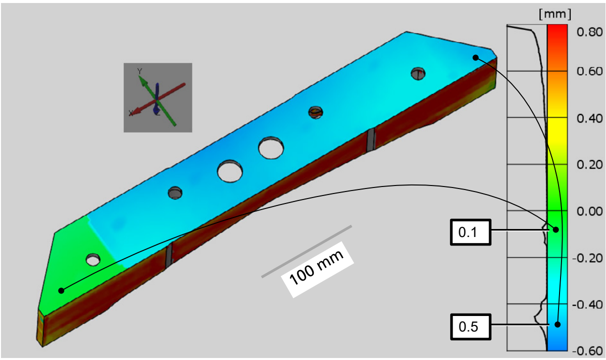


Fig. 15. Deviation of the demonstrator base surface

These results prove that the rigid platform design combined with the solution heat treatment could effectively reduce the distortion of the part to below 2 mm.

Based on the measurement data the last step of machining the pylon bracket demonstrator was planned with the CAM software Mastercam. Half of the demonstrator was milled according to the CAD-data. The remaining surface is left in the LMD processed state to allow a comparison of the processes involved. The final state of the pylon bracket demonstrator after successful machining is presented in Fig. 16.

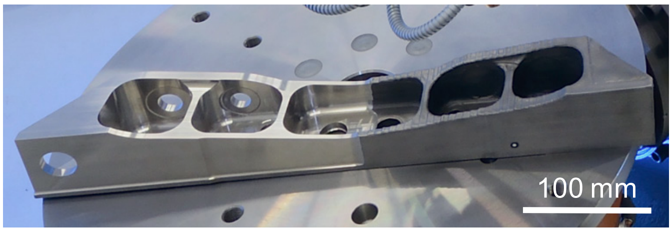


Fig. 16. Final pylon bracket demonstrator after machining

## 4. Conclusion

The manufacturing of a IN718 pylon bracket demonstrator by LMD served as a case study to analyse production and resource efficiency of the LMD process (chapter 2.3,2.4). Investigations on LMD track width were performed in respect to the deposition rate and build resolution. A Temperature limit was defined to avoid overheating which afforded cooling breaks and reduced the overall deposition rate. From the track size analysis, the 2 mm wide LMD tracks were selected for all the following samples as they showed the best overall performance. The 2 mm tracks offer high detail resolution with a deposition rate only 9% below the highest score of the 4 mm tracks when considering the temperate limit.

The trials on resource efficiency focused on minimizing deformation as it has a contradictory influence and increases the buy-to-fly ratio. Two approaches, preheating and increasing stiffness of the substrate, were investigated resulting in designing a rigid platform.

The final pylon bracket demonstrator was successfully built up on the platform with a distortion below 2 mm (chapter 3.2). To avoid internal stresses deflecting, the part when cut off from the platform, a heat treatment was applied before removal. The trimmed off pylon bracket was geometrically analysed by a GOM laser scanning system. The analysis results confirm the concept and all scheduled targets are reached (chapter 3.3):

- The CAD-geometry exhibits sufficient access material (offset thickness 0.4 to 1.9 mm).
- The deflection of the base is 0.4 mm and < 2 mm.

As the final step half of the pylon bracket was machined by milling to prove that the final geometry can be obtained from the LMD raw part which successfully could be demonstrated.

Considering the goal of improving the buy-to-fly ratio, a final result of 1.75 has been achieved which is 12.5% better than the targeted ratio of 2.

## 5. Acknowledgements

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