Whitepaper

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The Hitchhiker's Guide to Smart Fusion

This Whitepaper gives answers to:

- What the design guidelines for Smart Fusion are
- How to qualify Smart Fusion
- How Smart Fusion was used to produce real applications

Content

List of Figures

Introduction

Additive Manufacturing (AM) evolved over the years from prototyping to serial production of critical applications and is constantly challenged to produce more complex geometries with higher quality requirements at an increased throughput. These challenges do not only require innovative machine hardware but can also be addressed by improved exposure strategies and introducing new software features.

In the past, process monitoring was primarily used to identify disruptions in the building process, which were then linked to part properties. The data were also used to improve process parameters or part orientation for the next iteration of a part build. Nowadays, Smart Fusion, EOS' build control software, is taking process monitoring to the next level. It uses images from the EOSTATE Exposure Optical Tomography (OT) monitoring system to determine the optimal energy input to manage the thermal characteristics of parts.

By utilizing Smart Fusion on previously unbuildable geometries, clear improvements in buildability were made without any negative effects on the build time and material properties. Moreover, Smart Fusion made a significant reduction in support structures possible, resulting in reduced build time, post-processing time, and material waste – making Direct Metal Laser Solidification (DMLS) process even more sustainable.

This white paper showcases the principle of Smart Fusion, EOS’ qualification methodology and different applications and how this groundbreaking technology was used to:

→ Drastically reduce the support structures on a bracket

→ Produce an aerospace fuel tank with a 0-degree overhang without any support structures.

→ Enable production of a large impeller

2. Key Benefits of Smart Fusion

Intelligent heat management with closed loop in real-time

Smart Fusion does not use additional waiting or cooldown times in the process to conduct heat out of the part. It rather uses layer-by-layer sensor data to adapt the process parameters in real-time. Thus, the build time does not increase.

Shorter time to market

Processes do not have to be tweaked in an iterative approach to make a part buildable. For many applications, the EOS standard parameters can be used without tweaking and Smart Fusion will do the application specific process adaptions on the fly during the build.

Reduction of cost-per-part via support free building

Reducing supports has many benefits. Support build time is turned into part build time. Also, reduced supports lead to reduce the waste of material and a reduction of post-processing time to remove them. Engineers have greater flexibility in their designs. This means that more applications can be considered for manufacturing with a positive business case, and more legacy applications can be made viable without needing to change their design.

Working Principle of Smart Fusion

EOSTATE Exposure OT is used to monitor the thermal behavior of parts in each layer. A controller then determines the laser power correction factors that are necessary to maintain a homogeneous heat distribution. In the next layer these correction factors are considered, and the laser power is adjusted accordingly. This process repeats layer by layer at a high optical resolution of approx. 100 µm. Thus the number of iterations needed to get a part right is reduced to 1 along with the possibility to reduce support structures to a minimal level.

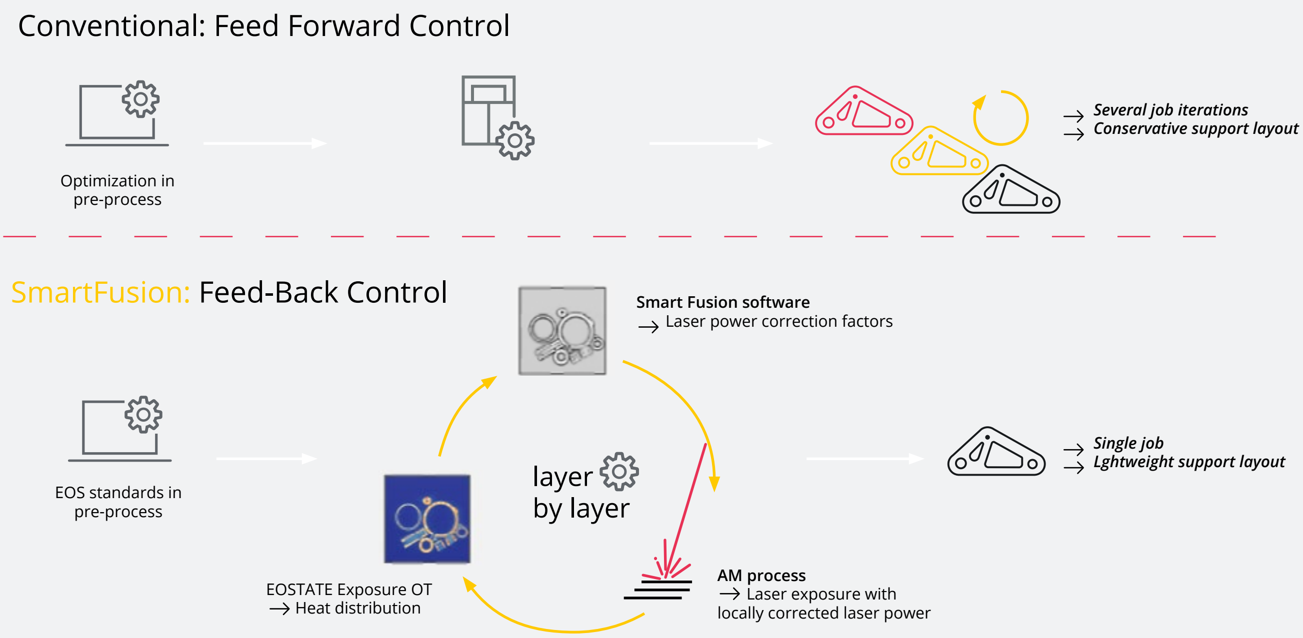
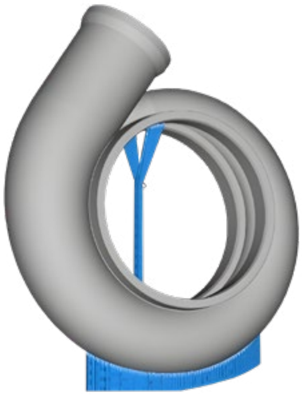


Figure 1. Smart Fusion Working Principle

3. Design Guidelines with Smart Fusion

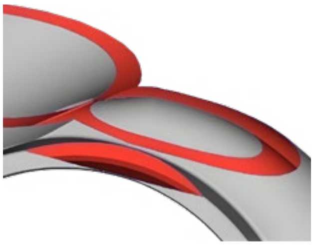
Holes

Holes can be built up to 50 mm without internal supports at outer edges or lowest line can be supported for better detail accuracy.



Domes

Domes (enclosed) with diameters up to 450 mm can be built without supports.



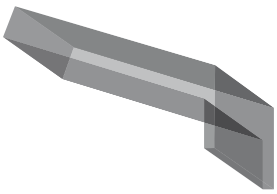
Overhangs

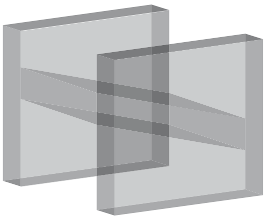
30°–20° overhangs can be built without supports

20°–15° can be built but might require some supports or constraining walls

< 15° overhangs can be built with two or more constraining walls or supported edges.

Horizontal overhangs can be built if constraint by all sides





4. Availability

The Smart Fusion technology is available for the EOS M 400-4, EOS M 300-4 and EOS M 290. We have been performing extensive testing of all processes, starting with the most utilized ones. For the actual availability of official release for individual processes, you can reach out to EOS.

5. Qualification

In industries with stringent control requirements like aerospace and medical, implementing an active feedback control system for production may require a dedicated qualification procedure. Nevertheless, Smart Fusion can be used to analyze and optimize the thermal characteristics of a part and process in order to create a repeatable and qualified production build file.

Critical to Quality – EOS Quality Triangle

EOS offers customers a sustainable competitive advantage across the entire additive manufacturing life cycle by consistently improving the interaction between process, material, and system. During the development phase and for every new powder batch, EOS materials undergo rigorous testing to assess characteristics like particle size distribution, chemical composition, process behavior, mechanical properties, and density. Critical-to-Quality features of EOS machines are thoroughly tested during assembly and installation. EOS processes are designed to deliver exceptional quality and productivity, with a continuous focus on improvement.

Highest Quality Due to Perfect Interaction between Process, Material and System

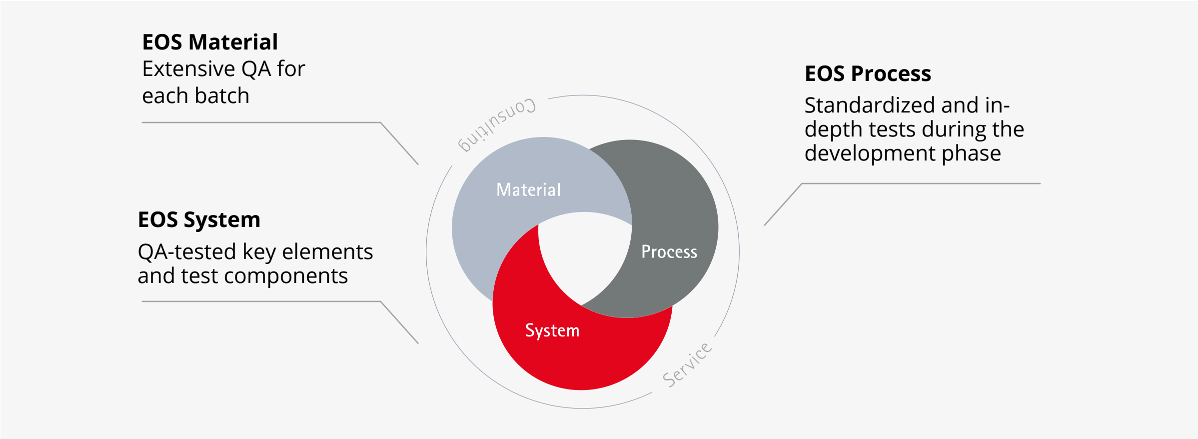


Figure 2. EOS Quality Triangle

Qualification is usually a three-stage approach. At EOS, we commonly use the terms Installation Qualification (IQ), Operational Qualification (OQ) and Performance Qualification (PQ). Derived from the medical industry, these terms are now commonly accepted in AM industries as well.

The FAT & IQ is part of a standard procedure offered by EOS. Field Service Engineers validate that on-site requirements of the machine and equipment are met and that the system's core components are working according to EOS specifications. In addition, a test job for quality assurance is built and evaluated with the customer. All results as well as the calibrated tools used to complete the IQ are documented in a final report.

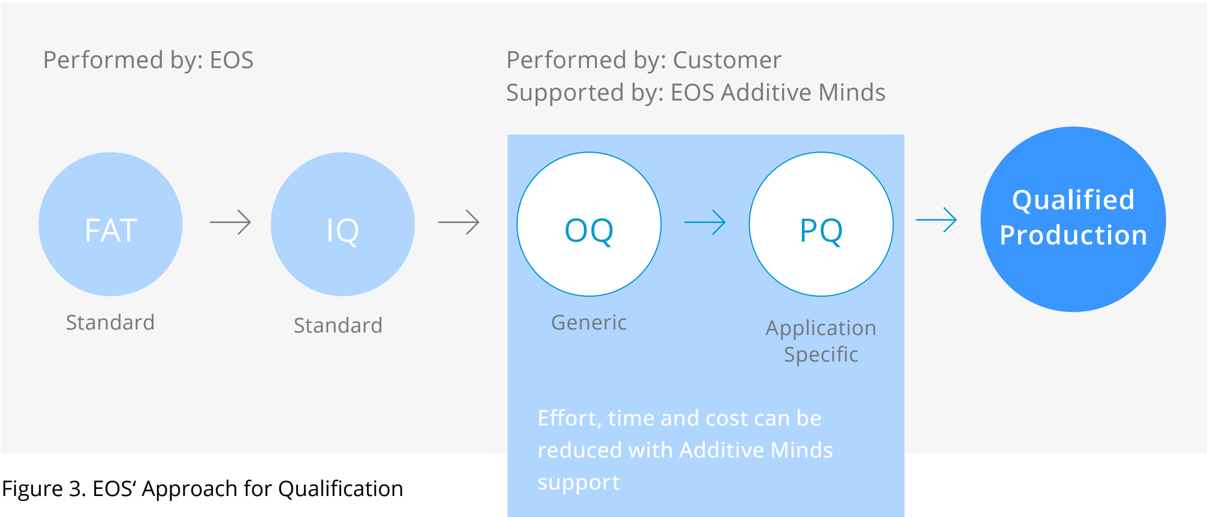


Figure 3. EOS' Approach for Qualification

Methodology

One of the important targets in the study was to prove that Smart Fusion doesn't alternate the processes too much in order to maintain the needed quality. Nevertheless, we recommend that you test your own application with your qualified parameters and Smart Fusion activated.

To qualify the Smart Fusion technology and validate the material properties, EOS used their official verification layouts to collect tensile and porosity data from jobs built with Smart Fusion. This data were then compared to similar jobs built using standard parameters. The comparisons are showed in graphs and micrographs on next pages.

The verification layouts are used to gather wide range of data from new processes developed at EOS. The data are used to see the performance across the building platform in more difficult, high-load conditions, which are often realistic to customers who fill the platform with a lot of parts. The layouts have large number of different parts that can be used to study a lot of various properties. In this study, the density cubes and the tensile bars were tested from each built job, each with their relevant standards. All relevant data was logged to confirm the job quality.

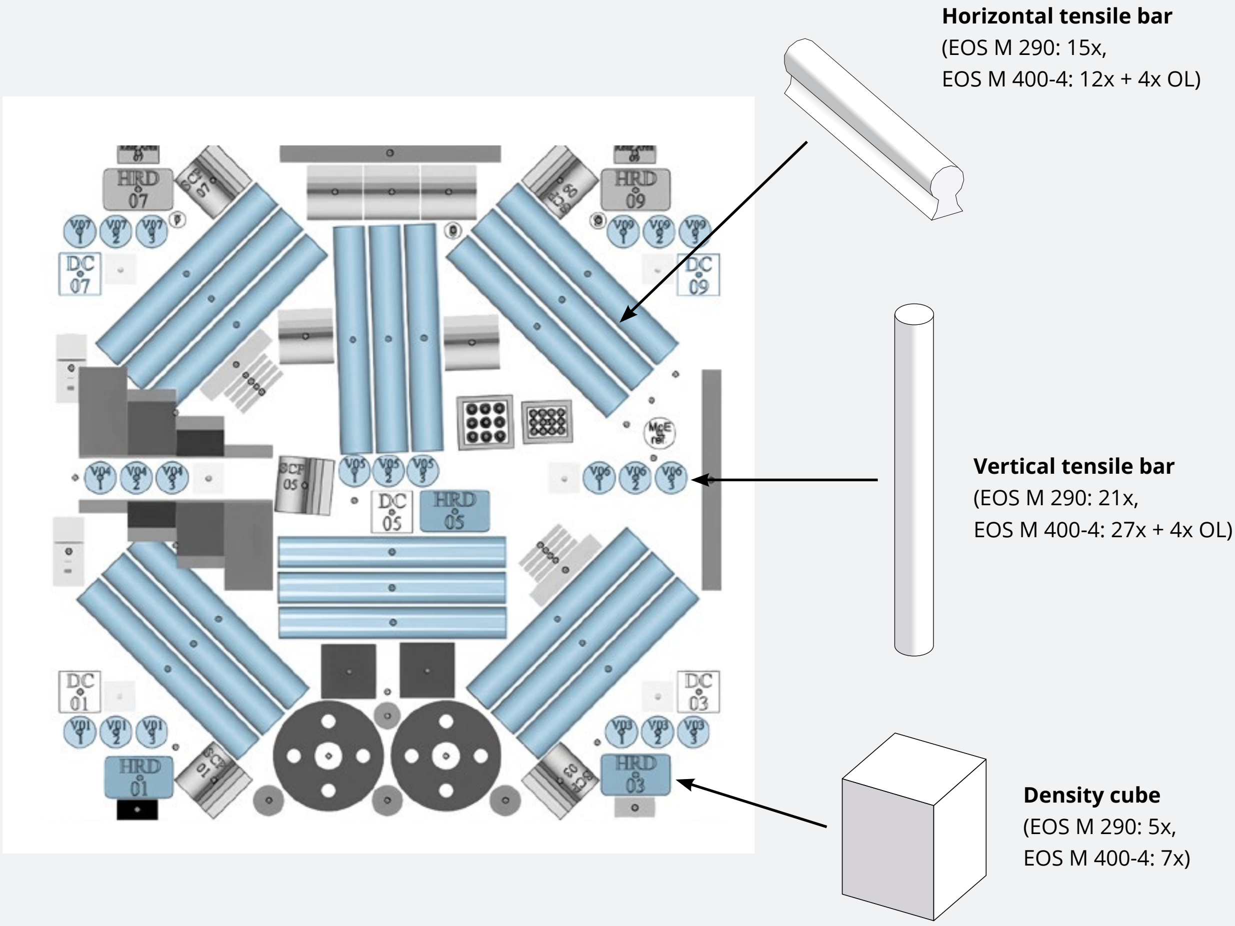


Figure 4. The build layout of EOS M 290. The tested samples are highlighted in blue. Grey samples were archived in these tests.

The sample IDs of EOS M 290 job layout are based on nine areas. Area 1 is located at front left area, and the ID grows towards right and then towards rear area, Figure 4. Exactly similar pattern is also used with the version of the layout in EOS M 400-4, where the larger building platform is divided to 16 areas.

The tensile bars were tested in both as-manufactured and heat-treated states. Two samples were heat-treated following EOS recommendations of the material, and one was left in as-manufactured condition. With most selected processes the heat-treated samples were the focus of testing, as applications are often used in heat-treated condition. Additionally, four horizontal and four vertical overlap tensile bars, built by two lasers at the overlap sections of the scan fields, were tested in heat-treated condition from the EOS M 400-4 job.

EOS M 290 IN718 40 µm Performance and 80 µm HiPro

EOS NickelAlloy IN718 is a precipitation-hardening nickel-chromium alloy that is characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700 °C. It is one of the most used and well-known nickel alloys in additive manufacturing due to its great properties and cost efficiency. The classic 40 µm Performance process known from its robust quality has been out for long time for EOS M 290, and also a novel high-productivity 80 µm HiPro process was introduced to the market. To study the effect of Smart Fusion to its mechanical properties, both of the two IN718 processes were built with SmartFusion and then enabled and then compared against a standard IN718 80 µm job with identical layout.

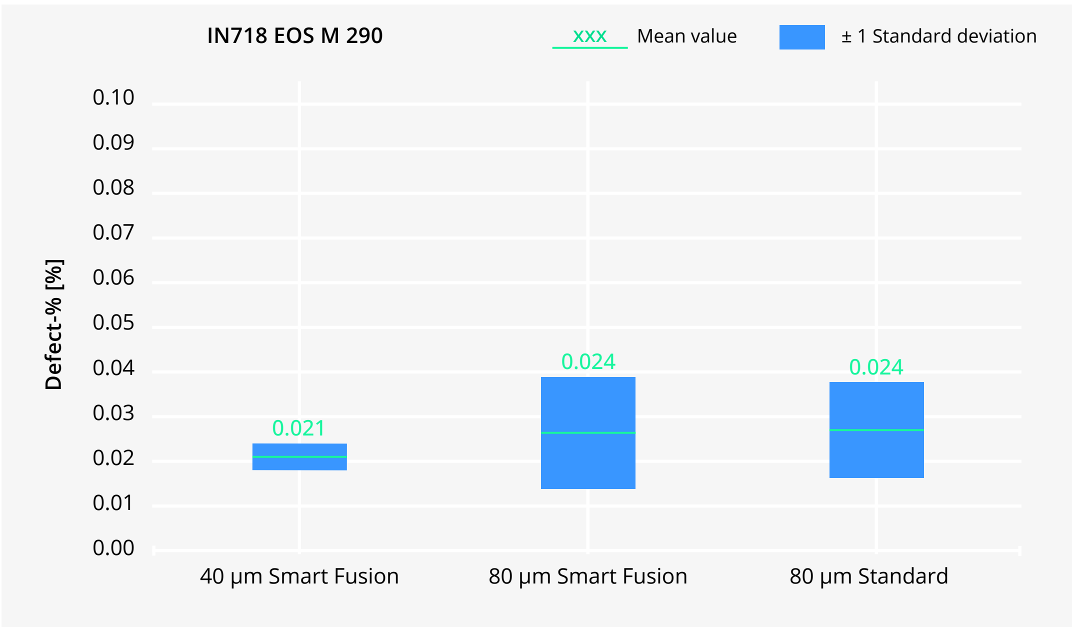


Figure 5. Porosity levels of built jobs as analyzed from XZ plane. The results mean that each sample across the jobs had density of 99.95 % at minimum.

The porosity of 80 µm standard and Smart Fusion processes were found to be equal, both having mean porosity of less than 0,03 %.

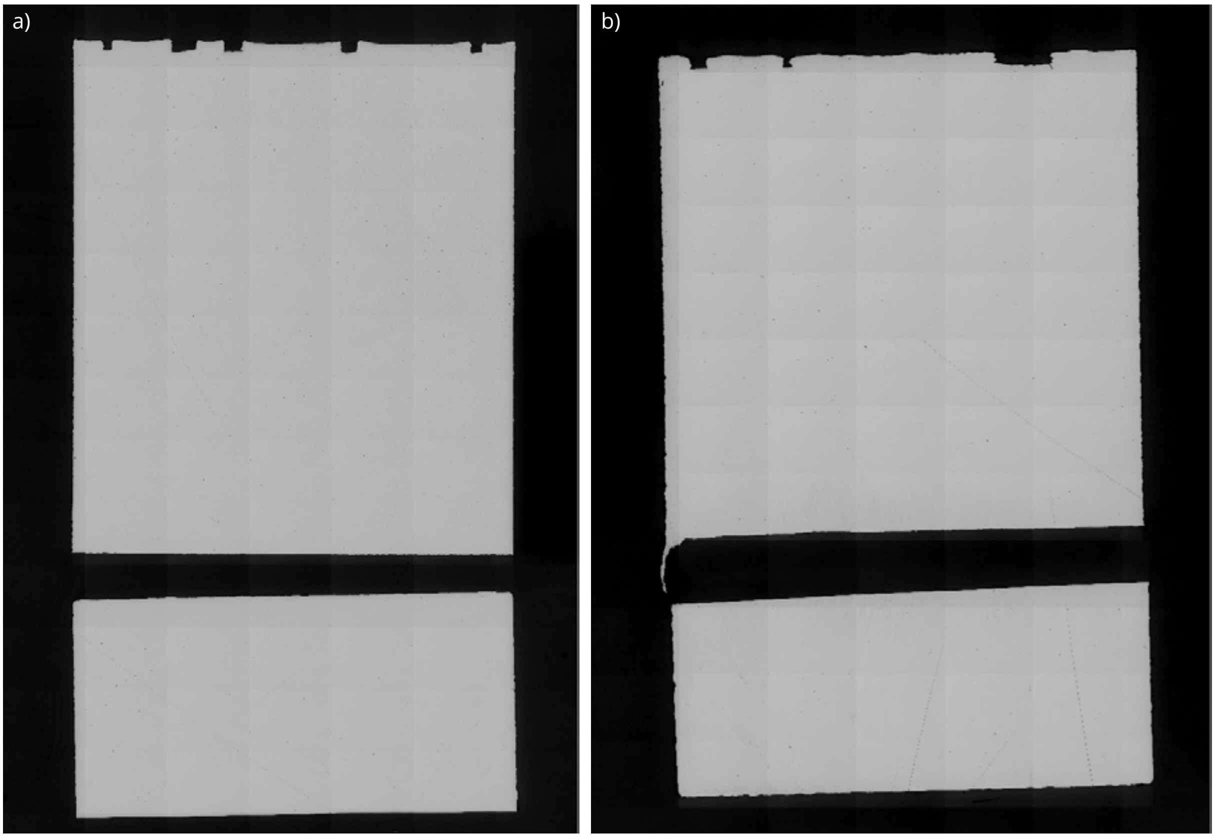


Figure 6. Cubes from location 5 from a) IN718 40 µm Performance and b) IN718 80 µm HiPro built when Smart Fusion was enabled. The top half of both micrographs is the XZ cut and the bottom half is the XY cut.

The tensile testing results further suggest that Smart Fusion doesn't destabilize the process of IN718 on EOS M 290. The high productivity 80 µm process with Smart Fusion reached pretty much identical values in all measured variables compared to the standard 80 µm process. The 40 µm process also reached expected strength and elongation, with slightly more difference between as-manufactured and heat-treated samples compared to 80 µm process, which is a result of lower layer thickness and hence different melt pool shape, as seen in Figure 7. The heat-treatment reduces the orientation dependency of the yield strength from more than 20 % to less than 5 %, respectively.

The samples were tested following ISO 6892-1 (Annex D). The heat treatment was performed following AMS 2774.

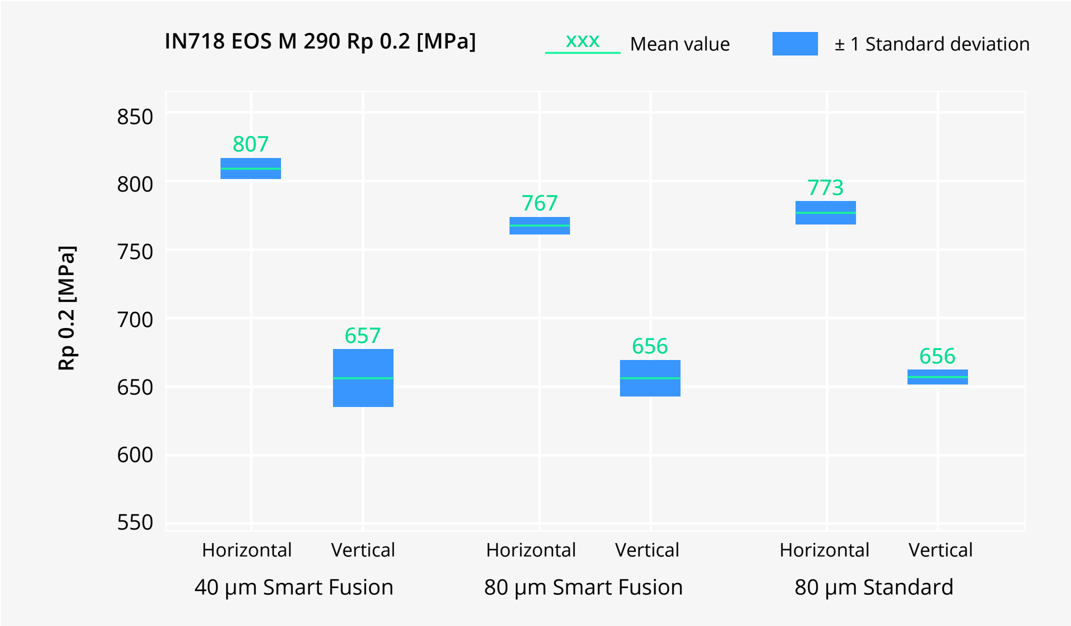


Figure 7a. Yield strength (Rp 0.2) before heat treatment in studied IN718 processes.

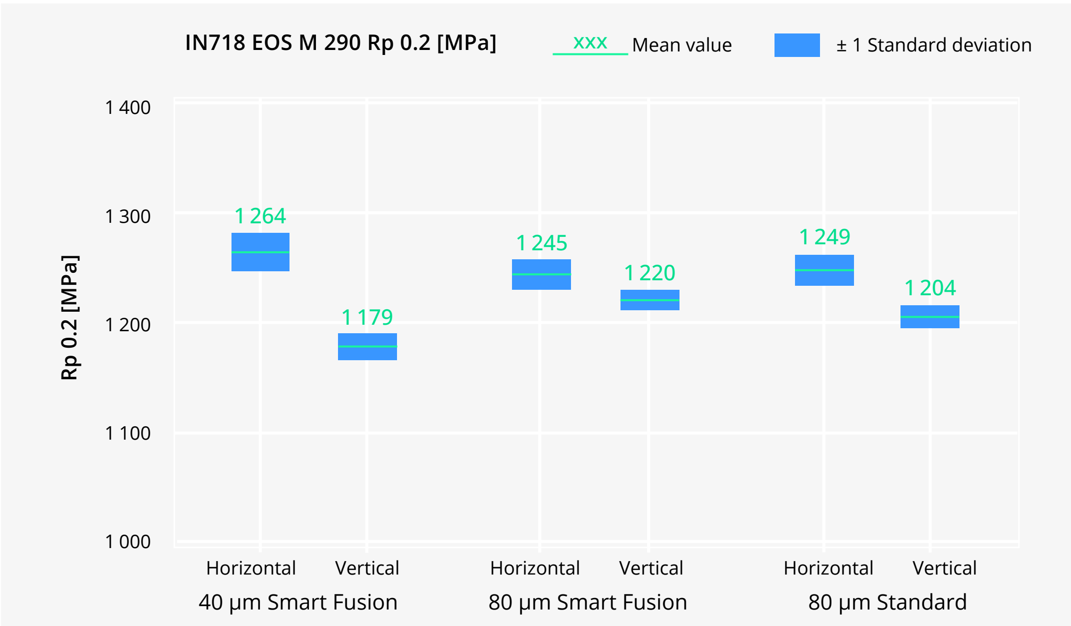


Figure 7b. Yield strength (Rp 0.2) after heat treatment in studied IN718 processes.

One of the main properties of IN718 is percent elongation of heat-treated samples, which quickly shows if there are any defects in the process and is important for fatigue properties of the parts. The 40 µm Performance process with Smart Fusion, has a stable and repeatable performance as every single sample passed the 12 % target with ease and vertical samples reached over 16 % mean. In the 80 µm HiPro process Smart Fusion also achieves reliable material properties as the percent elongation reached the target on most locations without issues, as the only samples with elongation lower than that were in location 1 at front-left area.

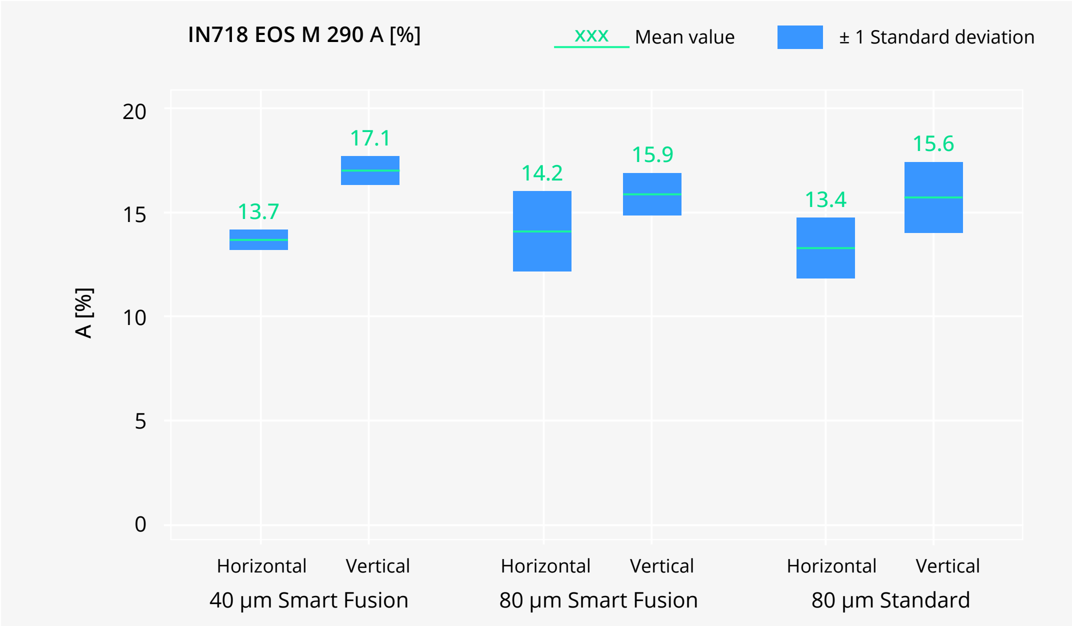


Figure 8. Percent elongation after heat-treatment in studied IN718 processes.

Overall, these porosity and tensile testing results showed that Smart Fusion does not decrease the properties of EOS Nickel Alloy IN718 when test samples were manufactured using the verification layout with high load. While it's good to keep in mind that job load may affect the result especially with an alloy like IN718 that conducts the heat quite poorly, these results hint that use of Smart Fusion is safe mechanically for this kind of an alloy.

EOS M 290 Ti64 and EOS M 400-4 Ti64

EOS Titanium Ti64 is a Ti6Al4V alloy, which is well-known for having excellent mechanical properties: low density with high strength and excellent corrosion resistance. The alloy has low weight compared to superalloys and steels and higher fatigue resistance compared to other lightweight alloys. EOS' classic 60 µm Speed process is available in both EOS M 290 and EOS M 400-4 machines.

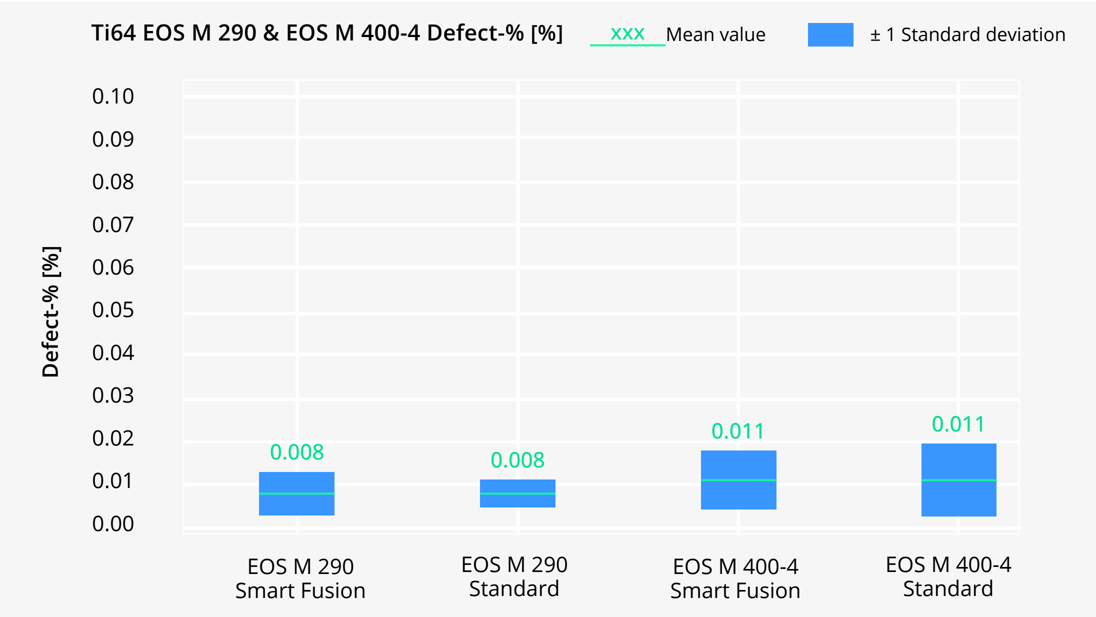


Figure 9. Porosity levels of built jobs as analyzed from XZ plane. The results confirm that each sample across the jobs had density of 99.95 % at minimum.

While the sample size of data available from Smart Fusion is much smaller, the porosity levels of the jobs built with Smart Fusion were equally good to standard jobs. The mean porosity in EOS M 290 was identical with and without Smart Fusion and below 0.010 %, while EOS M 400-4 processes seem to have similar scatter with most samples having less than 0.015 % of porosity, the highest peak with Smart Fusion being still as low as 0.03 %. This result was excellent for titanium, where porosity or lack of fusion could cause brittle fractures easily. Also, the microstructure of the as-manufactured samples looks very good on both machines.

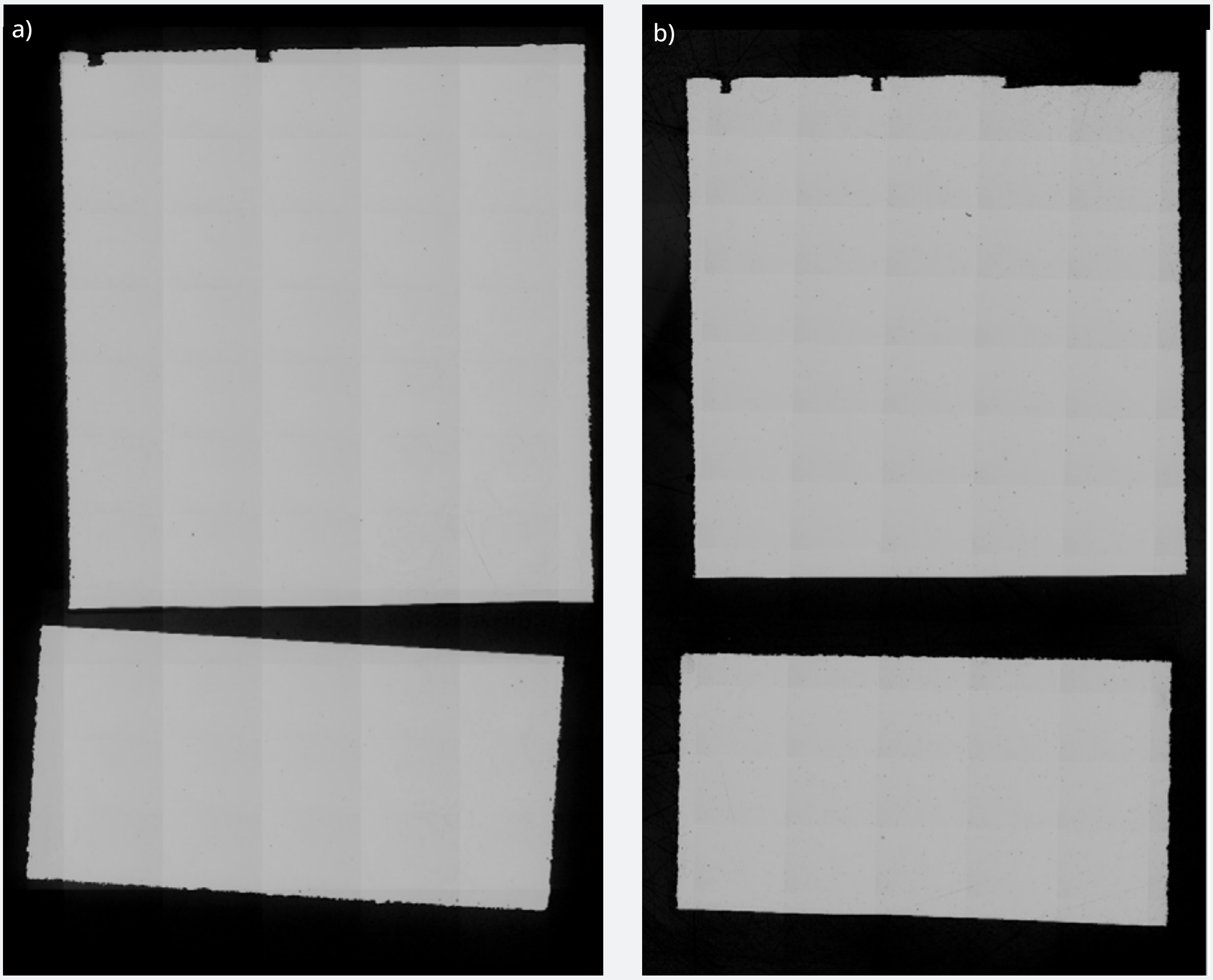


Figure 10. Cubes built with Smart Fusion using Ti64 60 µm Speed at a) location 5 in EOS M 290 and b) location 7 in EOS M 400-4. The top half of both micrographs is the XZ cut, and the bottom half is the XY cut.

In this whitepaper we focus on the tensile properties of heat-treated samples. The samples were tested following ISO 6892-1 (Annex D), ASTM F2024 and F3001 (4D). The heat treatment used was EOS' own recommendaton of 2 hours in 800 °C. As the tensile testing results from both machines were great, it seems like Smart Fusion works with both Ti64 60 µm processes stably. On EOS M 290, the samples built with Smart Fusion reached essentially identical yield strength and percent elongation values with EOS M 290 data it was compared with. The percent elongation after heat treatment was robustly over 13 % everywhere, which is comfortably over the 10 % target set in standard ASTM F1472. The yield strength easily met the minimum acceptance criteria of 860 MPa, passing it with ease and reaching a mean over 980 MPa. Moreover, the orientation dependency was just about 2 percentage points in elongation, and less than 20 MPa in yield strength.

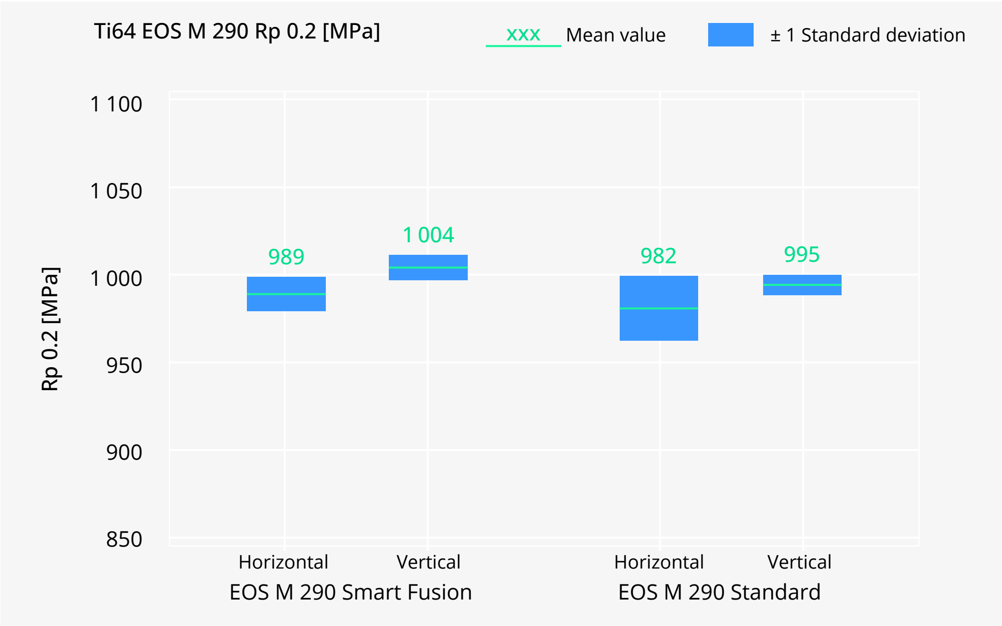


Figure 11a. The yield strength of samples built with EOS M 290 variants with and without Smart Fusion. Heat treated.

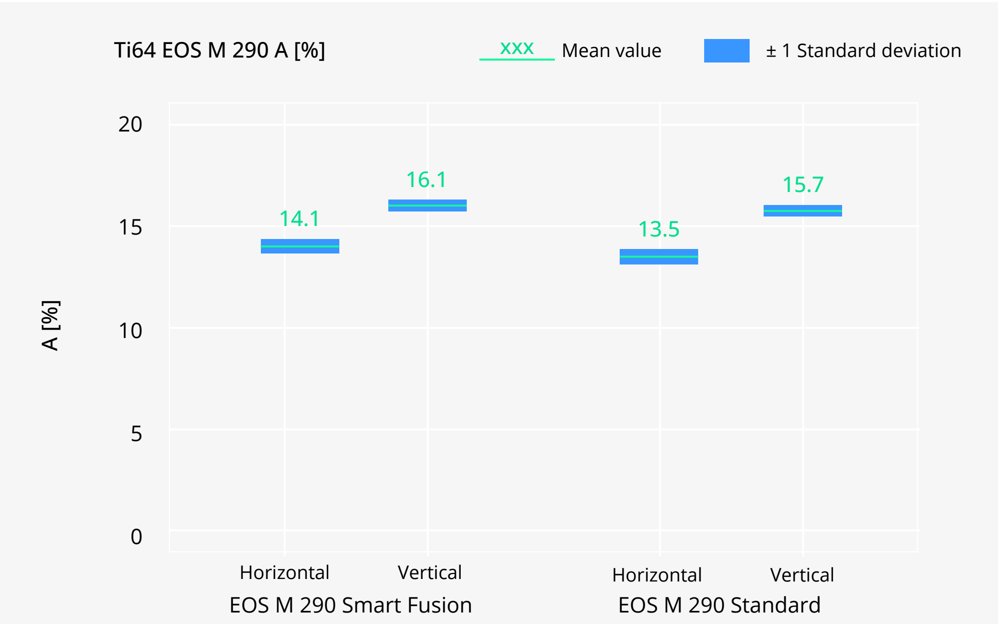


Figure 11b. The percent elongation of samples built with EOS M 290 variants with and without Smart Fusion. Heat treated.

On EOS M 400-4 the yield strength shows some difference between Smart Fusion results and comparison data. The yield strength of the samples built with Smart Fusion was slightly higher with quite similar scatter. The percent elongation also matched the comparison data, with overall very stable results and similar outliers in vertical tensile samples. The outliers were systematically the samples located in the middle section of the very front and rear borders of the building platform, where the flow of the inert gas is the weakest. Smart Fusion doesn't seem to affect that behavior. The other areas of the building platform, however, show great stability.

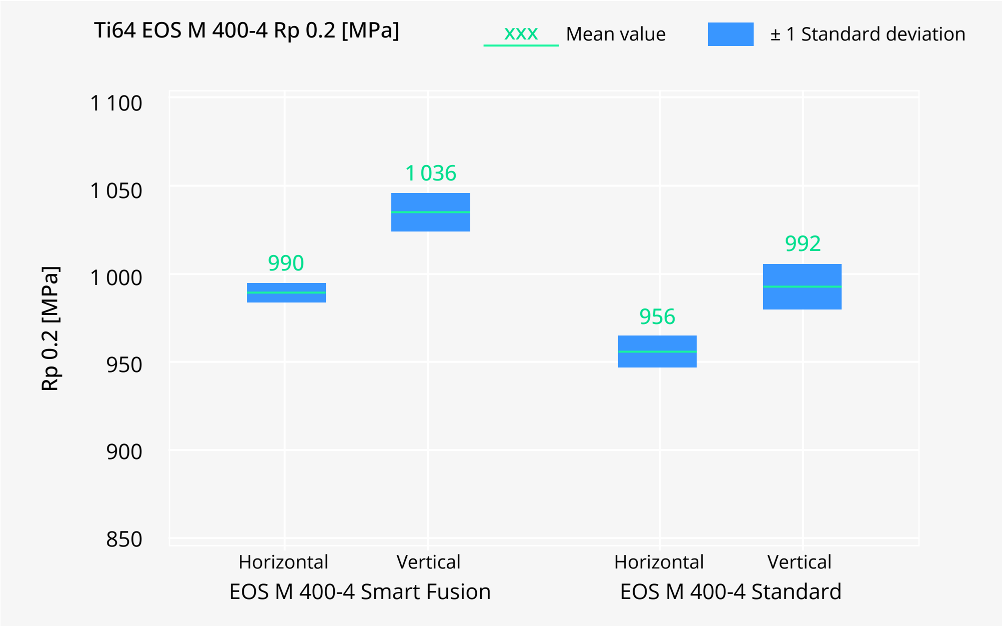


Figure 12a. The yield strength of samples built with EOS M 400-4 variants with and without Smart Fusion. Heat treated.

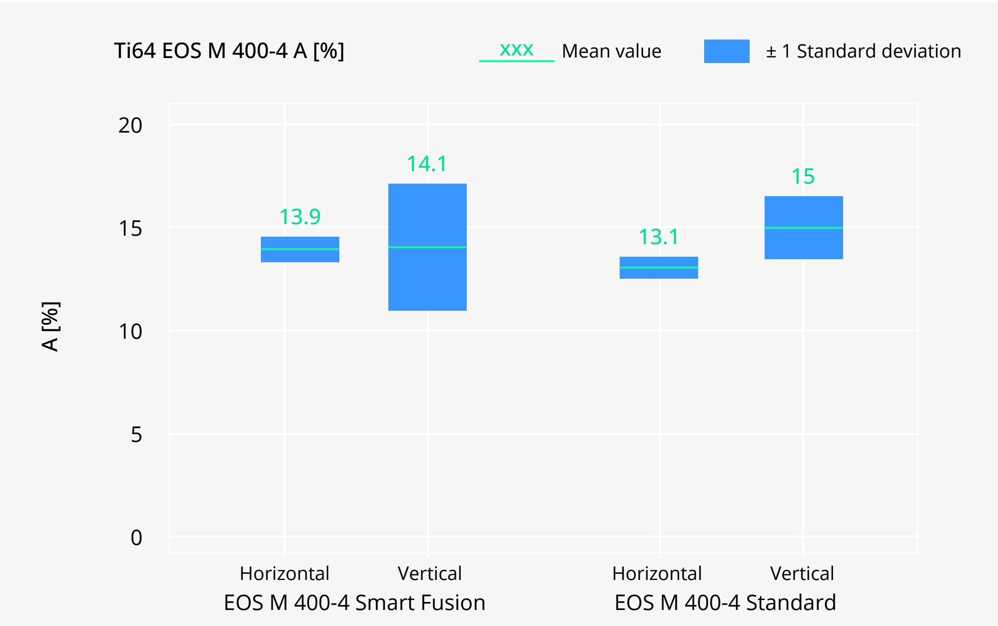


Figure 12b. The percent elongation of samples built with EOS M 400-4 variants with and without Smart Fusion. Heat treated.

Looking at these mechanical porosity and tensile testing results it can be concluded that Smart Fusion does not decrease the properties of EOS Titanium Ti64 when test samples were manufactured using the verification layouts with high load. Both machines provided similar results with dense microstructure with and without Smart Fusion.

6. Automotive Bracket

General Information of the Part and Challenges

The part to be built with Smart Fusion technology is an automotive bracket, that consists of housing for assembly (tube and circular section) and load bearing section with complex topology optimized design. Topology optimization uses mathematical algorithms to determine the optimal shape and structure of a part based on a set of design constraints to reduce material consumption, minimize weight, and optimize the overall performance of a component. Functional integration is achieved by reducing the overall number of parts required to assemble a particular system. The value add of AM for this case is the flexibility to manufacture different geometries in one single part.

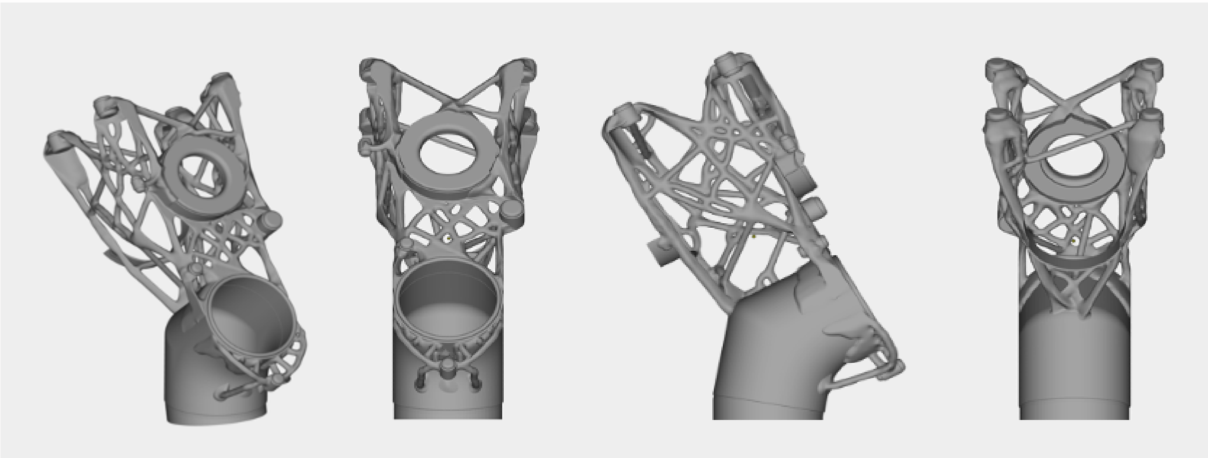


Figure 13. The topology-optimized functionally integrated bracket

The part was built on EOS M 290 from EOS Titanium Ti64 material with the Ti64_Speed parameters that has a layer thickness of 60 µm. Carbon fiber brush recoater was used. Conventionally areas with angles <35° are supported in metal AM.

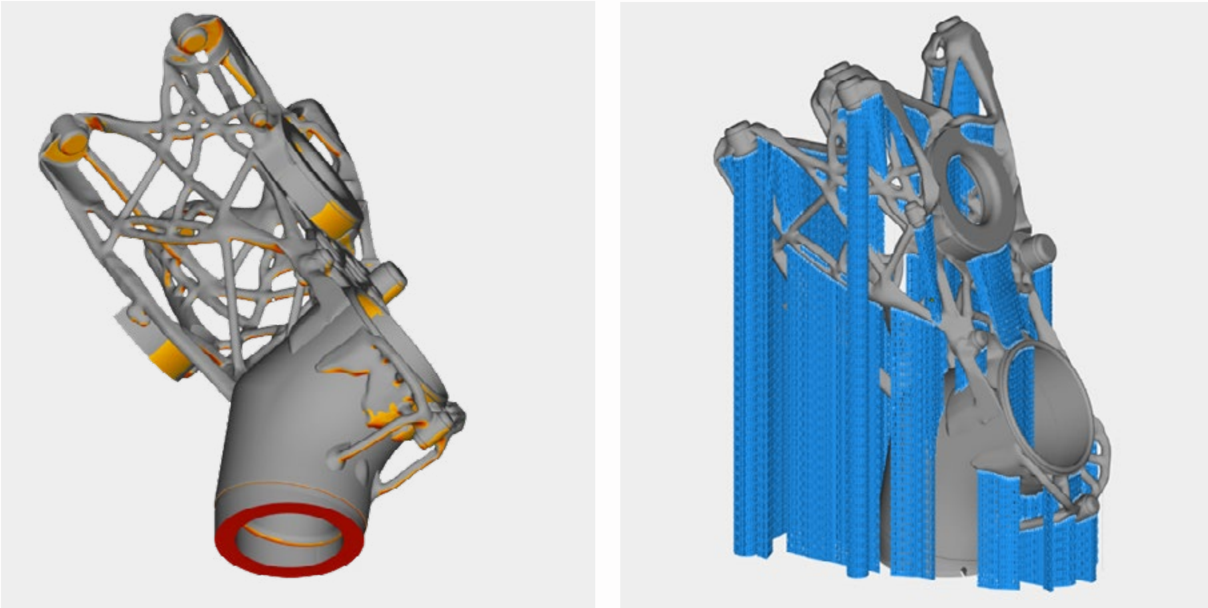


Figure 14. The overhanging surfaces of the part with angle <35°and the resulting support structures

With smart fusion the supported areas can be reduced to angles of 10 to 15 degrees. Some areas still require supports, for examples areas which would start to build in the powder bed or very low angles. Additionally, supports are still required to prevent distortions and to connect the part to the platform. In this case we extruded the bottom section of the part to ensure strong connection to the part.

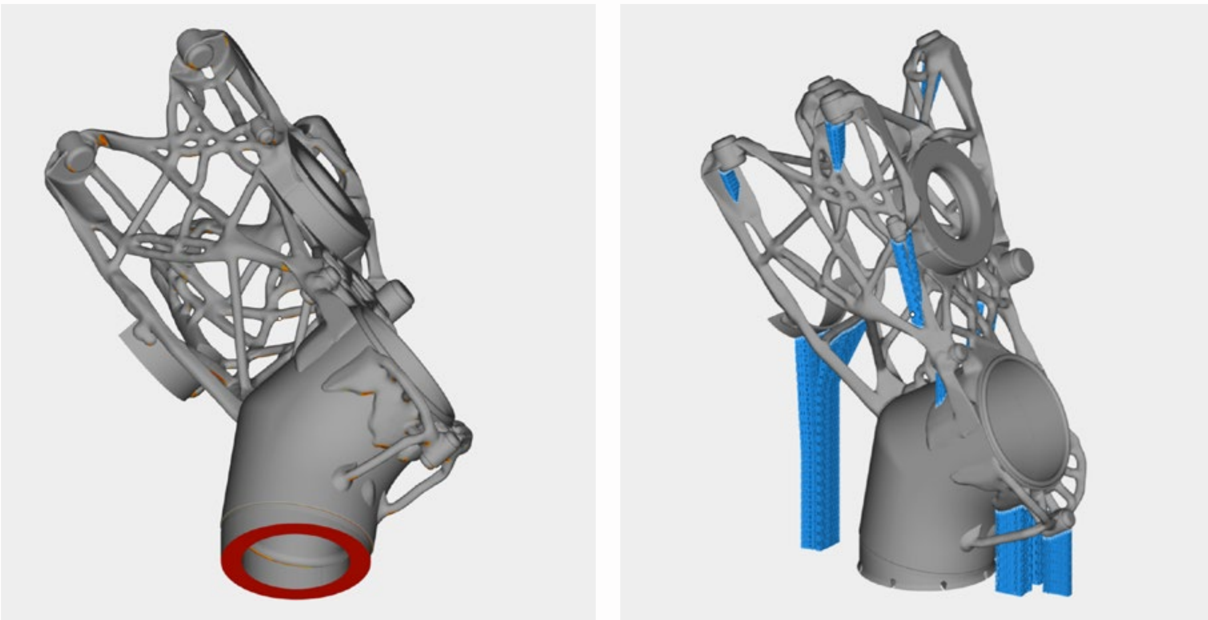


Figure 15. The reduced support-structures that can be built with Smart Fusion technology.

The Smart Fusion technology eliminates nearly all the limitations regarding the build angle, the only areas still need to be supported in this part are so called “island starts”, where the first angles are solely on the powder bed without any connection to the rest of the part.

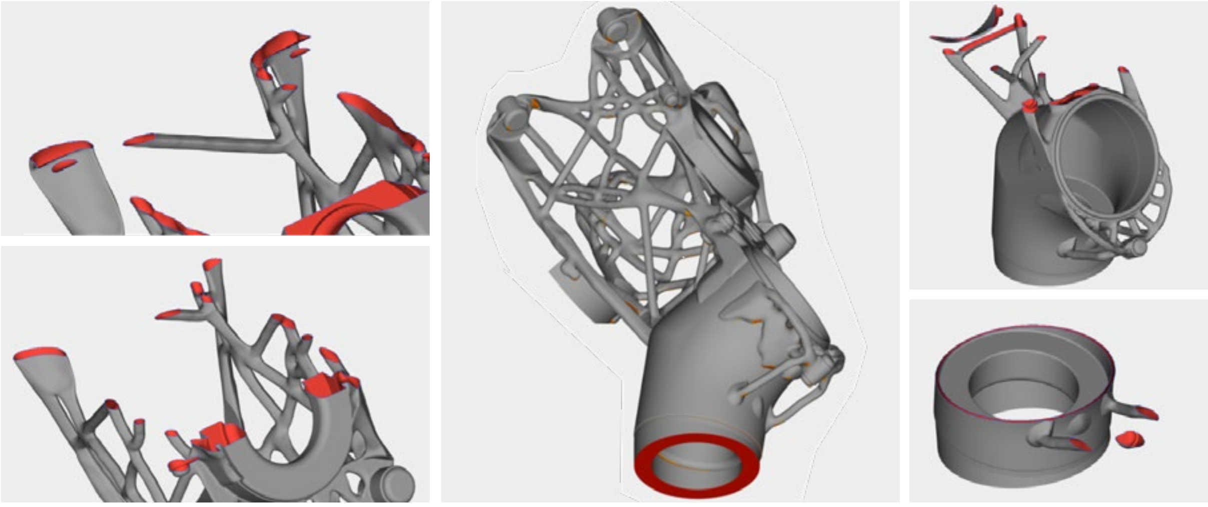


Figure 16. The details from the supported island start areas.

The resulting support structure designs are given below. The part has a height of 215 mm including the base extrusion and has a volume of 138 458 mm³ with a total support volume of 75 021 mm³ whereas the support volume is decreased to 8 722 mm³ with Smart Fusion, in other words reduced by 80 %. This design yields a build time of 20:37 h, which corresponds to 21 % reduction when compared to 26:05 h with the conventional support case. The reduction of CPP lies around 16 %.

Scenario	Building Time (Parts/Job [hh:mm]	Cost per Part [€]
Conventional Support	26:05	1039
Smart Fusion	20:37	868

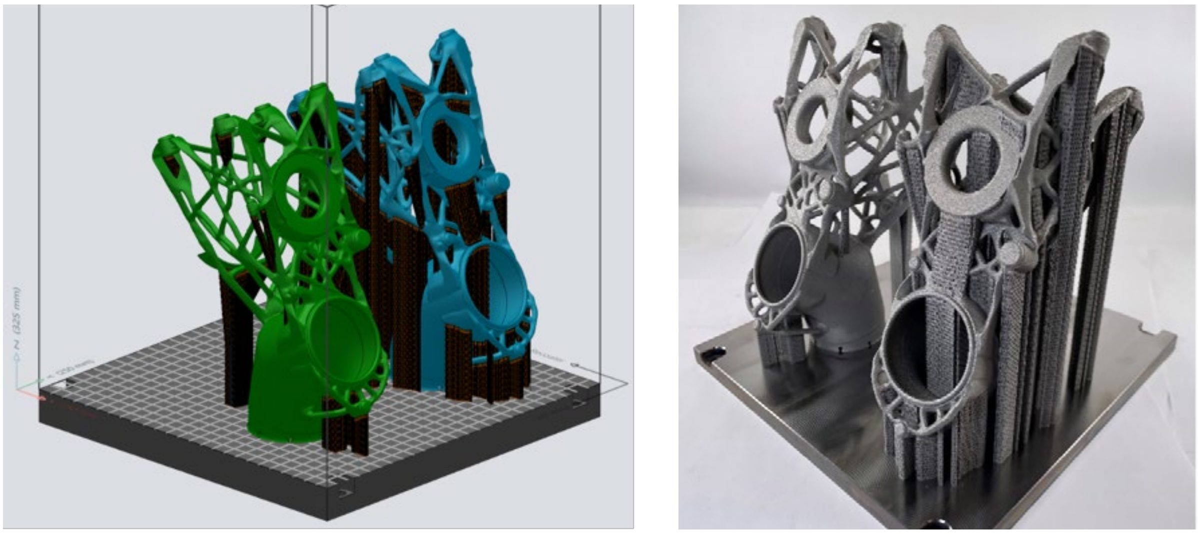


Figure 17. The EOSPRINT job view of the parts with Smart Fusion (green) and conventional design (Blue)

The Smart Fusion software analyzed each layer image recorded by the EOSTATE Exposure OT Camera and detected overheating areas based on the target gray value, which is the nominal signal value of the process.

7. Launcher Fuel Tank

General Information of the Part and Challenges

The second example for process improvements achieved by EOS' Smart Fusion technology is Launcher's Fuel Tank produced on an EOS M 300-4 system in Ti6Al4V alloy. The fuel tank is a crucial component of a spacecraft's propulsion system and stores the fuel that propels the spacecraft into space. Eight of these tanks are used to provide an orbiter satellite transfer vehicle and platform fuel for its journey to space. Figure 18 shows a model of the tank in EOSPRINT and the as-build part attached to an EOS M 300-4 build plate.

Figure 18. Launcher fuel tank: AM model, as-printed part and finished part with sectioned cap

The part presents two major challenges: a 10°-0° overhang in the cap of the tank and the goal to produce the part with as little support as possible. Both challenges must be addressed while meeting all functional requirements. With a diameter of 290 mm and a height of 400 mm the tank utilized the entire build envelope of a EOS M 300-4. The wall thickness of under 3 mm presents a challenge regarding deformation and geometrical accuracy. Figure 19 shows the sectioned tank from the inside – the unsupported overhang is highlighted in yellow (10-degree) and red (0-degrees).

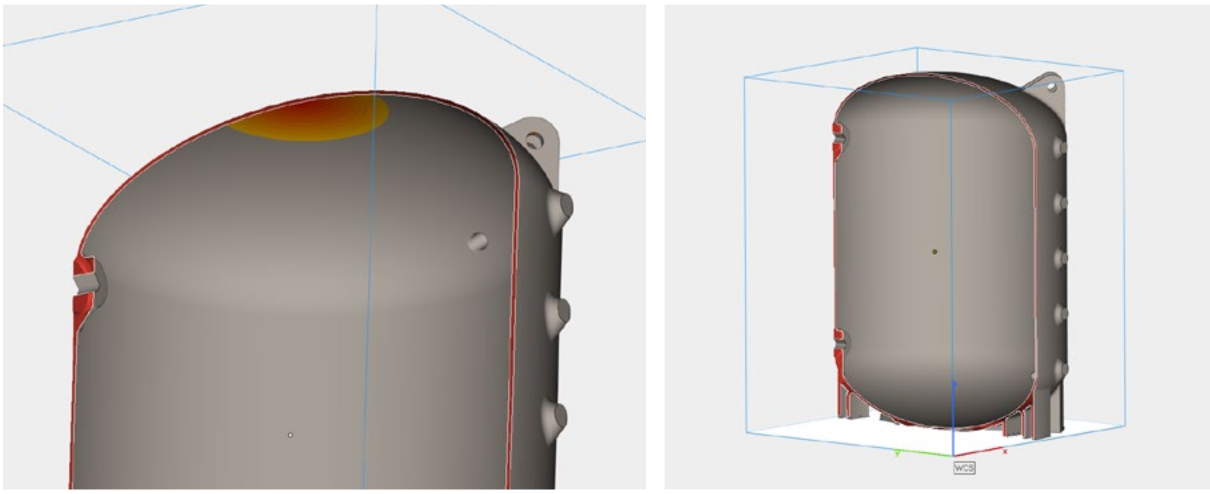


Figure 19. Cross section view of Launcher tank - looking at the inside of the cap. Yellow indicates the 10-degree overhang and red the 0-degree closing section of the tank

The Build Process

The improved heat management of the Smart Fusion process allows the production of the tank without artificial delay times and makes the unsupported 10°- 0° overhang buildable whereas a standard process would've only allowed 30 to 40-degree overhangs with additional processing delays during exposure. The tank was supported only to anchor it down to the base plate.

Test results are showing even surface finish that does not have open surface pores and stable geometry as shown in Figure 20.

Figure 20. Inner wall surface and cross section of tank

8. KSB Impeller

Introduction

Impellers are critical component of various mechanical systems used in the energy sector. These systems range from power generation turbines to pumps and compressors used in oil and gas production. The impellers play an important role in the efficient functioning of these systems. Efficient impeller design and operation can have a significant impact on the environment. By optimizing energy consumption efficient impellers can help to reduce greenhouse gas emissions and improve air quality. Additionally, efficient impellers can help to conserve natural resources, reducing the need for additional fuel and energy production.

There are several challenges associated with the manufacturing of impellers using L-PBF AM technologies.

→ Manufacturability of complex designs

→ Surface finish

→ Cost per part including post-processing

Part Design

The part was built with special solid support to ensure the stability against deformation and part weight of 28 kg with an angle of 62.5°. Only small areas with angles lower than 5 degrees were supported with minimal support lines. The 80 µm IN625 process was used with Smart Fusion. The build took 70 hours with hard recoating, which is the most challenging recoater type against any kind of deformation.

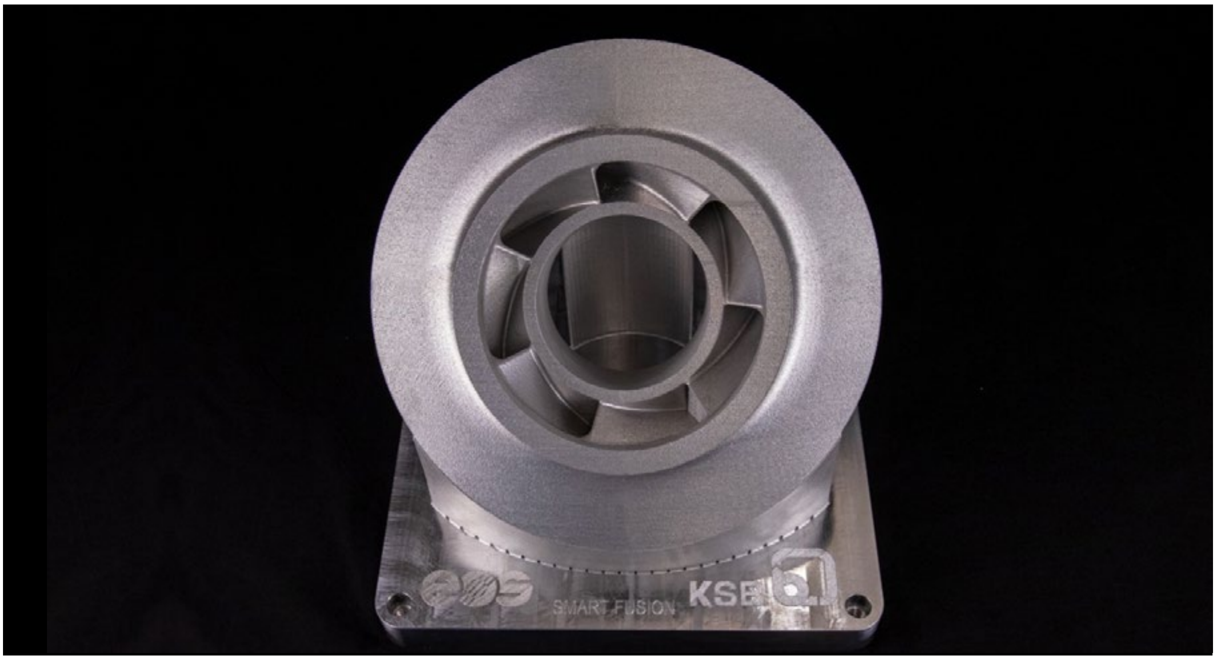


Figure 21. The impeller which was built on M 400-4 (Designed by: KSB) The diameter of this vast part is ~ 390 mm.

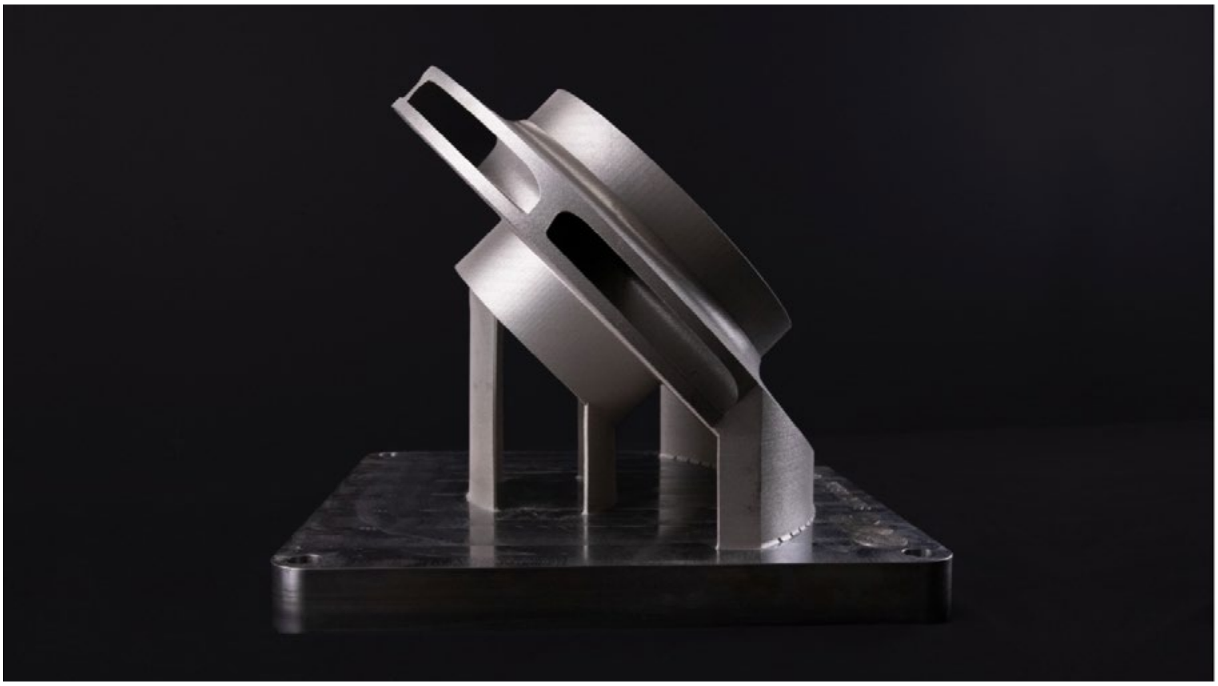


Figure 22. Part orientation and support design. (Courtesy: KSB)

The porosity levels were evaluated by crosscuts from the part on different locations to reveal the situations such as upskin, downskin and core areas. All the samples show regular porosity levels which are in line with standard EOS 80 µm process.

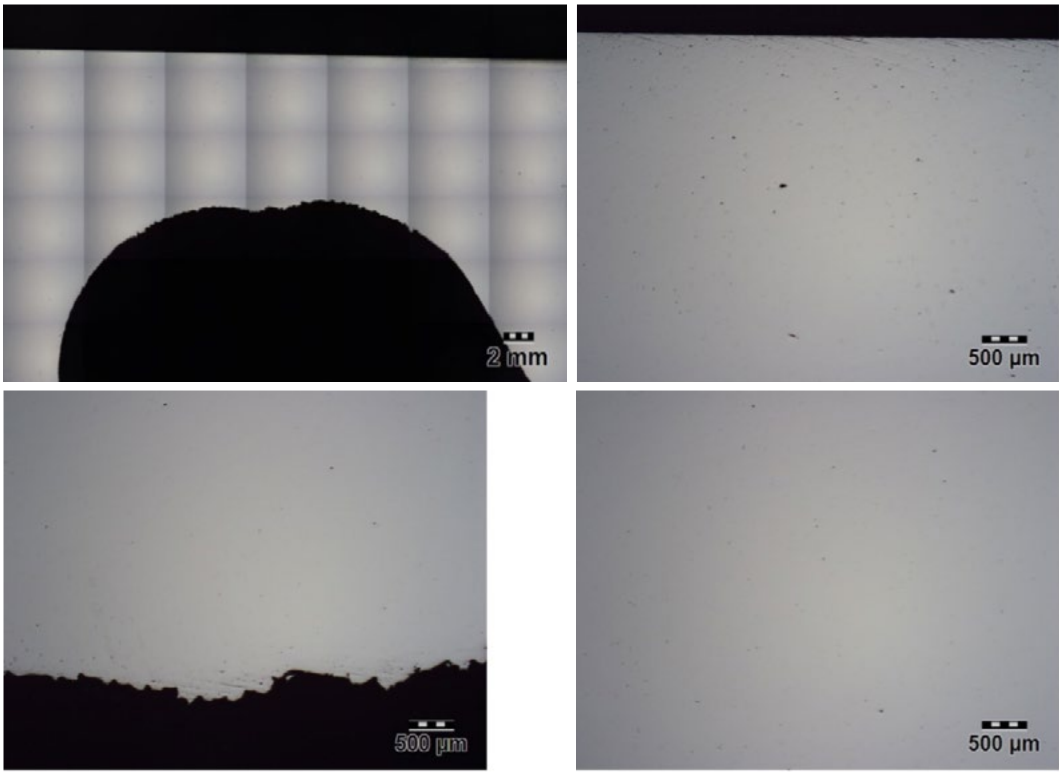


Figure 23. The cross sections from different locations of the part (unetched) a) Overview, b) Upskin, c) Downskin d) Core (Courtesy: KSB)

9. Summary and Conclusion

Smart Fusion is a new solution for additive manufacturing that addresses the challenges faced by engineers and the industry. It empowers engineers to build the impossible, reduces waste, and improves the quality of finished products. This new technology will be developed further in the future, providing even greater benefits to the industry, and enabling engineers to create even more innovative and complex designs.

→ **Build the Impossible**

Smart Fusion empowers engineers to design and create parts with radical geometric designs, like extreme overhangs, extremely thin walls or dome structures. This opens up an entire new range of applications.

→ **No Negative Effect on Build Time**

Unlike other solutions, Smart Fusion does not influence the build time. Smart Fusion does not work with wait or cooldown times.

→ **Increased Machine Utilization**

Smart Fusion reduces the need for support structures, which leads to increased machine utilization. This results in more efficient use of resources and lower production costs.

→ **Reduced Waste**

By reducing the need for support structures, Smart Fusion also reduces the amount of waste produced during the manufacturing process. This is both environmentally friendly and cost-effective.

→ **Flexibility in Design**

With Smart Fusion, engineers have greater flexibility in their designs. This means that more applications can be considered for manufacture with a positive business case, and more legacy applications can be made viable without needing to change their design.

→ **Shorter Time-to-Market**

Smart Fusion includes automation features that help engineers find the right parameters faster. This shortens the time-to-market for new products, which is essential for businesses that need to remain competitive.

→ **Reduced Cost-Per-Part**

(CPP) makes AM more attractive for supply chain integration. This leads to greater adoption of the technology and more widespread use in the manufacturing industry.

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Aydın's passion is exploring the mechanisms of laser - material interaction, inspired during his study in Metallurgical & Materials Engineering at METU, Ankara. After an early career of 6 years specializing in conventional manufacturing processes and materials, he completed his thesis on advanced materials characterization at MPI for Intelligent Systems in 2016 and received a M.Sc. degree in Materials Science from the University of Stuttgart. In the Additive Minds team, he focuses on materials behavior before, during and after the DMLS process to develop customer-specific approaches for industrial AM.

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Ilkka Pääkkönen
R&D Engineer

Ilkka Pääkkönen (M.Sc. in Technology) graduated from Tampere University with a major in Materials Technology. He joined EOS Finland Oy in early 2019, when he started his master's thesis focusing on heat treatment of additively manufactured aluminum alloys. In recent years he has worked mostly in development of new nickel and titanium processes for additive manufacturing. He also has strong expertise in process parameters in EOSPRINT.

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Anja Miles
Sr. Project Engineer - Quality

Anja Miles first gained experience with Additive Manufacturing and in-situ process monitoring for aerospace applications at MTU Aero Engines. She joined EOS GmbH's pre-development team in 2015. Later, she relocated to EOS Finland, where she focused on utilizing in-situ monitoring to advance process and material development while pursuing her master's degree in mechanical engineering.

In 2017, Anja transitioned to EOS North America, taking on the position of a Senior Project Engineer. In this role, she actively engages with different companies, offering her expertise to support the qualification of additive manufacturing applications. Anja also supports companies with the implementation of state-of-the-art in-situ process monitoring and control technologies.

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Many Thanks for your contribution to the EOS colleagues:
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