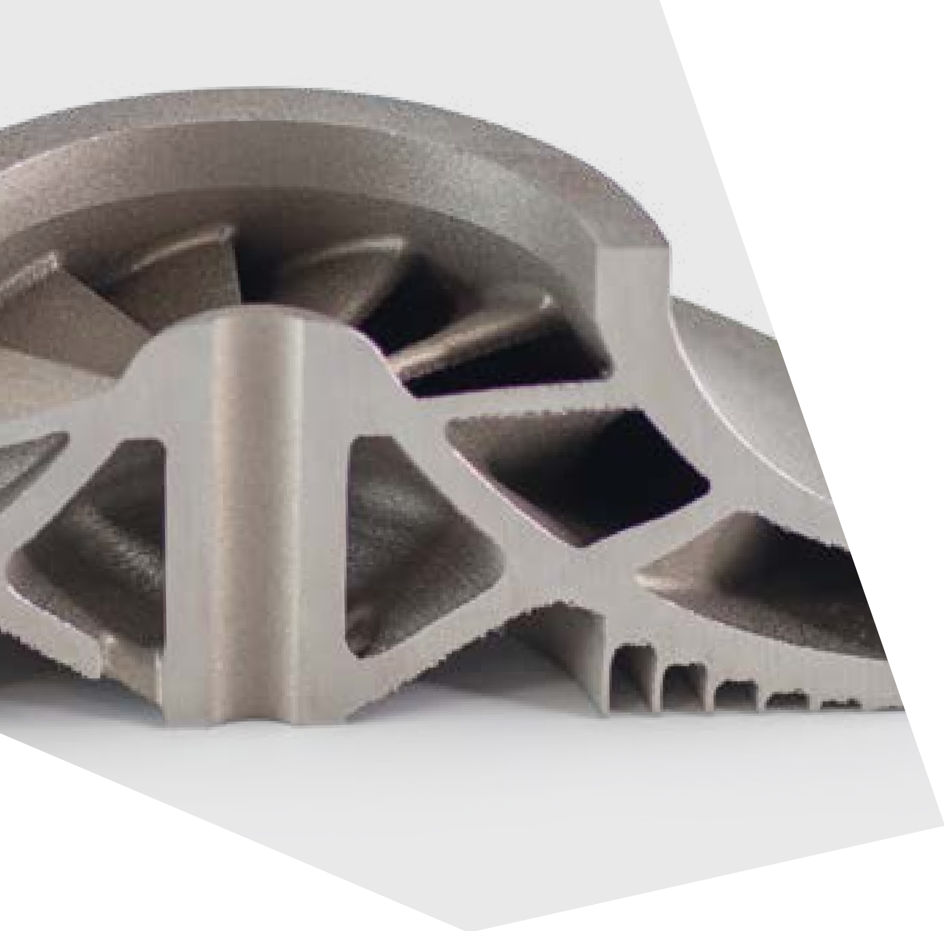

Whitepaper

This Whitepaper gives answers to:

- How to orient impellers for printing
- How to avoid supports when printing impellers
- What is the impact on the business case

Support-Free Printing of Closed Impellers

By
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Support-Free, Supportless or Supported?

Probably the most common paradigm of Metal AM is that you cannot print below a certain overhang angle without supports, which often limits users of metal AM systems in their choice of applications. This critical angle, typically around 45°, is now being greatly challenged by many equipment OEMs and AM software companies. Software and parameter packages have now become available that enable users to print overhangs and bridges at much lower angles (sometimes even with no angle at all), requiring far fewer, if any, supports. It is also clear that there are certain physical limitations that even the most high-performance machines and intelligent exposure strategies cannot overcome – constraints like part deformation resulting from the kind of residual stresses that typically occur in LPBF processes. Supports are often needed to hold the parts in place and keep them within the geometrical tolerances.

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Introduction

There are a wide variety of applications that could potentially manage with fewer supports. In recent years, supportless building has enabled the development of applications that were hitherto simply not feasible in additive manufacturing. A few examples are stator rings, housings, turbo pumps, fuel tanks, heat exchangers, valves and impellers, the latter being one of the more prominent ones.

Closed or shrouded impellers are found in many industries, and they vary greatly in size, shape, material and performance requirements. Closed impellers are frequently exposed to a wide range of extreme conditions, such as mechanical loads resulting from high rotational speeds, highly corrosive media, and extreme temperatures. Examples are turbopump applications in space rockets, compression systems in micro gas turbines, and seawater pumps in oil and gas applications.

Figure 1: AM - Titanium impeller [Source: KSB]

The challenges that all impeller manufacturers face are:

Design:

An impeller design is very specific to the application, which necessitates a high degree of customization for it to match the use case. Manufacturers and OEMs need to be able to supply several variants of the basic product in order to meet the expectations of end users.

Small lot sizes:

Lot sizes of 1-10 variants are very common, particularly with spare parts. This is reflected in the general high prices of the final products.

Lead time:

Spare parts need to be provided at short notice, which means that it is necessary either to hold a large stock of many parts over a period of years or to speed up the manufacturing and supply chain processes of those components.

AM can provide a solution to all those challenges, as it presents few constraints in design freedom, small lot sizes are far less costly, and users can react very quickly to customer demands.

Nevertheless, the printing of impellers presents challenges of its own, due to the nature of the process. There are several questions that need to be answered:

- → What material can I use? Is there an alternative in case the regular one is not available in AM?
- → What is the best way to orient a part in a 3D printer?
- → What about supports? How many do I actually need?
- → Is it necessary to adapt the AM process in certain areas to avoid a build crash?

  If so: how do I do that?
- → What type of post-processing is necessary and what techniques provide the best results at the lowest cost?
- → Does my business case still make sense? What is the cost per part and how can it be reduced?

In this whitepaper, our aim is to provide an insight into the findings we have made in recent years in the course of various customer projects, in order to provide answers to the above questions.

Material Selection

As in all other AM applications, the material selection for impellers depends on the requirements of the application. Stainless steels are the most frequently used materials in impellers, followed by nickel-based alloys, titanium alloys and aluminum alloys.

Some typical requirements for impellers are:

→ High corrosion resistance
→ High strength to weight ratio
→ Elevated operating temperature
→ Low surface roughness

Information about EOS materials, their properties and some typical applications can be found at **www.eos.info**. EOS is unique in that it is able to supply custom materials (e.g. bronze) and processes according to customer specification.

EOS Aluminium AlSi10Mg	Used for impellers that do not require elevated temperature stability, enhanced abrasion resistance or the most stringent mechanical properties. It is often used in gas compression applications in aerospace, due to its lightweight characteristics.
EOS Aluminium Al2139 AM	Typically used to compress gases at a high RPM under moderate temperatures. It offers a better strength to weight ratio than AlSi10Mg and can in certain cases be used as a substitute for Ti64.
EOS NickelAlloy IN718	Used for turbopumps in rocket engines and micro gas turbine compression systems due to its corrosion resistance and high temperature resistance.
EOS StainlessSteel 316L	The standard material used when pumping liquids in any industrial environments other than aerospace.
EOS StainlessSteel 17-4PH	Used in similar industrial pumping applications to 316L. It exhibits higher strength but lower corrosion resistance than 316L.
EOS StainlessSteel 254	Typically found in seawater pumps, pulp and paper equipment, and in the chemical industry.
EOS StainlessSteel SuperDuplex	In widespread use for impellers employed to pump fluids in oil & gas applications as well as in the chemical and petrochemical industries. They are also frequently used in the paper industry and for slurry treatment.
Titanium Ti64 Grade 5	Typically used to satisfy high RPM requirements, thanks to their high strength to weight ratio and good fatigue resistance, such as for pumping fluids and compressing gases in the aerospace industry.

Support-Free Additive Manufacturing

Laser powder bed fusion (LPBF) traditionally requires support structures to avoid part deformation resulting from thermal stresses and to conduct the heat away from the melt pool. These supports are part of the design and manufactured as a unit. After building, the support structures are removed and disposed of. However, at EOS, we have developed a variety of process optimization techniques for producing 3D printed parts without the need for support structures.

Additive manufacturing without the need to remove supports saves a large amount of time in the post-processing stage, freeing up employees to apply their time and energy elsewhere. Removing the need for support structures also reduces waste, since only a minimal amount of material needs to be removed and every aspect of the part design is necessary (e.g. platform connection and machining offsets). However, it isn't a straightforward process, and for years our experts have been working to solve the challenge of support-free designs. This white paper shows how support-free methodology was applied to print an impeller.

Figure 2: Cross section of a support-free impeller

Design Considerations

Several impeller designs are in use; these vary in size and complexity depending on the application. In general, all impellers can be manufactured additively, but the design will determine the nature of the support structure needed. The most important design constraints are the diameter of the impeller, the number of blades and the angle of the shroud.

Whereas the diameter is mainly relevant to the volume and therefore to the stresses resulting when building, the number of blades and the angle of the shroud determine the low overhang areas and distances to be bridged either by supports or using optimized building strategies.

Figure 3: Bottom view of the impeller shroud (cross section and close up)

The impeller used to demonstrate support-free building and the capabilities of the DMLS process has a diameter of 150 mm with twelve blades and was designed by EOS.

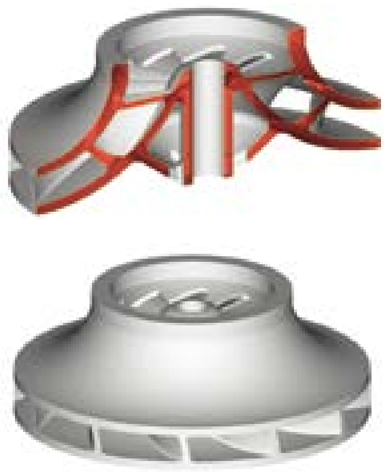


Figure 4: Cross section and side view of the designed impeller

Orientation

Impellers are often printed at an angled orientation to avoid the need for internal supports, as these are very difficult to remove. However, this typically results in longer building times and inhomogeneous surface quality; moreover, the roundness of the part might suffer. A flat orientation offers several advantages, such as a shorter building time, better roundness and accuracy, and a more homogenous surface quality throughout the part. However, the low overhangs would typically require many supports. With current DMLS processes, larger overhangs (> 3 mm) with angles of less than 35° require supporting. Supports are used to dissipate the heat from the melt pool, prop up part overhangs, and compensate for recoating forces and internal part stresses.

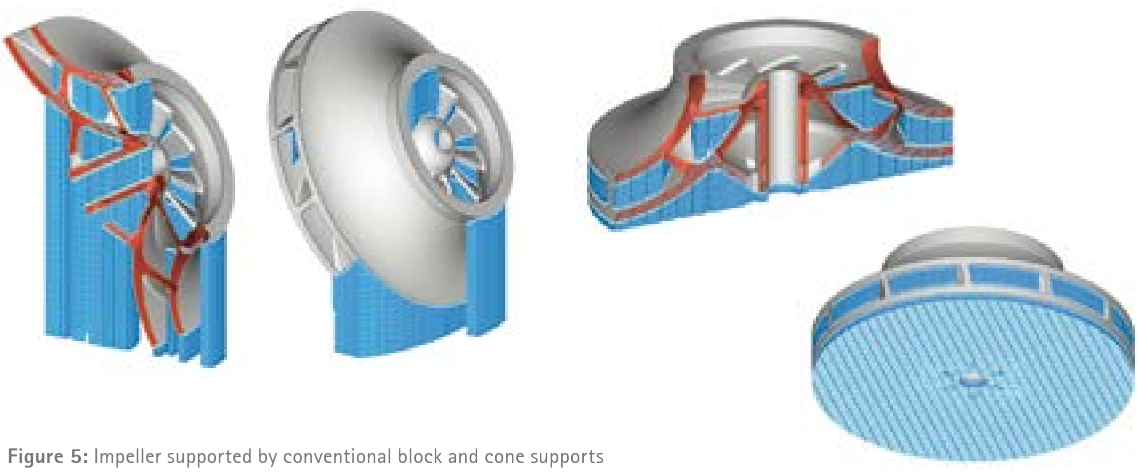


Figure 5: Impeller supported by conventional block and cone supports

After the building process, the supports are removed, which can be quite challenging, as they are often not suitable for machining or are simply not accessible to machine or hand tools. Chemical processes can be applied to dissolve them or thermal techniques to vaporize them (EOS & ExtrudeHone), but even after these additional steps, the resulting surface quality might still be insufficient.

Support-Free Design Optimization

The need for internal supports can be reduced significantly using advanced techniques. It is therefore important to optimize the design for AM. Although internal supports can generally be avoided by adjusting the exposure strategy, external support structures are still required.

Rather than using a solid extrusion, the bottom of the part can be modified with self-supporting arches and thin walls to ensure a strong platform connection and prevent deformation during the build. This reduces the amount of material needed compared with traditional supports while offering high strength and improved machinability.

Figure 6: Impeller with closed outer diameter and optimized platform connection

The outer diameter of the impeller is closed to supply more stiffness to the part during building and to prevent the loss of geometrical accuracy on the edges of the outlets. Moreover, the wall provides a better and more stable connection for the overhang when closing.

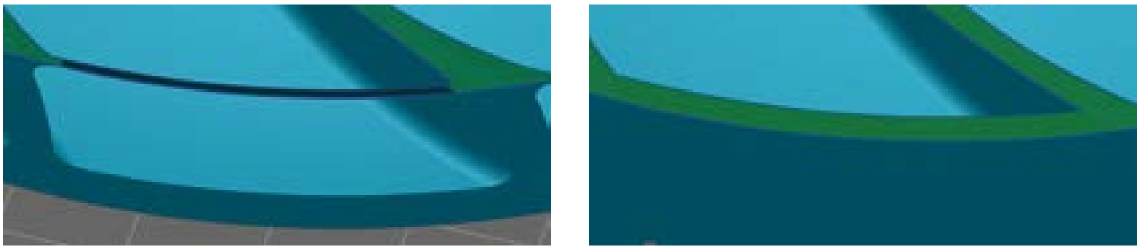


Figure 7: Exposure vectors of unsupported open (left) and closed (right) impeller

Figure 8: Bridging supports between blades

As found in a number of DOEs, distances of 35-60 mm can be bridged with optimized processes, depending on the geometry and material. For distances greater than 60 mm, small support walls or bridging supports can be used to extend or bridge the support-free area.

The advanced design of this impeller results in 15 % less material, optimized machining, self-supporting structures and no internal supports.

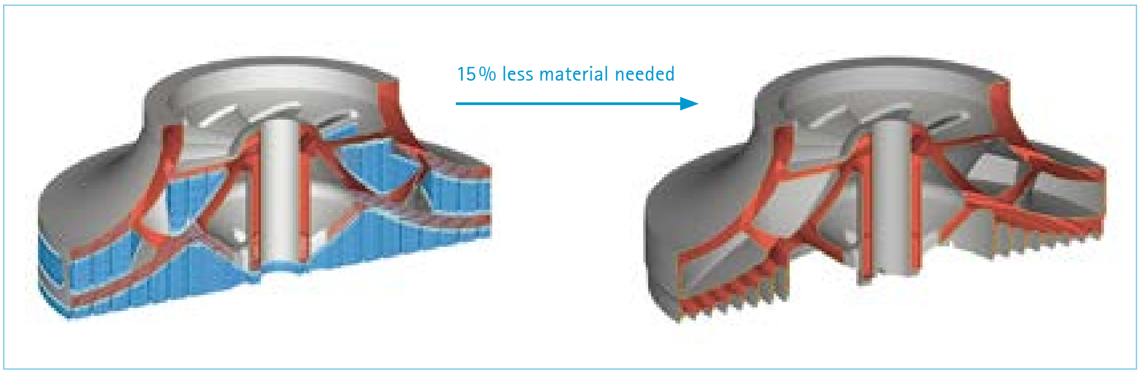


Figure 9: Impeller with traditional support structure vs. support-free impeller

Process Optimization

This section describes how the process can be optimized to enable support-free building of an impeller and affords an insight into the strategies used. The hope is that the reader will be encouraged to begin developing his or her own support-free application. We begin by highlighting the optimized process parameters and explain the benefits of these changes to building support-free impellers. The reader can also obtain an impression of the results from the EOSTATE PowderBed and surface quality images (as built) and from the discussion of productivity and mechanical properties.

Unlike other support-free techniques, the high energy downskin method does not sacrifice the build rate or, in turn, the business case, to avoid the use of supports.

The impeller was built using the so-called high energy downskin method. In essence, this method increases the energy density input of the downskin exposure by increasing the laser power while simultaneously adjusting other downskin parameters. This results in a bigger but more stable melt pool, especially with building overhangs on top of loose powder. The method has been used successfully with many materials that are frequently employed to build impellers (e.g. Ti64, 316L, AlSi10Mg, IN718, ...).

In order to increase the energy input, the optimized process has an increased laser power (370 W) and a reduced scan speed (800 mm/s). Additionally, the downskin thickness and ridge are adjusted to enlarge the downskin exposure area. It is thus assured that all critical angles can benefit from this optimized parameter. Also note that the scan pattern is changed to NoPattern, TimeOptimized, which results in a more homogeneous and yet faster process. Unlike other support-free techniques, the high energy downskin method does not sacrifice build rate or, in turn, the business case, to avoid using supports.

The process obtained with the high energy downskin method is characterized by large yet stable melt pools in the downskin area. Traditional low energy input downskin exposure focuses on improving dimensional accuracy and surface roughness by reducing the energy input. However, the low energy level is often not sufficient to sustain a stable melt pool when printing overhangs on top of loose powder. The unstable melt pool typically results in uncontrolled roughness and balling as well as discolored overhangs. The discoloration is a result of bad recoating due to the rising edges which are present in overhangs when using standard parameters. The high energy downskin pushes the overhangs deeper into the powder bed and thus ensures good recoating (see EOSTATE PowderBed images below).

Figure 10: EOSTATE PowderBed images highlighting the recoating behavior of the high energy downskin exposure for a 316L impeller

In the absence of any countermeasures, the high energy downskin method results in parts that are oversized in the z-direction in the downskin area due to the deeper melt pools. Parts can be given the right size either by post-processing or modifying the design. The downskin is also relatively rough, but the roughness is homogenous, which facilitates bulk surface treatment techniques like Abrasive Flow Machining (AFM, see section on post processing). There is also hardly any porosity (see Figure 11), and then only in the downskin. Therefore, the bulk mechanical properties are unaffected, meaning that is still possible to rely on the high quality InFill processes developed by EOS. Similarly, no secondary processes like hot isostatic pressing are needed to obtain sufficient mechanical properties.

Figure 11: Crosscut high energy downskin exposure

One challenge that is not resolved by the high energy downskin method is the presence of thermal stress. Stress and deformation must be tackled either through design or pre-deformation or by minimal use of bridging – or other – supports (see section on supports / design).

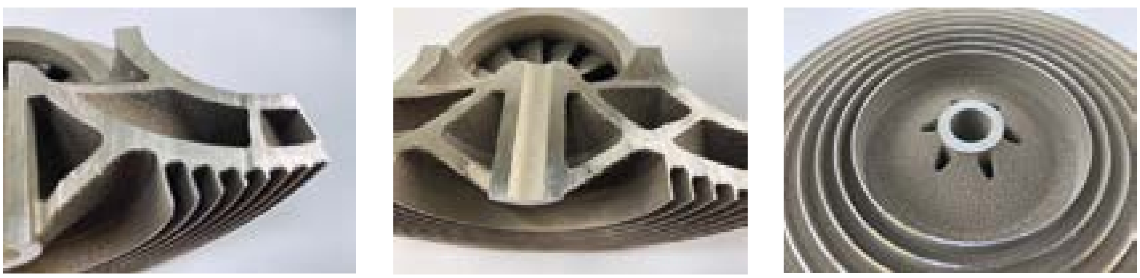


Figure 12: Images highlighting the as-built quality of the high energy downskin approach

Surface Finishing of Impellers

When printing parts with standard exposure strategies and support structures, the resulting surface quality of areas with a building angle of 0-30 degrees typically results in roughness values of Ra = 25-46 µm. This depends on how efficiently the support structure was removed. The remains of the supports in particular can lead to very high protrusions (Rz = 200-500 µm).

Using the high energy downskin method, values of Ra = 32-95 µm were measured for building angles of 0-30 degrees on representative samples. These high values can be explained by the deeper melt pool and higher penetration of the powder bed. Although the roughness is higher in magnitude, even low angles can be built without any supports – which also means that there are no supports that need to be removed.

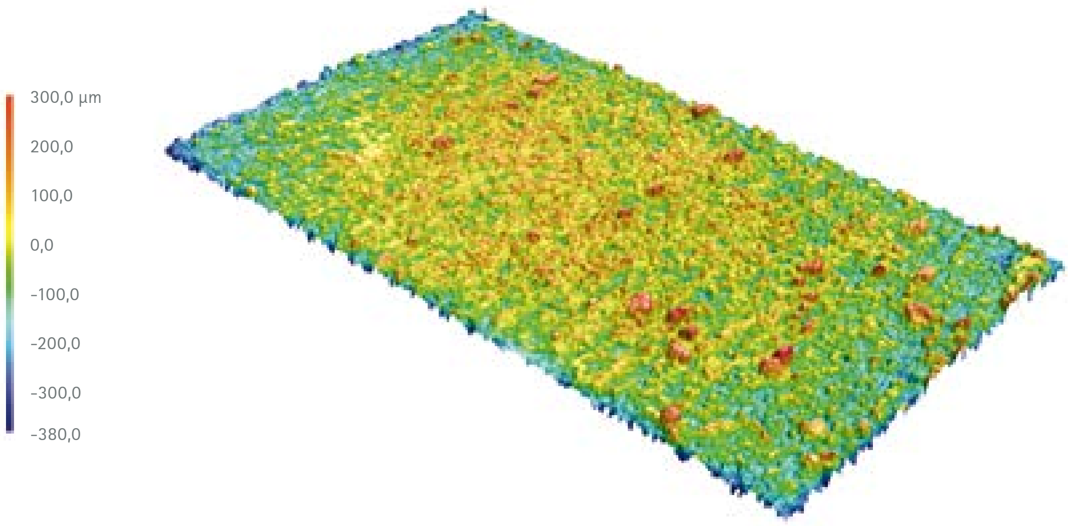


Figure 13: Downskin surface under the microscope and close-up view on downskin surface (15°)

Since the outer surfaces are easy to access, many processes can be applied as a finish, although they are typically machined. Only a few techniques are suitable for finishing internal surfaces.

Abrasive Flow Machining (AFM)

Abrasive Flow Machining is a surface finishing technology commonly used in flow applications and for internal geometries. The processed part is clamped in a fixture and an abrasive medium is pushed through the part bi-directionally by two hydraulic cylinders. The abrasive particles in the media grind and polish the surfaces along the flow path. A very high-quality surface finish can be achieved in areas not otherwise accessible by machine tools.

Figure 14: Abrasive Flow Machining setup (Source: Extrude Hone)

An optimized finishing strategy for this impeller was developed in collaboration with AM Metals GmbH, an EOS Ecosystem partner. AM Metals supplies a broad range of optimized DMLS® processes, including unique post-processing, for impellers and similar applications. A specially adapted fixture for optimized AFM flow was used to create the internal finish (patent application pending).

Figure 15: Manufacturing workflow for closed impellers

To prepare for the internal surface finishing, the closed, outer diameter must be machined open and the diameter and part height adjusted to the fixture used for the AFM process. After pre-machining, the part is clamped and the abrasive medium is pushed through the part with the aid of the fixture. After completing the AFM process, the impeller is machined to its final dimensions.

Figure 16: Top view of impeller after AFM

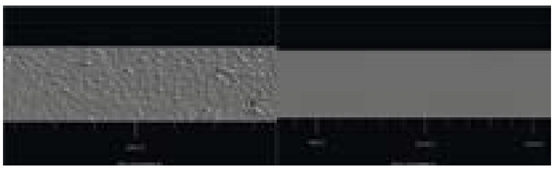
Figure 17: Detailed view of upskin surface after AFM

Figure 18: Detailed view of downskin surface after AFM

Figure 19: Bottom impeller surface after machining

Carrying side

Pressure side



Suction side

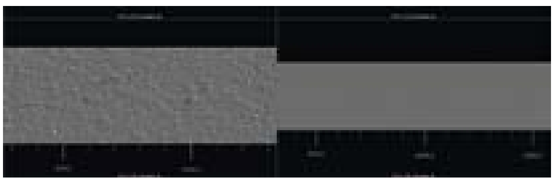


Figure 20: Surfaces before (left) and after (right) the AFM process (Source: AM Metals)

In the AFM process, the internal side and upskin surfaces (suction side, pressure side and carrying side) were polished to Ra = 0.3-0.4 µm, resulting in a tremendous improvement to the finish. Typically, areas with building angles of 60-90 degrees show as-built roughness values of Ra = 5-10 µm.

Deck side (Shroud)

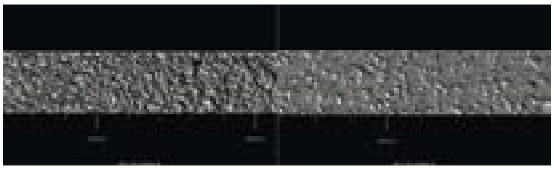


Figure 21: Microscopic view of the downskin surface after AFM (Source: AM Metals)

Beginning with a value of Ra = 87 µm, the final measurement on the downskin areas of the outlets (15 degree overhang) shows a great improvement at Ra = 30 µm but remains rougher than the other surfaces. Even though this might not be a perfect finish, it does show that roughness can be improved quite dramatically, considering the initial roughness.

One possible reason for increased roughness after finishing is the behavior of the viscous medium used in AFM. Regarding the topology of the surface and its roughness, the flow can stagnate at the surface and result in lower relative movement, causing less abrasion. However, the DMLS process is optimized for buildability and repeatability and will be further adapted to achieve better as-built surface quality. Additionally, the AFM process can be further fine-tuned by modifying the abrasive medium in terms of its viscosity, abrasive particles and processing time.

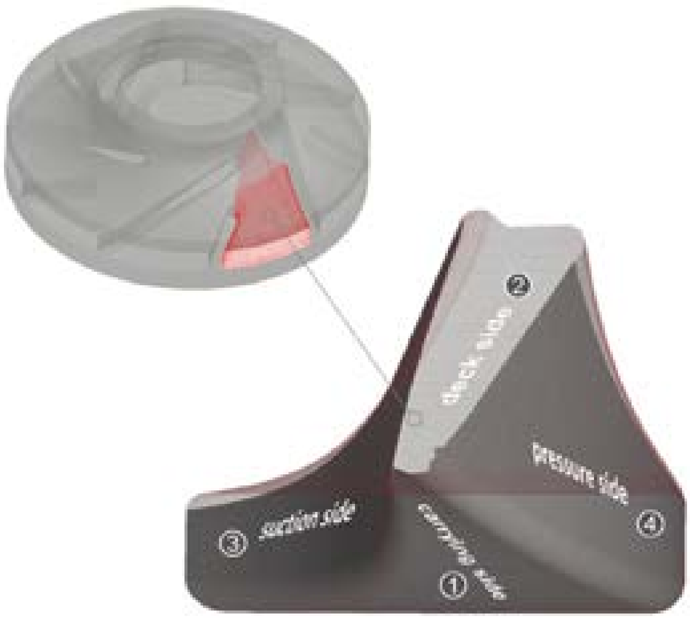


Figure 22: Key to the nomenclature of the various surfaces (Source: AM Metals)

Cost Analysis

Does the business case justify support-free impellers? One of the most important factors of a business case is the cost per part analysis. The following section compares the cost per part for a support-free and supported impeller and discusses whether from an economical point of view there is a business case for support-free impellers.

Highlights:

- From a cost per part (CPP) perspective, a support-free impeller works out up to 35% cheaper than the same impeller with supports
- Cost per part includes data preparation costs, system investment, service, material, consumables and post-processing costs

When comparing the costs of AM versus traditional manufacturing, an important factor that technology users often miss is the added value that comes with AM. Comparing only the direct costs is a pitfall that we have all experienced recently, as it is not comparing like with like. AM has several advantages that impact costs indirectly by reducing lead time or increasing performance, such as those discussed above. A reduction in lead time can have a substantial effect on the cost of overage or underage, as it is possible to print locally on demand. It is therefore essential to analyze costs from both a direct and an indirect perspective.

In the following analysis we will take a deeper look at AM costs, in a comparative case study of supportless and supported impellers. Overall, a support-free impeller is 35% more economical than a supported model. This is due to various factors, ranging from data preparation to (unsurprisingly) post-processing.

Supported vs Support-Free Impeller

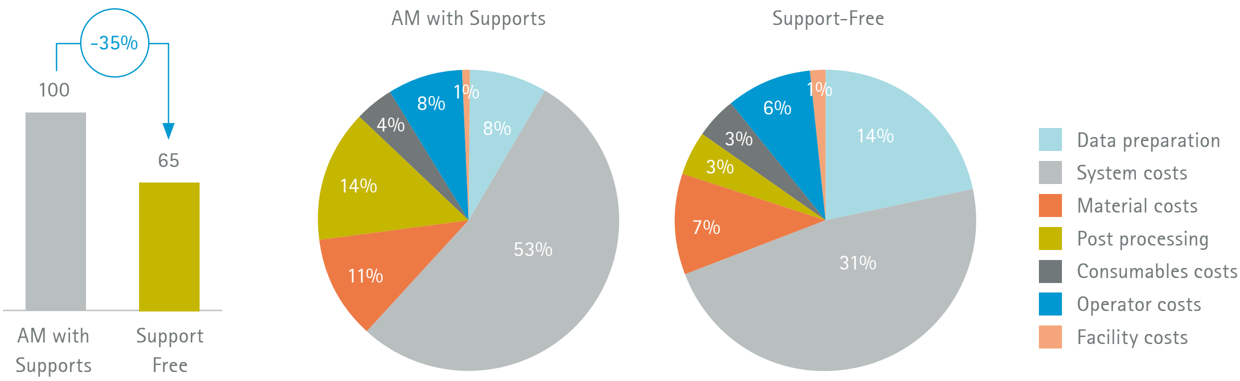


Figure 23: Percentage reference decrease from supported impeller to support-free impeller along with the percentage segregation of each vertical impacting the cost per part.

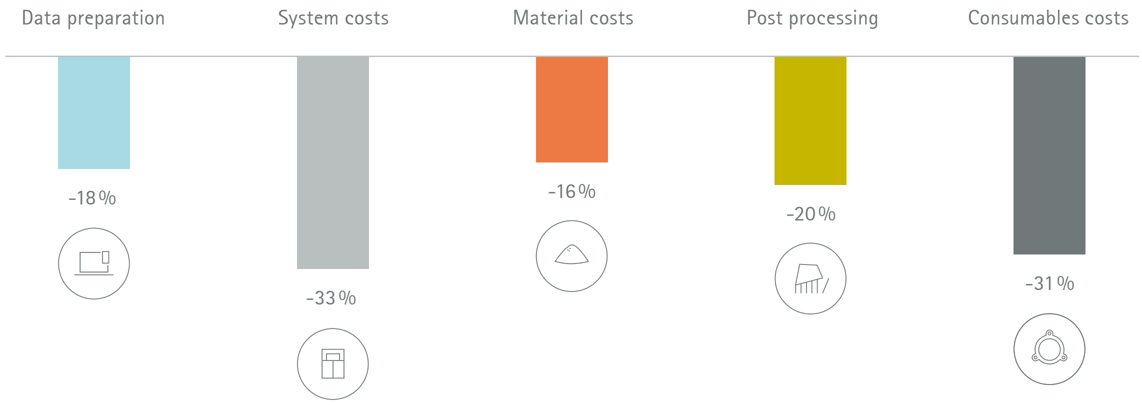


Figure 24: Percentage decrease along the process chain for a support-free impeller from the perspective of a supported impeller

- Data preparation costs include the costs of knowledge transfer for process development in terms of support-free capabilities, design of experiment and data preparation itself. For supported impellers, the data preparation would focus on the support strategy for each impeller. The emphasis is on low-quantity lot sizes, hence we assumed 150 impellers of different sizes to aggregate the costs of data preparation.
- With lower build times and higher throughput, more impellers can be produced per year, thus reducing the overall system costs
- Obviously, less material is used for support-free impellers, hence the material costs are lower than for the supported impelller
- Post-processing includes the cost of part removal from the build plate, support removal (where appropriate), machining, and the use of AFM technology to achieve the required surface finish of the final part. With no need for support removal and with lower machining costs, a support-free impeller will be less expensive than a supported impeller.
- Consumables refer to the costs of build plate, recoater blade, filter, power, and inert gas consumption per job. Consumables have a limited lifetime and need to be accounted for per job and part. Due to the faster overall build times of support-free impeller consumables, the cost will be expected to be lower than its supported counterpart.

Conclusion

The aim of this whitepaper is to demonstrate that the DMLS process can be optimized for support-free building using EOS tools such as the Parameter Editor in the EOSPRINT Premium Module. Using an optimized part design for printing and downstream processes, a closed 316L impeller was built in a flat orientation with no internal supports. The results show that even with hard recoating, this impeller could be built without the use of supports with overhangs of 10-15 degrees. The part was subsequently machined and finished internally using abrasive flow machining (AFM), achieving a surface finish of Ra = 0.3-0.4 µm on the suction, carrying and pressure side. The roughness of the low angle downskin (front shroud) was also improved, but it indicates that there is still potential for future improvement to attain a higher as-built surface quality, as the primary concerns of the development at this stage were buildability and repeatability.

Considering the business case of closed impellers, this method might lead to a cost

Contact

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Davy's passion for additive manufacturing started in 2012 while writing his master thesis in mechanical engineering at KU Leuven. After his studies, he began working as a project engineer, focusing on the development and serial manufacture of medical applications. This was his first contact with both lattice structures and the medical industry. For the last 6 years, he has been Additive Minds consultant at EOS for all matters relating to processes, such as support-free process optimization. Since the end of 2021, he has been responsible for Additive Minds Consulting EMEA, which leverages all relevant knowledge and capabilities to ensure customers' success when using EOS technologies.

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Korbinian joined EOS in 2016 as a metal application engineer. He has a bachelor's degree in aeronautical and mechanical engineering, and his previous work experience is in the field of manufacturing aerospace components. In the application department, Korbinian focuses on post-processing metal parts, as well as customer projects and enablement.

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reduction of 35 % compared to impellers manufactured with standard supports. Less material is needed in the process and no supports need to be removed from remote cavities which are difficult to access. Additionally, abrasive flow machining (AFM) offers significant capabilities for finishing the internal surfaces of the impeller and further improving the efficiency of the application.

The findings of this application are incorporated into future parameter developments for various materials, such as the new IN718 process with a dedicated parameter set to improve low angle buildability and provide customers with more tools to boost their applications.

If you would like to find out more or you are interested in developing your own application, please feel free to contact us either directly or through your sales representative.

If you wish to start right away, you might like to take a look at our new e-learning course for support-free additive manufacturing.

https://store.eos.info/collections/training/products/support-free-additive-manufacturing-metal

Lukas Fuchs
Additive Minds Consultant

Lukas is responsible for business development for the turbomachinery industry at EOS. Lukas first encountered additive manufacturing in 2012 while studying laser physics. After receiving his master's degree, he specialized for 3 years in the in-process monitoring of 3D metal printing as an application development consultant. He is currently working on AM technology enhancements with a focus on efficient post-processing methods.

Michael Wohlfahrt
Senior Additive Minds Consultant

Michael has a passion for sustainable energy, the chemical industry, and aerospace. He holds an M.Sc. in chemical engineering from FAU Erlangen-Nuremberg. With many years' experience in the additive manufacturing industry, Michael knows both sides of the business, first as a user of the technology starting in 2013, and since 2017 as a member of the Additive Minds consulting team at EOS, where he supports strategic customers on their way towards serial production. In October 2020, Michael took on the position of key account manager to drive long-term strategic account development in the vertical of efficient energy & electronics. Since May 2022, Michael is Senior Additive Manufacturing Consultant at EOS North America advising customers and supporting the establishment of EOS' West Coast Innovation Center.

Syed Nameer
Additive Minds Consultant

Nameer is currently working at Additive Minds as a strategy & innovation consultant. He gained a bachelor's degree in mechanical engineering and a master's degree in management at ESMT Berlin, which led to his interest in new technologies. He has consulted numerous customers over the past three years in developing their journey towards adopting additive manufacturing. His expertise lies in determining business cases and financial feasibility for customers planning to enter additive manufac-turing. Syed brings a wide diversity of experience along with him together with a passion for data-driven decision making when consulting clients.

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