Process method for manufacturing impellers by Selective Laser Melting (SLM)
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Sulzer uses additive manufacturing processes (AM) in all its divisions for many different applications. These range from rapid prototyping in product development to tooling in manufacturing processes to the fabrication of customer parts. In addition, these technologies are used for repairs and retrofits.

The correlation between the material properties, the process parameters, and the build-up strategy are all key for the successful creation of parts with AM processes. That is why Sulzer does a lot of application-related research in this field of technology.

This Sulzer White Paper explains how we optimized the buildup process for a closed impeller manufactured using selective laser melting (SLM). It was created in the scope of a development project funded by Innosuisse (formerly Kommission für Technologie und Innovation KTI) in close cooperation with the University of Applied Sciences and Arts Northwestern Switzerland. The study has encouraged us to proceed with selective laser melting for other Sulzer parts.

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Abstract

In the water industry a strong market demand exists for small, high pressure pump systems. However, the casting of impellers for such small pumps in the required quality is difficult or impossible because of their low wall thickness and their unfavorable ratio of impeller diameter to channel height. Selective Laser Melting (SLM), one of the primary metal additive manufacturing technologies, is well-suited to be used for such impellers as the full potential of SLM can be achieved best with such small, complex parts. In this work, we describe the SLM manufacturing of an already existing impeller design at the lower limit of castability. If this geometry can successfully be SLM-manufactured, there should be no major obstacle for a scale-down to smaller sizes (down to a certain limit), but this SLM-manufactured existing impeller design can be tested on an already existing pump prototype and directly compared to the cast counterpart.

Therefore, the effort described here was to find the optimal orientation of build direction as well as to design suitable support structures. This was done in a heuristic and iterative process with concurrent manufacturing trials. The final SLM-processed prototype impeller fulfilled all geometrical requirements and will be tested in the existing prototype pump in the near future. While the full potential of SLM manufacturing is only reached by fundamental part redesigns, the process setup (build orientation optimization and support structure design) for a pre-existing part geometry as performed here is of large practical importance in the service and reconditioning market in the water industry and beyond.

Introduction

Starting with the patent by Meiners et al. [1] in 1996, there has been a steadily growing interest in the powder-bed additive manufacturing process of Selective Laser Melting (SLM). Over the last decade, industrial applications in different fields have undergone the process from research effort to full-scale serial production [2]. Most prominent among these fields are the biomedical, tool-making, aerospace, and power generation industries (cf., e.g., Yap et al. [3] and references therein).

Chief benefit of the SLM technology is that it enables a dramatic size increase of the design space for a given product, meaning that SLM is capable of producing parts that are not manufacturable through any other technology [4]. Furthermore it allows for lead time reduction because no tooling is required. In the pumps industry, pump impellers are complex parts that have long caused manufacturing difficulties [5]. Moreover, there is a size limit below which impellers are not manufacturable anymore at all since the most suited conventional manufacturing method, investment casting, cannot handle the complex 3D geometry at very small scales. There is, however, a large market demand for small, high-pressure pumps – and accordingly, small impellers (below an outer diameter of roughly 100 mm). This makes them a suited target for SLM manufacturing.

For SLM, the situation regarding (impeller) part size is effectively reversed as compared to investment casting. The smaller a part is, the simpler it is to manufacture by SLM (down to a certain limit on the order of SLM manufacturing accuracy of around 0.1 mm). This is because of the main SLM manufacturing constraint, which is the necessity to add support structures to overhanging geometries forming an angle of typically less than about 45 degrees with the horizontal [6]. These supports are not needed however if the extent of the overhang is small enough. Thus if scaled down suitably, a given geometry can be SLM-processed without supports even though its scaled-up counterpart cannot.

Because of the above considerations, in this work we describe the manufacturing of a pump impeller by SLM whose size is at the lower limit of castability*. We do this with the reasoning that if we can produce this impeller size, there should be no major obstacle to scale it down.

* The other existing powder bed Additive Manufacturing technique of Electron Beam Melting (EBM) would also be a possible choice for manufacturing the impeller. SLM and EBM each have their advantages and drawbacks (see, e.g., Niendorf et al. [9] and references therein). In this work we make use of SLM due to its advantage in surface quality as opposed to EBM [10].
to smaller sizes. At the same time, the impeller so produced can directly be compared to its cast counterpart in terms of its features and performance. For this endeavor, we choose an already existing impeller geometry, allowing this direct comparison with the cast part also in a full-speed test. The effort therefore lies entirely in finding optimal part orientation, designing the support structure, as well as determining the adequate post-SLM machining steps to obtain the desired geometry. In this work, we describe our heuristic and iterative design process through which we were able to produce the desired impeller with suitable accuracy. While there have been some efforts in the past to manufacture a pump impeller by additive manufacturing via the fused deposition method using polymeric material [7, 8], to our knowledge there exists thus far no documented attempt in the literature toward an SLM processed pump impeller.

We further point out the following: while the potential of SLM manufacturing is greatest if one can come up with an entirely new design that makes use of all design possibilities enabled by SLM, the development of a new design is not possible if a conventionally-produced part shall be produced again by SLM (e.g. as a spare part due to shorter lead time). There is thus considerable practical interest in the type of procedure described herein where the SLM support structure for a pre-existing geometry is designed and optimized.

**Impeller geometry**

The part under consideration is a radial impeller with an outside diameter of 92.4 mm and a height of 46 mm; see Fig. 1 and Fig. 2. Final machining by milling and turning is possible on all outer surfaces and the shaft bore, however not in the impeller channels. In operation the fluid flows axially into the impeller channels (between hub shroud and front shroud). Due to the rotating blades, the fluid is redirected and finally ejected radially with an increased relative pressure.
Optimization of build direction

In order to determine a suitable orientation of the impeller in the build chamber of the SLM machine, all surfaces of the impeller were first analyzed and divided up into three categories:

A. support removal easily feasible
B. support removal requiring effort but certainly possible
C. support removal difficult or impossible.

These three categories are depicted in Fig. 3. Next, two angles, $\alpha$ and $\beta$, were introduced specifying part orientation. $\alpha$ and $\beta$ stand for rotations about the local (part-specific) x- and z-axis, respectively; see Fig. 4. The range of $\alpha$ and $\beta$ is $0^\circ$-$72^\circ$ and $0^\circ$-$180^\circ$, respectively, due to cyclic symmetry of the impeller.

The angle $\alpha$ thus has no influence on the orientation of the hub and front shroud regions of the impeller (cf. Fig. 2). It was therefore decided to first examine different angles $\beta$ and their consequence for necessary support structures of type C on hub and front shroud, while disregarding necessary support for the blades. The blade support areas could then be optimized via the angle $\alpha$ after finding a suitable $\beta$.

Downskin angles (angle between the horizontal plane and a downskin surface, lying between $0^\circ$ for a horizontal downskin plane and $90^\circ$ for a vertical plane; cf. the recent VDI norm on Additive Manufacturing [11]) between $0^\circ$ and $45^\circ$ were deemed to need supports as mentioned above. In the CAD suite Siemens NX 10.0, downskin angles of surfaces can be suitably visualized.
As evident from Fig. 5, the orientations $\beta = 0^\circ$ and $\beta = 180^\circ$ both produce large areas on the hub and front shroud needing supports of type C. Effectively, as $\beta$ is increased from $0^\circ$ and beyond $45^\circ$, the hub and front shroud areas needing support gradually decrease as shown in Fig. 6. They reach a minimum at $\beta = 90^\circ$ and then increase again. An angle $\beta$ of close to $90^\circ$ thus seems suitable.

Next, for angles $\beta$ close to $90^\circ$, the angle $\alpha$ was examined revealing that the C supports on the blades increase strongly as $\beta$ approaches $90^\circ$. $\beta = 80^\circ$ was therefore chosen as a first orientation. Varying $\alpha$ for this $\beta$ showed that the amount of necessary C supports on the blades is only weakly coupled to $\alpha$. Minimum C supports are reached for $\alpha$ around $10^\circ$, leading to $\alpha = 10^\circ$ as second orientation parameter*. We point out that this choice of the two parameters also keeps reasonable the maximum molten cross section in a single layer.

** Support design iteration 1**

After the optimal build orientation was determined, a first support structure design was carried out. This was done entirely in the commercial software Materialise Magics 20.0. We generally put supports in all areas with an overhang angle (angle between surface and the horizontal plane) of less than 45 degrees. For all areas accessible with a chisel and lathe, we chose simple block supports as shown in Fig. 7. For the areas not accessible this way, lying mainly between the blades, gusset supports were used as shown in Fig. 8. (Note that both block and gusset supports consist of single laser melt tracks.)

** We note that instead of our manual approach chosen here, optimization of build orientation can also be performed in commercial programs e.g. Materialise Magics 20.0. However, easy-to-reach surfaces, where support structure removal does not pose a problem, cannot be excluded from the optimization.
A manufacturing trial was performed for the first support design iteration. The target material for the impeller is the nickel-base superalloy IN625; however, the manufacturing trial was performed with a stainless steel of inferior strength than IN625 due to short-term powder unavailability. For this manufacturing trial as well as all manufacturing further discussed in this work, an SLM machine of type Realizer SLM125 was used.

In Fig. 9 the result of the manufacturing trial is depicted. It is clearly visible that the block supports macroscopically cracked in several locations. This rendered the built part unusable due to excessive part distortion resulting from the supports losing their function. An example of such distortion is the lower hub region of the impeller that is shown in detail on the right in Fig. 9.

Removal of the part from the substrate plate was performed with a band saw. The block supports were then broken off with hammer and chisel, while the gussets were successfully removed by shot peening. The part was subsequently used for a trial of the post-machining steps on the lathe.
Support design iteration 2
Due to the widespread cracking observed in the first manufacturing trial, the support design strategy was subsequently altered. For the second support design iteration, the cracked block supports were replaced by supports created in the native CAD program Siemens NX 10.0. These new supports are beams as shown in Fig. 10, possessing higher strength and allowing greater heat flux away from the processing zone than in the earlier support design***. Their rectangular cross sections have more massive dimensions between 1.5 and 12 mm and are hence termed volume supports. Further, as mentioned before, the angle $\alpha$ only very weakly influences the amount of necessary supports. In order to provide as much local strength as possible in the regions where volume supports are connected to the impeller, the $\alpha$ angle was therefore changed to $\alpha = 54^\circ$. For the lower hub region, volume supports were used too. They are shown in Fig. 11.

A manufacturing trial was then performed in IN625. The result of the trial is shown in Fig. 12. The cracking earlier observed was successfully suppressed. The lower hub region shown in Fig. 13, too, showed clear improvement. The gusset supports, however, were not all successfully removed by shot peening due to the superior strength of IN625 used in this case. For the subsequent prototype manufacturing it was thus decided to attempt the manufacturing with no gussets at all (except single ones at the very ends of two blades), owing to the rather small typical channel widths of around 5 mm.

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*** In SLM, pre-heating of the substrate plate decreases the temperature gradient across the part being built, and hence also decreases thermal stresses. An equally possible strategy for crack mitigation would therefore be to increase substrate pre-heating. In our specific case, however, the pre-heating was already set to its maximum of 200 °C and thus did not allow pursuing this strategy.
Regarding the lower hub region, due to the remnants of the volume supports after their removal, this area needed to be post machined on the lathe. Apart from being an additional post-SLM process step, a consequence of this was also the creation of a sharp transition between machined and unmachined surfaces in the waterways that is deemed hydraulically unfavorable. For the prototype a further support modification in this region was therefore decided upon.

Fig. 12  Manufacturing trial of the second support design iteration on the substrate plate after SLM (tensile specimens also visible).

Fig. 13  Manufacturing trial of the second support design iteration: volume supports in the hub region showing clearly improved lower hub geometry.
Prototype design and manufacturing

The final prototype design was largely the same as the one of the second support design iteration except for the hub region. There, the volume supports were modified as shown in Fig. 14. Both ends of these volume supports lie on machining stock material; thus any remaining support stub is machined away automatically. Behind these volume supports, only thin line supports are needed (width of one laser melt track) that can be removed without any remainders, thus eliminating the need for post-machining in the waterways.

The prototype was manufactured by SLM in IN625. The result is shown in Fig. 15. The manufacturing of the waterways without gusset support proved successful. No cracks were visible, and the modified supports in the hub region also served their purpose as intended.

The prototype was subsequently removed from the substrate, supports were removed, a stress-relief heat treatment was performed, and post-SLM machining followed.

A detailed 3D scan performed with a 3D scanner (type GOM ATOS III Rev. 02) revealed that geometric accuracy of the prototype lies within +/- 0.2 mm, satisfying the requirements for full-speed testing scheduled in the near future.

![Fig. 14 Modified volume supports in the hub region for prototype.](image1)

![Fig. 15 Left: Prototype on the substrate plate after SLM (tensile specimens also visible). Right: Prototype after all post-SLM processing steps.](image2)
Conclusion and outlook

In this work we demonstrated a process setup to manufacture a pump impeller via SLM. The process setup comprised (a) finding the optimal build direction as well as (b) designing suitable support structures in a heuristic and iterative approach.

First, all impeller surfaces were analyzed and categorized according to the degree of difficulty to remove possible support structures thereon. Possible impeller orientations were considered via two angular parameters and a suitable build direction was chosen. Subsequently, support structures were designed in the commercial software Materialise Magics 20.0. A manufacturing trial, however, showed severe support cracking and part deformation. Therefore a second support design was elaborated with more massive supports designed directly in the native CAD program Siemens NX 10.0. The corresponding manufacturing trial confirmed elimination of the cracking earlier observed. Finally, a prototype was successfully manufactured which fulfilled all geometric requirements. This prototype impeller will be tested in a prototype pump in the near future.

Since a scale-down of size typically increases SLM manufacturability due to small overhang areas being able to support themselves, the successful prototype production implies a large potential for SLM production of impellers of smaller size in the future.

Finally, we point out that the effort documented herein was focused on an existing impeller design in order to be able to test the impeller prototype in an existing pump system prototype. While the full potential is typically reached by fundamental part redesigns unlike done here, the SLM process setup for an existing geometry as described here is of large practical importance in the service and reconditioning market in the water industry and beyond.
References


