Conference Paper

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Publication Date:
2018-09-26

Permanent Link:
https://doi.org/10.3929/ethz-b-000313394

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DEVELOPMENT AND VALIDATION OF AN INTEGRATED PITOT TUBE – MANUFACTURED WITH SELECTIVE LASER MELTING AND ABRASIVE FLOW MACHINING

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ABSTRACT
Selective Laser Melting (SLM) belongs to the group of manufacturing technologies called additive manufacturing or 3D Printing. The design freedom of SLM can be used for complex internal geometries, but at the same time the SLM produced parts usually have a high surface roughness (SR). In order to improve the SR of complex internal structures Abrasive Flow Machining (AFM) is applied. In this work a novel pipe-integrated Pitot tube (PT) was developed, manufactured by combining SLM and AFM, and validated on a test bench. The validation of the PT function showed a distinguished precision of measurement. The newly developed PT system is able to generate an added value by reducing assembly time, increasing manufacturing speed, and generating a compact design. Within this paper, the potential of surface finishing of complex internal SLM structures by AFM is pointed out. The general concept of combining SLM and AFM is still at the beginning of the research stage and requires further fundamental research.

1. INTRODUCTION
Selective Laser Melting (SLM) belongs to the group of manufacturing technologies called additive manufacturing (AM) or 3D Printing. The SLM technology uses a laser to solidify a powder to create three-dimensional objects [1]. The design freedom of SLM can be used for complex parts and can be utilized for function integration to generate an added value [2][3][4].

This paper focuses on a SLM manufactured volume flow measurement system named Pitot tube (PT). PTs are commonly used for measuring volume flows of a large range of fluids. The PT system can be used for a wide range of temperatures and many fluids including water, oil, air, etc. Up to now, pipe-integrated PTs had to be assembled from many different parts and had to be manufactured in many steps from pipes or milled from a single block, which is cost-intensive. For pipe-integrated PTs the design freedom of SLM can be used to generate a compact design and a minimum effort of assembly after manufacturing. SLM produced parts usually have a high surface roughness (SR) [5]. In particularly hard-to-reach areas, such as pipe surfaces are problematic to improve the SR [18]. One potential post-process to improve the SR of internal pipes is Abrasive Flow Machining (AFM) [19].

In hard-to-reach areas, as they occur on integrated PTs, AFM has a potential to reduce the SR [6]. AFM also improves the technical cleanliness which is especially important for safety, durability, and the performance of a product [15][16][17]. In addition, the notch stresses can be reduced on the surface, which leads to a longer lifetime of a pipe under high pressure. [7] Some examples of application industries for the integrated PT are the aerospace industry, racing cars, and process engineering. Currently, external PTs made by SLM exist [8]. A PT integrated in a pipe, manufactured from a single SLM part, with integrated channels does not exist as yet.

This work addresses the following questions: 1) How can an integrated PT be designed in two orientations and be optimized for an AFM process to reduce the SR? 2) How can the function of this system be validated?

2. STATE OF THE ART
2.1 Selective Laser Melting
To design SLM parts it is necessary to consider the part orientation to avoid support structures and rough surface qualities [9][10][2][5][11]. The minimum overhang for a standard parameter on a SLM machine is 45° (Fig. 1). If the angle decreases, the SR becomes significantly worse. [20]

![Figure 1. Orientation of down-skin surface: 45°](20)

Typically, the surface characteristic of a SLM-manufactured part is not smooth, but rather has a certain amount of semi-sintered or semi-melted material on top [12]. Especially in internal pipes, a high SR occur [13]. The raw powder particle diameters vary between 2 μm and 60 μm and can be stuck in-between the semi-melting powders [14]. Especially for internal and hard-to-reach areas it is a challenge to remove the remaining powder. The surface of SLM parts often require post-processes to reduce the SR.

2.2 Abrasive flow machining
AFM is a process which is generally used for reducing the SR of internal pipes and inner surfaces in a wide
range of applications including aerospace, automotive parts, and medical or dental components [6]. During AFM, an abrasive-laden medium is pushed through the pipe or across the work piece by two cylinders, generally in a cyclic process. By pushing a semisolid visco-elastic or visco-plastic abrasive-laden medium across the surface of work piece, material is removed. Surfaces with complex shapes and hard-to-reach areas can be manufactured by AFM. [6] The abrasive particles in the semi-solid media slightly erode the surface with every cycle and reduce the surface. [21] The amount of removal depends on parameters influenced by the machine, the medium and the geometry of the work piece. The main influence factors are the extrusion pressure, the number of cycles, the rheological properties of the media, the material of the work piece and its geometry [19]. Fig. 2 shows the schematic process of AFM including a simple example of a work piece.

![Figure 2. Schematic display of an AFM process](image)

The focus of this paper lies on the geometrical design of the part, while the other AFM parameters are kept constant.

### 2.3 Pitot tube

The orientation of the PT is against the flow direction of the fluid in the pipe to measure its pressure at the stagnation point and a channel on the sidewall to measure the static pressure. The equations that are used to measure the flow velocity are based on the principle of conservation of energy for incompressible fluids. The derived equation is the Bernoulli equation (Eq. 1) with the geodetic height \( z \) and the gravitational force \( g \). [22]

\[
p + \rho \cdot \frac{u^2}{2} + g \cdot z = \text{const.}
\]  

(1)

The dynamic pressure \( p_{\text{dyn}} \) is the difference between the pressure at the stagnation point of the PT \( p_{\text{stag}} \) and the static pressure of the pipe wall \( p_{\text{stat}} \) (Fig. 3).

![Figure 3. Schematic design of the pressure in the PT](image)

With the help of Eq. (1) the equation for the PT is derived. The formula to measure the velocity \( v_{\text{pitot}} \) by a PT has the following form (Eq. 2). [23]

\[
v_{\text{pitot}} = \sqrt{\frac{2 \cdot p_{\text{dyn}}}{\rho}} = \sqrt{\frac{2 \cdot (p_{\text{stag}} - p_{\text{stat}})}{\rho}}
\]  

(2)

### 3. DEVELOPMENT

#### 3.1 The design of the Pitot tube

An effective PT design needs to meet the following criteria to be manufactured in two orientations:

First, to generate an appropriate SLM design the design guidelines, described in Section 2, need to be considered.

Second, a constant volume flow of the AFM fluid is required [19]. The cross-section of the designed pipe is kept constant over the entire length of the pipe to avoid a narrowing part and an increase of the surface removal by AFM. In Fig. 4 and Fig. 5, the vertically oriented (VO) and the horizontally oriented (HO) PT are plotted and the design elements are named.

![Figure 4. VO PT with flow-optimized shape](image)

![Figure 5. HO PT with flow-optimized shape](image)

For both orientations, the base diameter of the pipe is 10 mm and the length is 80 mm. The diameter of the stagnation pressure channel and of the static pressure channel is 0.5 mm. The stagnation point lies in the center of the flow profile. The static pressure is measured by five or four static pressure channels in the pipe wall, on the height of the stagnation points to generate average data with a minimum of disturbances (Fig. 4 and Fig. 5). The main dimensions are plotted in Fig. 6 and Fig. 7.
The design of the HO PT differs from the VO PT by the shape of the cross-section of the pipe. In order to be able to produce the pipe of the HO PT in these dimensions, a self-supporting peak with 45° is required, in accordance with the existing design guidelines (Fig. 6) (Section 2). Furthermore, the PT design needs supported structures to be manufacturable in the SLM process. Therefore, the area behind the stagnation point was used to add the support (Fig. 5).

The cross-sections of the PTs airflow were the following: VO PT 78.5 mm², HO PT 81.9 mm².

### 3.2 The manufacturing of the Pitot tube

The PT was manufactured using an “M2 cusing” 200 W laser by ConceptLaser machine with a layer thickness of 0.75 mm and stainless steel powder CL 20ES, which corresponds to 1.4404 (316L or X2CrNiMo17-12-2). After the SLM process, the AFM process, the static pressure channel and the stagnation pressure channel had to be post-treated separately due to particles stuck in these tubes. By piercing a 0.5 mm spring steel wire through the tubes, the powder could be removed, such that a static pressure in the channels reached the pressure sensors. Especially the HO stagnation pressure channel caused the problem of sticking powder. In order to analyze the internal SR of the pipe, the manufactured parts were sliced using wire-cut EDM. The parts were sliced 3 mm outside of the center, to analyze the surface of the PT.

After the SLM process, a homogenous surface is visible in the VO PT on the pipe surface and on the PT (Fig. 8 left). After the AFM process the surface is mirroring, which indicates an improvement of the surface quality (Fig. 8 right).

After the SLM process (Fig. 9 top), the HO PT presents a higher SR on the down-skin than on the up-skin surfaces. After the AFM process, the side surface is mirroring, but on the down-skin a high SR is still visible (Fig. 9 bottom).

### 3.3 Test bench

A test bench was developed to investigate the performance of the volume flow measurement and the pressure drop measurement of the PTs. The main elements of the test bench are the following: A pressure supply of 1.1 to 1.6 bar, a throttle to adjust the volume flow, a valve to open and close the volume flow, and diffusor 1 are implemented (Fig. 10). In the centre of the test bench the PT is assembled and connected with the difference pressure sensor (SDP 1000-R, Sensirion) and an Arduino, which was connected to a computer. At the outlet of the test bench, the air leaves the test bench at diffusor 2 into the environment, at a constant room temperature of 22 °C.

Fig.11 shows a cross-section of the test bench with the main dimensions.
For each measurement, the pressure values were determined by a mediation test series of 30 seconds each. During the volume flow measurements, the openings of the interfaces of the pressure difference were locked. As a reference sensor of the real volume flow, a hot-wire anemometer CTV 210-R transmitter by KIMO Instruments was applied.

4. RESULTS

4.1 Surface roughness and dimension changes

The SR values of the surface were measured by a confocal 3D laser scanning microscope “Keyence VK-X200”. The measure lines on the PT were selected to analyse relevant surfaces after SLM and after AFM processes. For each measurement, the measuring distance was 8 mm. The Ra values are measured and plotted in Fig. 12.

On the VO PT side, the initial Ra values changed from Ra 5 µm to Ra 1.7 µm. The value of the vertical pipe side changed from Ra 5.8 µm to Ra 1.6 µm.

On the HO PT, the side surface value were reduced from Ra 6.7 µm to Ra 2.1 µm, while the horizontal pipe side was reduced from Ra 4.7 µm to Ra 1.3 µm. A significantly increased SR value was detected on the down-skin surface, where the values were reduced from Ra 81.6 µm to Ra 35.7 µm.

The reduction of the measured Ra values are correlate with the corresponding Rz and Rq values (Table 1.).

Table 1. SR values after SLM and after AFM process:

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>After SLM process</th>
<th>After AFM process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra (µm)</td>
<td>Rz (µm)</td>
</tr>
<tr>
<td>1</td>
<td>5.0</td>
<td>36.2</td>
</tr>
<tr>
<td>2</td>
<td>5.8</td>
<td>42.3</td>
</tr>
<tr>
<td>3</td>
<td>6.7</td>
<td>46.8</td>
</tr>
<tr>
<td>4</td>
<td>4.7</td>
<td>31.6</td>
</tr>
<tr>
<td>5</td>
<td>81.6</td>
<td>361.7</td>
</tr>
</tbody>
</table>

4.2 Volume flow measurement

The calculation of the velocity, as measured by the pressure difference of the PT and based on the Bernoulli equation, is explained in Section 2, state of the art. By multiplying the cross-section with the velocity of the fluid, the volume flow can be calculated.

To evaluate the quality of the PT measurement data, the measured values were compared with those of the reference sensor. As a reference sensor, a hot-wire anemometer was used, as explained in Section 3.3.

For this purpose, measurements were taken at seven different volumetric flow points, with the PT and the reference sensor. The starting volume flow of the reference sensor is 2.7 $10^{-4}$ m³/s to 2.7 $10^{-3}$ m³/s (Fig. 13). The volume flow measured with the VO sensor is shown on the x-axis and the volume flow measured with the reference sensor on the y-axis. Both measurements show a linearity to each other. The coefficient of determination $R^2$ showed a value of 0.99984.

4.3 Pressure drop

The pressure drop was measured between the inlet and the outlet. It was measured with eight different volume flows, starting with a velocity of 2 m/s and going up to 28 m/s (Fig. 15).
The lowest pressure drop is indicated by the optimized VO PT design, followed by the HO PT design. The AFM post-processing also reduces the pressure drop of the VO and the HO designs, as shown in Fig. 15. By increasing the velocity the pressure drop increases.

4.4 Material removed

The material removed was measured at the inlet of the PTs (Fig. 16). The measurement was taken with a digital calliper (TESA Messschieber digital TWIN-CAL ± 0.01 mm). The VO PT has a diameter of 10.81 mm after SLM and of 11.23 mm after AFM. The HO PT has a diameter of 9.86 mm after SLM and 10.02 mm after AFM.

As expected, the empirically determined values show that the pressure drop decreases after applying the AFM process. The pressure drop are in a low range. The values in Table 2 show that the value of the pressure drops correlate with the removal rate and the surface improvement of the AFM process.

5. DISCUSSION

A flow-optimized PT was developed, produced by SLM, and post-processed by AFM. The flow-optimized geometry ensured that the material was steadily removed from the surface such that the SR could be reduced by applying AFM. The final SR was satisfactory except on the down-skin of the HO pipe. The function of the PT volume flow measurement was validated and showed a coefficient of determination $R^2$ of practically 1.

The SR of the entire test series significantly improved after the AFM process (Fig. 12 and Table 1). The measurement of the SR before and after the AFM process was indirect because the PT had to be cut to analyse the surface. Since both samples were built on one built jobs and under the same parameters, the values are comparable. The SR improvement of the side surface is promising in contrast to the down-skin of the HO pipe, which was still rough after the AFM process. A correlation between the reductions of the SR, an increase of the pipe diameter, and the reduction of the pressure drop of the inlet was observed.

An OB20 sensor was used as a reference for the VO PT after AFM. The coefficient of determination $R^2$ was practically one (Fig. 13). Consequently, this proves that the PT achieves a good model fit with the calibrated reference sensor. Further, the coefficient of determination $R^2$ of the comparison between the calibrated VO (AFM) PT and the other PT achieved an excellent coefficient of determination $R^2$ (Fig. 14). The results show that if a good surface quality for PTs is required, a surface improvement by AFM can be carried out without any negative influence on the measurement performance of the developed PTs.

The HO PT had the highest pressure drop after SLM. After the application of AFM the pressure drop was reduced significantly (Fig. 15). The VO PT pressure drop was lower after the AFM process than that of the HO PT. The pressure drop of the HO PT was further reduced by AFM.

The inside distance of the pipe increased after the AFM process at both the HO PT and the VO PT. The measured dimension is plotted in Fig. 16. The measured values clearly show that the cross-section of the whole pipe increased.

Table 2 shows the relevant measurement values of the pressure drop at 28 m/s, the material removed and the Ra values of the investigated PTs.

As expected, the empirically determined values show that the pressure drop decreases after applying the AFM process. The pressure drop are in a low range. The values in Table 2 show that the value of the pressure drops correlate with the removal rate and the surface improvement of the AFM process.

6. CONCLUSION AND FURTHER WORK

A Pitot tube (PT) was successfully developed and manufactured from one part and was integrated in a pipe using Selective Laser Melting (SLM). It was shown that the PT can be successfully designed in a vertical orientation (VO) and in a horizontal orientation (HO). Abrasive Flow Machining (AFM) was successfully applied to significantly reduce the Surface Roughness (SR) of the PT geometry. The SR of the HO PT was satisfactory. The HO PT showed a satisfactory SR as well, with the limitation of the SR on the down-skin in the pipe, which was still rough. The volume flow measurement was validated on a newly developed test bench. As expected, the pressure drop, measured by various sensors was very low. A comparison of the pressure drop, between the inlet and outlet of the different PTs, showed that the pressure drop correlates with the abrasion of the PT. This fact can be used as a quality control of the SR of the SLM and AFM processes and has a significant potential to save cost by reducing machining time. In order to apply this quality control, the statistical accuracy of the pressure drop has to be investigated in detail. The results of the volume flow measurements of the PT were compared to those
obtained by an established volume flow measurement system. The resulting coefficient of determination proved a distinguished performance. The developed PT system is able to generate an added value by reducing assembly time, increasing manufacturing speed, and generating a compact design.

This paper shows, the applicability of AFM in a complex internal SLM part is shown. The cross-section of the pipes has been increased significantly after the AFM process due to an irregular abrasion. This could affect leakage and needs to be investigate in further work. The influence of the AFM parameters must be investigated more in detail. It was shown that the static measurement channels with a small diameter can be produced and is not blocked after applying AFM, but they have to be cleaned manually afterwards. To further improve the surface quality of the pipe, the SLM process parameters need to be optimized, especially on down-skin surfaces. The general concept of combining SLM and AFM is still at the beginning of the research stage and needs further fundamental research.

7. REFERENCES