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Functional testing of additively manufactured hydraulic rod seals

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Hydraulic rod seals are crucial machine elements in a lot of applications [1]. The malfunction of rod seals can cause, among other things, huge economic loss by long shutdown times for repair. In addition, the last years have shown that geopolitical incidences, such as a war or a pandemic, can have a huge impact on international channels of trade. To avoid or at least minimize machine shutdown times, it seems desirable to have local production solutions for rod seals by using easy-to-handle machinery and a single, simple raw material. A possible solution to circumvent delivery challenges can be the use of an additive manufacturing (AM) method. The research question addressed in this study is whether it is possible to produce functional rod seals using a simple AM method. The functional tests conducted on a rod seal test rig showed that the research question can be answered in an affirmative way for tested pressures up to 15 MPa. Even in a long-term test, the function of the additively manufactured seals met the demands.

1 Introduction

The results of a method screening and the preliminary investigations were presented at the 21st International Sealing Conference in Stuttgart in 2022 [2]. The main results were the choice of Fused Filament Fabrication (FFF) as the AM method for the study, thermoplastic polyurethane (TPU) as the material class to be used, and a choice of TPU filaments for the tests. The latest results, the outcomes of two series of functional tests conducted with these different filaments, will be the core of this paper.

2 Materials and Methods

A reference part was chosen to be able to compare the additively manufactured specimens with an existing conventionally made seal. The chosen seal is a U-cup seal [3] made from TPU as shown in Figure 1.

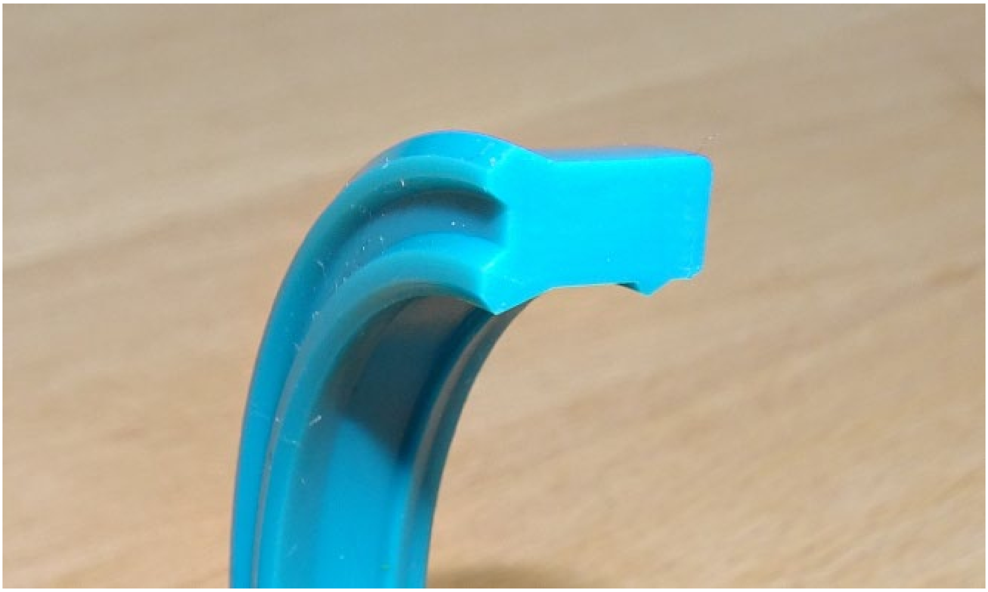

Figure 1: Cut specimen of the reference seal

2.1 Materials

In the preliminary studies, a variety of different commercially available TPU filaments was characterized with the goal of finding the most promising ones for the functional tests. The selection criteria were processability and comparability with the reference seal in terms of radial force, temperature range, friction coefficient, and shore hardness.

The following filaments were examined in the functional tests:

- Extrudr TPU Hard D58
- BASF Ultrafuse TPU 95A
- Extrudr TPU Semisoft A85
- Extrudr TPU Medium A98
- Polymaker Polyflex TPU 95A
- TreeD Flexmark 9

2.2 Production of the test parts

The test parts were produced on a standard FFF 3D printer with a 0.4 mm nozzle. The printing speed was set to a low value of 20 mm/s, which worked with every filament. The other start parameters, bed temperature and nozzle temperature, were set to the values suggested by the filament manufacturer for the first test phase.

2.3 Test rig

The test rig that was used for the functional tests was originally designed for optical investigations and therefore did not comply with the specifications of the ISO 7986:1997 [4] standard, which defines test methods to assess the performance of rod seals. The maximum speed achievable is 0.25 m/s, and the maximum pressure is 15 MPa. The traveling distance is 150 mm. Nevertheless, the functionality of the additively manufactured seals can be assessed with the test rig up to the aforementioned parameters.

Figures 2 and 3 show the test rig.

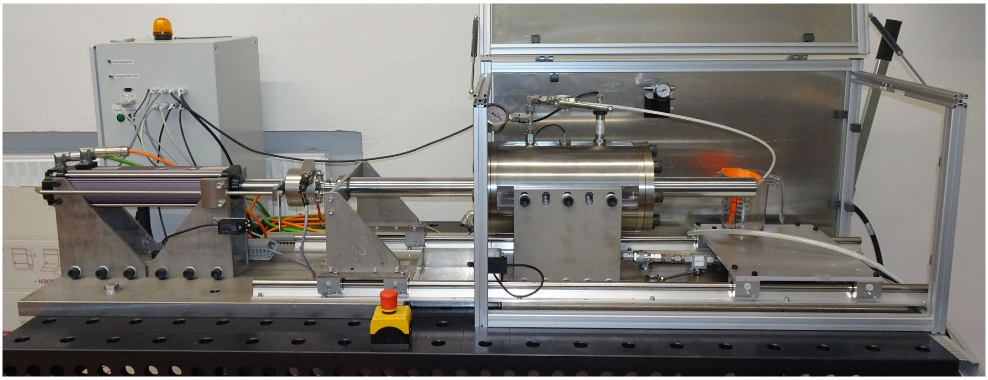

Figure 2: Rod seal test rig

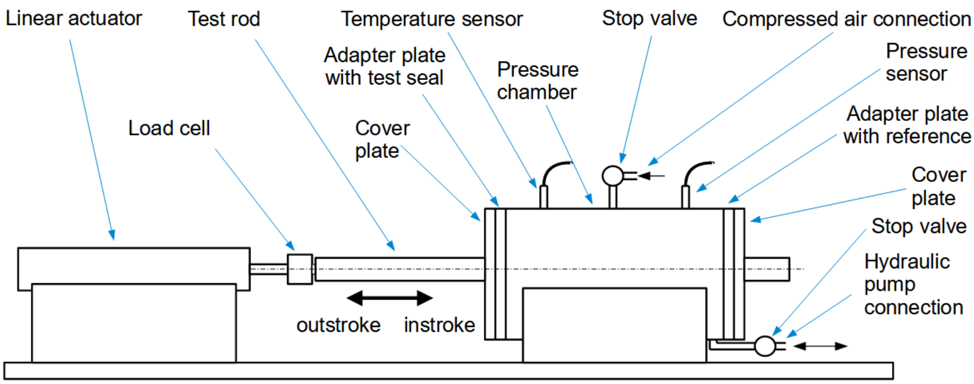

Figure 3: Rod seal test rig — Schematic view

On the left side of the pressure chamber (toward the actuator), a test seal was mounted. On the other side, there was always a reference part. To have force values to compare with, three reference seals were also tested. For these reference tests, reference parts were mounted on both sides of the chamber. The fluid used for the tests was a mineral oil (ISO 32 HLP).

2.4 Test procedures

Before the functional tests were conducted, some preliminary examinations took place. The following functional tests were conducted in two phases. The first one was supposed to determine whether the additively manufactured parts are likely to fulfill the main function: to avoid fluid leakage. The maximum pressure applied and the number of test cycles were moderate in that phase.

In the second phase, tests were conducted up to the maximum pressure the test rig was designed for. The parts tested were manufactured with optimized parameters regarding the outcomes of the first test phase. Also, a long-term test with a total sliding distance of 5,320 m was performed with one test part.

2.4.1 Preliminary examinations

Before and after the tests, the following values were measured and documented: the mass, the inner diameter, and the radial force. The measurement method for the radial force was first described by Debler in [5]. Because of the different mounting methods (no compression of outer diameter), the measured radial force is not the force in the application. Nevertheless, it allows the comparison with reference parts, and it shows possible deviation after the functional tests.

2.4.2 First test phase

In the first phase, ten cycles were performed with an acceleration of 0.8 m/s² and a maximum speed of 0.05 m/s. The stroke length was 100 mm.

This was done with the following system pressures: 0, 1, 2, 3, 4, and 5 MPa. After every pressure change, there was a waiting time of 10 minutes.

Since the test rig does not allow leakage measurement so far, the following distinction was defined to evaluate the tests:

- no visible leakage;
- slight leakage, like single drops on the adapter plate or a fluid film on the rod (as in Figure 4); or
- severe leakage, leading to an abortion of the test—this was done in case fluid dropped down the adapter plate (see Figure 5).

The main goal of the first test phase was to see whether the additively manufactured test parts had the potential to fulfill their main purpose: to avoid leakage.

The tests were performed with three test parts per filament, as listed in Section 2.1.

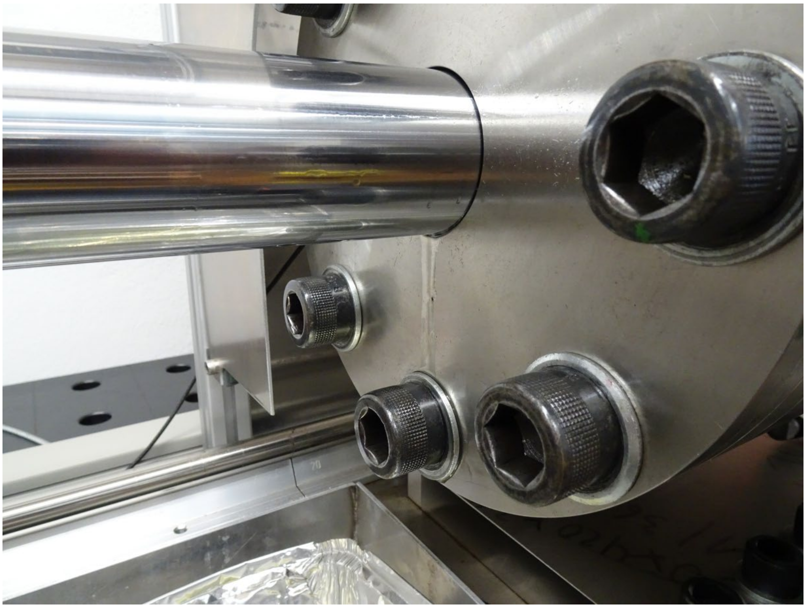

Figure 4: Slight leakage with the assembled test seal 10 at 0 MPa

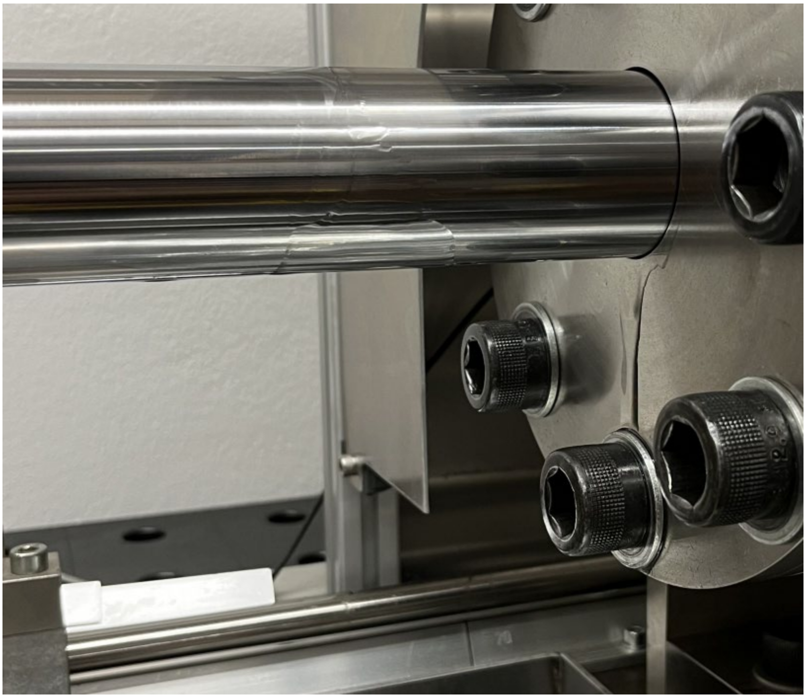

Figure 5: Severe leakage at 5 MPa with the assembled test seal 36

2.4.3 Second test phase

Based on the findings of the first test phase, the manufacturing parameters were optimized to achieve denser parts. The goal was to achieve a theoretical filling degree of 100 %. Therefore, the actual mass of the parts was compared to the theoretical density based on the CAD file and the measured density of the filaments.

Also, one filament (Extrudr Hard D58) was excluded from the second test phase because in the first phase, the parts made from that filament turned out to be too hard, leading to very high radial forces, and in case of different seal references, they were not mountable.

In the second phase, the goal was to test up to the maximum pressure of 15 MPa, which is achievable with the test rig. Also, the number of cycles was changed to 100. The pressure stages were: 2.5, 5, 7.5, 10, 12.5, and 15 MPa. The values for acceleration, speed, and stroke length remained the same. A waiting time of 8 hours after mounting the test parts was implemented to achieve material relaxation before the tests started.

After these tests, a longer test at a pressure of 6.3 MPa was conducted with 1,000 strokes. With one test part, a test with a sliding distance of 5,000 m (25,000 cycles) was added.

3 Summary and Conclusion

The following sections show the general qualitative results of the test phases, the long-term test, and comparisons of axial force measurements with reference parts.

3.1 First test phase

The following list shows the assignment of the test part numbers to the filaments, while Table 1 shows the qualitative results of this first phase:

- TreeD Flexmark 9: 01, 15, 16
- BASF Ultrafuse TPU95: 02, 03, 04
- Extruder Hard D58: 05, 06, 22
- Polymaker TPU95: 07, 08, 17
- Extrudr Semisoft: 09, 10, 18
- Extrudr Medium: 19, 20, 21

Theoretical filling degrees beyond 100 %, as seen in Table 1, can have two reasons.

The actual dimensions can differ from the nominal size because of over-extraction, and the actual density can differ from the one listed in the datasheet. To avoid the latter, the actual density of the filaments was measured before the second test phase.

Table 1: Results of the first test phase

Nr.	Mass before test in g	Mass after test in g	Δm in %	Filling degree in %	Result
01	8.938	9.195	2.88	91.14	Aborted at 1 MPa
02	9.280	9.363	0.89	103.02	Successful
03	9.161	9.220	0.64	101.70	Successful
04	9.214	9.277	0.68	102.29	Successful
05	8.946	9.069	1.37	94.26	Successful
06	8.964	9.156	2.14	94.45	Successful
07	9.034	9.184	1.66	92.12	Successful
08	8.991	9.217	2.51	91.68	Successful
09	8.571	8.808	2.77	91.84	Aborted at 1 MPa
10	8.519	8.846	3.84	91.29	Aborted at 1 MPa
15	9.087	9.366	3.07	92.66	Successful
16	8.936	9.204	3.00	91.12	Aborted at 1 MPa
17	8.948	9.144	2.19	91.24	Successful
18	8.036	8.604	7.07	86.11	Aborted at 1 MPa
19	8.785	8.933	1.68	93.35	Successful
20	8.437	8.933	5.88	89.65	Aborted at 2 MPa
21	8.408	8.920	6.06	89.34	Aborted at 2 MPa
22	8.224	8.920	8.46	86.66	Aborted at ambient pressure

The results of the first phase showed the importance of a high filling degree. Therefore, the manufacturing parameters were optimized to achieve a filling degree near 100%, although given the manufacturing method, there will remain a certain porosity in any case. Figure 1 shows the axial forces of three test parts made from the BASF filament compared to three reference seals. “Left” and “right” refer to the mounting position, as explained in Section 2.3.

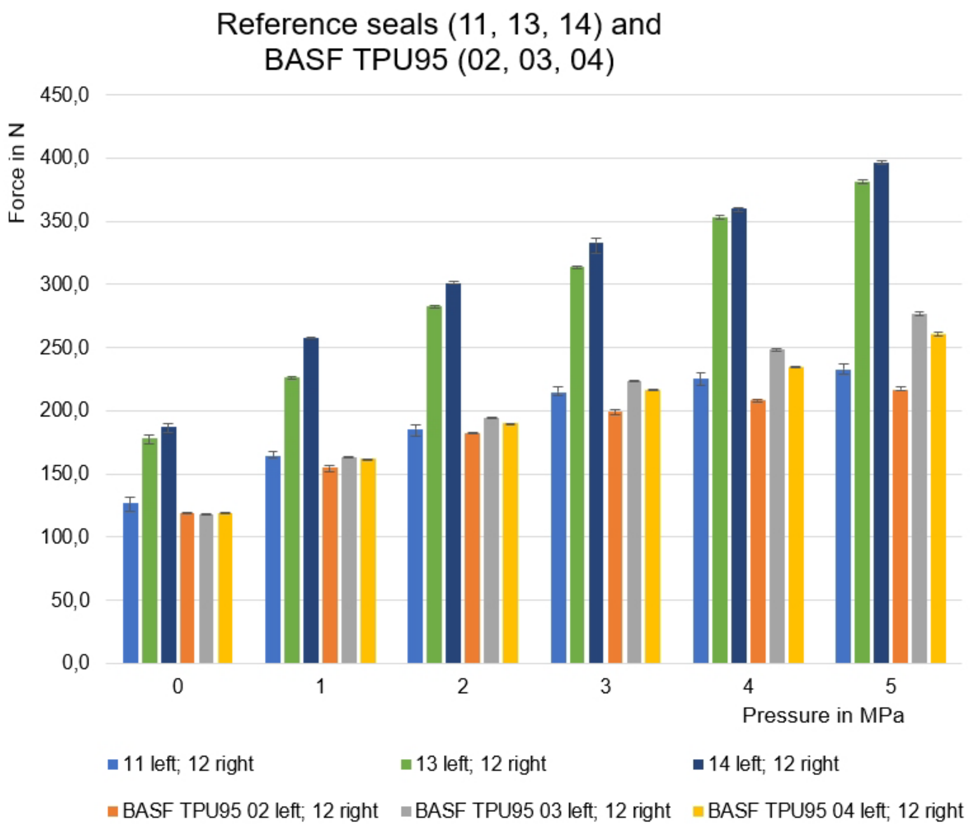

Figure 6: Axial forces (Outstroke) — Reference parts and BASF TPU95 (Phase 1) [6]

The axial forces tend to be lower than with the reference seals, although in various cases, the radial forces were higher. This is due to a higher compressibility of the additively manufactured parts because of their porosity, compared to the conventionally made reference parts.

3.2 Second test phase

The following list shows the assignment of the test part numbers to the filaments for the second phase, while Table 2 shows the qualitative results of the second phase:

- TreeD Flexmark 9: 44, 45, 46
- BASF Ultrafuse TPU95: 32, 33, 34
- Polymaker TPU95: 38, 39, 40
- Extrudr Semisoft: 35, 36, 37
- Extrudr Medium: 29, 30, 31

Table 2: Results of the second test phase [6]

Nr.	Δm in %	Filling degree in %	Result
29	1.00	98.11	Successful, slight leakage
30	0.92	98.97	Successful, slight leakage
31	0.54	98.37	Successful, slight leakage
32	0.69	98.65	Successful, slight leakage
33	0.68	98.73	Successful, no leakage
34	0.68	99.05	Successful, slight leakage
35	1.40	98.86	Successful, slight leakage
36	1.33	99.41	Aborted at 5 MPa
37	1.36	99.94	Successful, slight leakage
38	0.46	102.27	Successful, slight leakage
39	0.34	101.95	Successful, slight leakage
40	0.40	101.62	Successful, slight leakage
44	0.46	99.79	Successful, slight leakage
45	0.62	100.68	Successful, slight leakage
46	0.64	100.67	Aborted at 10 MPa

The axial forces still tend to be lower than with the reference seals. Parameter optimization in the forefront of the second test phase led to a higher filling degree; thus, less porosity decreased that gap.

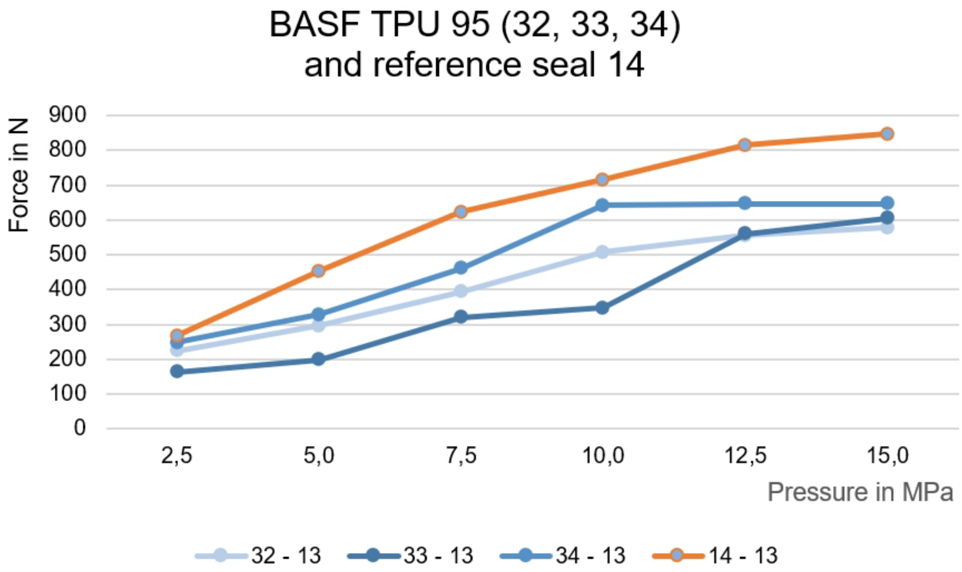

Figure 7: Axial forces (Outstroke) — BASF TPU95 (Phase 2)

It is noticeable that in some cases, the force increase stagnates from 10 MPa on. This can be seen, for example, in Figure 7 with the test part 34. This is supposedly a sign of a forthcoming failure with pressures beyond 15 MPa. Parts made from other filaments such as Extrudr Semisoft or Polymaker showed less tendency of stagnation. Such tendency was more distinctive with the parts made from Extrudr Medium and TreeD Flexmark 9.

The long-term test with one of the BASF parts (33) showed no visible sign of wear after a total sliding distance of 5,320 m.

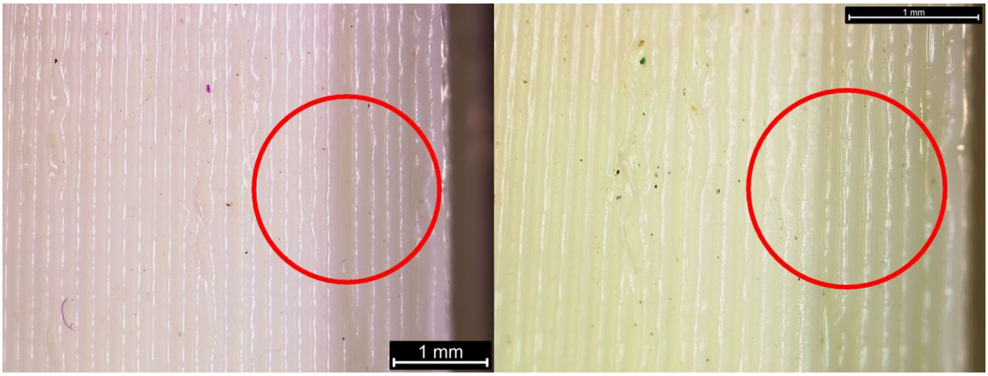

Figure 8: Microscope pictures of part 33 before (left) and after (right) the long-term test

Figure 8 shows pictures of the inside of the seal, taken using a prism. The circles indicate the sealing edge. Apart from discoloration caused by the fluid, no signs of abrasion or surface breakdown are noticeable. Although the loads act normally to the layers, which often leads to delamination, there are no signs of this being visible. The polished cut images in Figure 9 also do not indicate visible signs of wear.

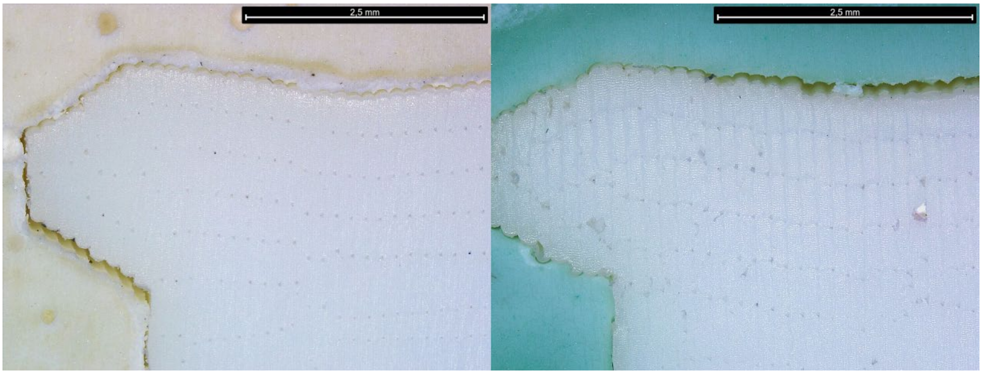

Figure 9: Polished cut images of part 33 (right) and an untested part made from the same material (left)

3.3 Conclusion

The functional tests have shown that at least within the conditions used for the tests, additively manufactured seals can be successfully used. Numerous seal types have delivery times of up to three months, and in recent years, it has become especially evident that supply chains can be vulnerable for geopolitical reasons such as wars or pandemics. This makes it desirable to enable distributors to locally produce spare parts so as to avoid or reduce costly machine shutdown times. The functional tests described in this paper show that such a local production using inexpensive machinery and a single raw material can be a realistic option.

Similar results were achieved by investigating two-component rod seals, consisting of a TPU component and an NBR (acrylonitrile butadiene rubber) component, both additively manufactured [7][8].

In the future, these tests will be continued with higher pressures and sliding distances after a redesign of the test rig. It also seems advantageous to conduct further functional tests with parts made from materials optimized for the application that are already used for the conventional production of rod seals.

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