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Vacuum compatibility of ABS plastics 3D-printed objects

T. CHANELIÈRE

Laboratoire Aimé Cotton, CNRS, Univ. Paris-Sud, ENS Cachan, Université Paris-Saclay,
91405 Orsay Cedex, France
thierry.chaneliere@u-psud.fr

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Abstract

I pump down ABS plastic objects produced with an entry-level 3D printer. I propose to use KF blanks printed flanges as a testbed to establish a simple procedure for reproducible testing of different printers and raw materials. I show that the outgassing rate of ABS objects can be reduced by two orders of magnitude by applying a layer of Vacseal® surprisingly opening perspectives in high vacuum applications.

I. INTRODUCTION

Additive synthesis revolutionize rapid prototyping by facilitating the production of small series just after the design stage. 3D printing is well adapted to scientific research where custom apparatus and instruments are necessary to explore the unknown. A 3D printer is nowadays a standard equipment in scientific laboratories. The free and open source movement popularizes their use for individuals through fab labs. The most widely available printers use plastic as raw material: Acrylonitrile Butadiene Styrene (ABS) is mostly used. Different polymers are also available like polycarbonate, polyamide, polystyrene... Plastics generally have a poor behavior under extreme conditions: vacuum [5, 1] or high pressure, cryogenic or high temperatures for example. 3D printed objects have poor vacuum compatibility by nature. First, they are porous because of the additive synthesis. Even generic metallic objects have poor outgassing characteristics because multiples pores are created during the growth restricting the technique to titanium and silver which have shown good properties [2, 3] or more recently to 3D-printed Al-Si10-Mg laser melted alloys [6]. Secondly, most of the 3D-printer use plastic as raw materials. Plastics as organic substances outgas massively under vacuum because of their enhance capability to trap molecules contained in the air, especially water and organic molecules [4].

Theses disadvantages should be counterbalanced by the simplicity and the wide availability of the process. This statement motivates me to consider 3D printed plastic objects under vacuum.

The goal of the present paper is actually twofold. Firstly, I'd like to establish a reproducible procedure to test different printers and raw materials. For

this purpose I study ABS plastic KF flanges because ISO-KF standards are available in many labs. I will describe my experimental testbed to characterize the objects under vacuum. I then describe a series of four identical samples and measure their pump-down curves. Secondly, I'll finally show that a layer of Vacseal® sprayed on the inner surfaces of the sample can reduce the outgassing rate by two orders of magnitude after proper baking. I finally question the reproducibility of the printing process by analyzing the pump-down curves of two unreliable samples.

II. TESTBED DESCRIPTION

As a test-sample, I printed a KF40 blank flange. The rudimentary vacuum chamber (see appendix B for details) is simply composed of a tee connecting pipe between the pump, the measurement gauge and the sample. The samples are designed using the OpenSCAD software (see fig.1). The script in appendix A can be adapted to different KF flange sizes.

I printed 6 test-samples that will be systematically evaluated under vacuum. The 3D-printer is an UP EASY 120 from UP3D. The printing thickness parameter is 0.15mm with the maximum filling factor. 3D-printing is not fully perfect and the samples requires a minimum deburring to fit the KF centering ring and ensure a tight contact of the O-ring. Deburring should be done with precaution to avoid the opening of air pockets as I will discuss in V. I finally slightly polish the flange surface with a fine sandpaper to reduce the surface roughness from the growth process. The O-ring is soaked with a thin layer of vacuum grease. The different operations takes few minutes. A typical sample is visible in fig. 6.

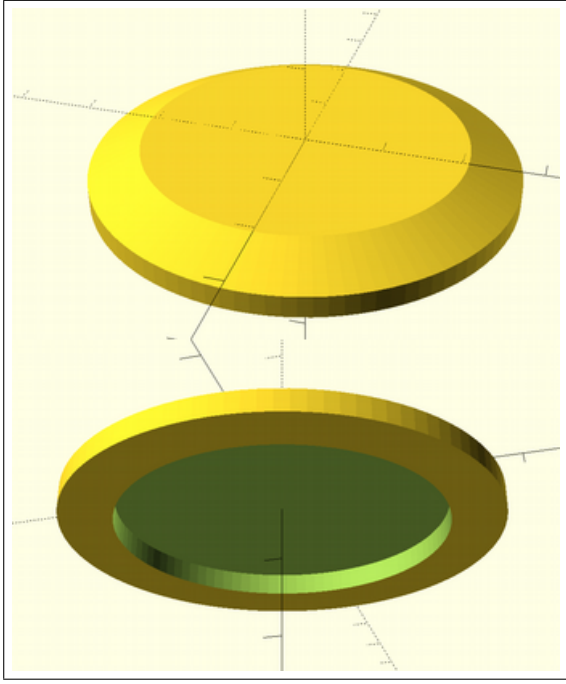


Figure 1: 3D OpenSCAD bottom and top views of the KF40 blank flange used as a test-sample. The script can be found in appendix A.

III. ABS SAMPLES UNDER VACUUM

The 6 test-samples (labeled from 1 to 6) are now ready for measurement under vacuum. A complete study would certainly require a mass spectrometry during the pump down [4]. Being motivated by a certain frugality compatible with the open science philosophy, I have decided to keep a minimal setup with a turbo pump and a gauge. The pump-down curves are automatically recorded during ~ 20 hours to properly estimate the ultimate pressure. In this section, I focus on samples 1,3,5 and 6. The others, 2 and 4, will be discussed in V as special cases.

For sample 1, as we can see in figure 3, I reach the pressure range of few 10^{-4} mbar. A stainless steel blank flange is used as a reference to evaluate the intrinsic performance of the pumping system and the vacuum chamber (black in fig. 3, reaching few 10^{-7} mbar). To objectively evaluate the ultimate pressure as a figure-of-merit, I fit the pump-down curve with the following formula:

$$P(t) = P_{\text{atm}} \exp\left(-\frac{t}{\tau}\right) + Q_0 t^n + P_f \quad (1)$$

Pressures are expressed in mbar and time in seconds. The first term is the initial volume evacuation (P_{atm} is the atmospheric pressure). The second one represents an effective out-gassing term where the exponent n is left as a free parameter to phenomenologically accounting for both, desorption and diffusion. The last term P_f is the floor pressure characterizing the sample under test. For samples 1,3,5



Figure 2: Typical test-samples after printing (top), after polishing with fine sandpaper (middle) ready for testing. Same sample with a Vacseal® varnish coating (bottom) giving a glossy finish (after baking, see IV).

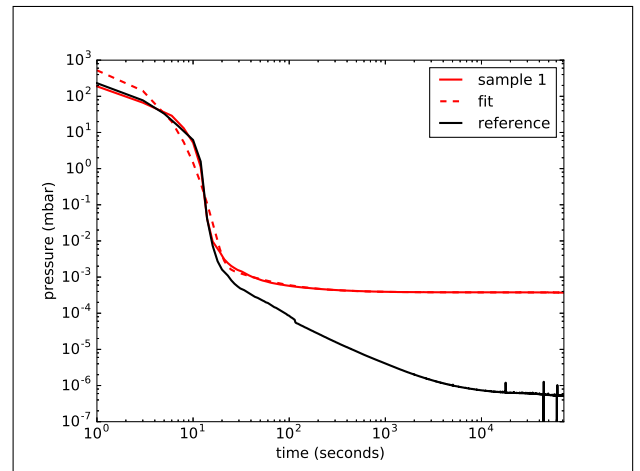


Figure 3: Test-sample 1 pump-down curve (red). This latter is fitted (dashed red) with the formula discussed in the text. A stainless steel blank flange is used as a reference (black).

and 6, I respectively obtain $P_f = 4 \times 10^{-4}$, 5×10^{-4} , 8×10^{-4} and 6×10^{-4} mbar as final pressure. This shows a certain consistency in the sample preparation. The fitted parameter values are summarized in the following table:

	sample 1	sample 3	sample 5	sample 6
τ	1.5	1.6	1.5	1.5
Q_0	5×10^{-2}	6×10^{-3}	7×10^{-3}	8×10^{-3}
n	1.2	0.7	0.6	0.6
P_f	3.7×10^{-4}	5.3×10^{-4}	8.3×10^{-4}	6.3×10^{-4}

The vacuum level obtained using standard ABS plastic with an entry-level 3D-printer are consistent but relatively poor despite the small size of our vacuum chamber. This restrict their use to small objects and/or to rough vacuum applications. I'll now show that outgassing from the surface can be significantly reduced by a proper Vacseal® coating and baking.

IV. VACSEAL® COATED SAMPLES UNDER VACUUM

Vacseal® is a widely available varnish with low outgassing properties. It is commercially available in aerosol spray and can then be applied without special equipment. A metallic coating would be certainly an interesting alternative but they require electroplating which is not direct on non-conductive ABS plastics [4].

The previous samples are first cleaned with alcohol to remove traces of vacuum grease. I then spray a thin and uniform layer of Vacseal®. The coated samples are finally baked at 95°C for 24 hours approximately. The baking temperature is chosen slightly below the melting point of ABS (~ 105°C) but significantly high to allow the out-gassing of the trapped substances. Higher temperature could be tested but one take the risk to soften the sample and distort it during the curing process as we observe during preliminary testing. 95°C as baking temperature appears as good trade-off.

As in III, the pump down curve is recorded to characterize the coated samples. As we see in fig. 4, the vacuum level is significantly reduced by the Vacseal® coating reaching typically few 10^{-6} mbar not so far from the minimum measurable pressure with a stainless steel blank flange (few 10^{-7} mbar).

Using the fitting procedure described in III, I now obtain $P_f = 2 \times 10^{-6}$, 1×10^{-6} , 2×10^{-6} and 2×10^{-6} mbar as final pressure for samples 1,3,5 and 6 respectively. The different fitting parameters are summarized in the table:

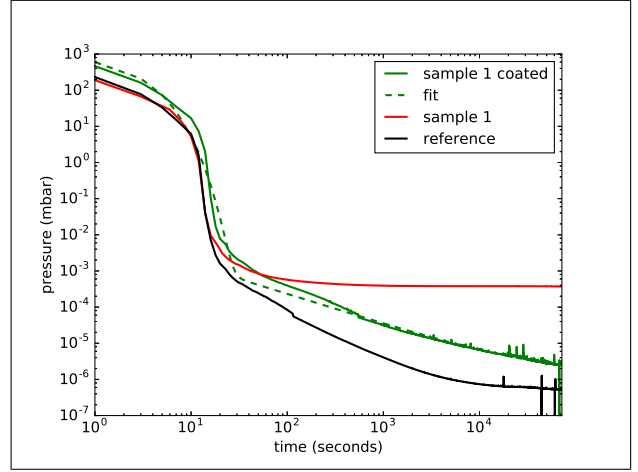


Figure 4: Test-sample 1 pump-down curve after Vacseal® coating (green). The red curve correspond to the uncoated sample as in fig. 3 (in black, the reference curve).

	sample 1	sample 3	sample 5	sample 6
τ	1.9	1.7	1.9	1.6
Q_0	1×10^{-2}	9×10^{-3}	1×10^{-1}	7×10^{-3}
n	0.8	0.9	1.1	0.8
P_f	1.6×10^{-6}	1.5×10^{-6}	1.6×10^{-6}	1.9×10^{-6}

The coating procedure makes the different samples compatible with high vacuum and corresponds to a significant improvement of the outgassing by two orders of magnitude. This approach as a post-processing of ABS plastic printed objects is clearly promising.

V. PROCEDURE REPRODUCIBILITY

Among the six prepared test-samples, four of them consistently give the same vacuum level when coated and uncoated. The whole procedure is nevertheless not fully reproducible as I will discuss now. As observed in fig.5, the samples 2 and 4 have a different behavior as compared to the series 1,3,5 and 6 discussed previously.

Sample 2 is the worst. First of all, after the deburring and polish process, it reaches only few 10^{-3} mbar as compared to few 10^{-4} for the 1,3,5,6 series (see III). I attribute this to gas pockets that are produced during the deburring stage. This latter is necessary because of imperfections appearing during the growth. This roughness can certainly be reduced by employing a more sophisticated printer with well controlled growth conditions. In that case, deburring would not be necessary. A light polishing of the flange surface would be certainly sufficient thus significantly reducing the risk of creating gas pockets.

Coating sample 2 with Vacseal® actually improves the final vacuum pressure but the pump-

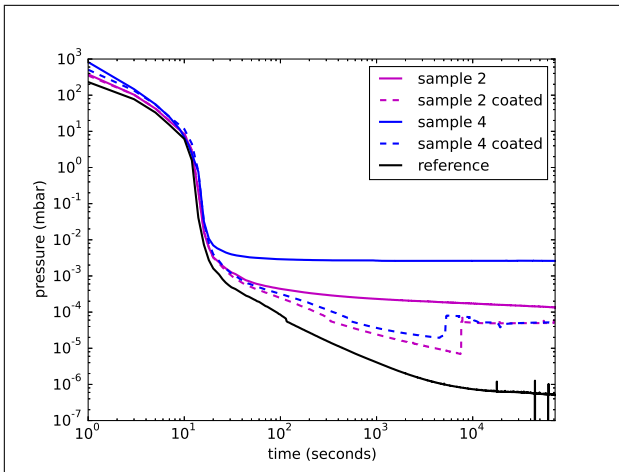


Figure 5: Test-sample 2 (in magenta) and 5 (in blue) pump-down curves after printing and polishing (solid lines) and after Vacseal® coating (dashed). Sudden jumps in the curves correspond to the opening of gas pockets.

down curve is perturbed by a abrupt jump of the pressure corresponding to the sudden opening of a gas pocket. The same behavior is observed for sample 4 only when coated even if this latter has not revealed any suspicious performances when uncoated by reaching few 10^{-4} (as my reference 1,3,5,6 series).

The results obtained by the four reference test-samples are sufficiently encouraging to validate the procedure. Nevertheless, the reproducibility has to be questioned as revealed by two samples showing very limited vacuum compatibility. The goal of the present report is to give points of comparison in that sense.

VI. CONCLUSION

I have described a procedure that is conceived to be reproducible and easily accessible in different labs. This should allow a direct comparison of printer models and raw materials (plastic or metallic). Plastic objects can be directly used if their have a limited outgassing surface (feed-through or sample mount for example) and/or if a large pumping capacity is available.

The goal of the present paper is to motivate researchers to investigate the vacuum compatibility of small parts produced by additive synthesis with a minimal testbed. Plastic objects are clearly the worth case scenario under vacuum. Their incomparable flexibility of use and availability should nevertheless trigger more studies.

I show for example that a proper coating of Vacseal® varnish significantly extend the use of plastic parts under vacuum. This approach can certainly be extended to metallic deposited layer. In that case, the present study offers a point of comparison.

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A. OPENS CAD SCRIPT FOR A KF40 BLANK FLANGE

The dimensions have been slightly adapted from the KF standard to account for imperfections during the printing process. They may change for different printers.

```
A=55;
B=41.2+.4;
L=6;
H=2.8;
fn_val=100;
difference(){
union(){
  cylinder(L-H,B/2,A/2,$fn = fn_val);
  translate ([0,0,L-H])
  cylinder(H,A/2,A/2,$fn = fn_val);
}
translate ([0,0,L-H])
cylinder(H,B/2,B/2,$fn = fn_val);
}
```

B. MEASUREMENT SETUP

A KF25 tee pipe connects the pump, the gauge and the sample. KF25-KF40 reducers are used to adapt the pump and sample diameters. The sample appears in black at the top.

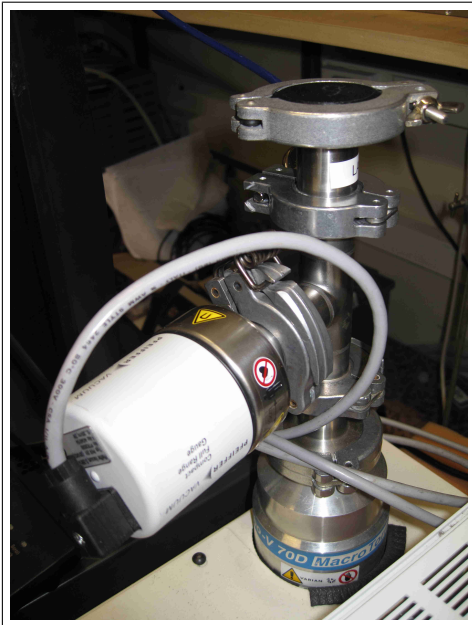


Figure 6: Rudimentary vacuum chamber.

The pump is a Varian Turbo-DRY 65 and the measurement gauge is a Pfeiffer PKR 251.