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THE USE OF AM TECHNOLOGIES FOR HV AND UHV COMPONENTS AND VESSELS

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Abstract

AM (Additive Manufacturing) technology (3D Printing) in plastics and metals has now been in commercial use for over 30 years. However, the application of this technology in vacuum environments has been limited, due to the material porosity and additives used in the manufacturing techniques. This paper reports on the testing and use of FDM (Fused Deposition Modelling) PEEK (Polyether ether ketone) and DMLS (Direct Metal Laser Sintering) metal components inside a UHV (Ultra-High-Vacuum) environment. Specifically covering the use of DMLS to successfully produce a complex vacuum vessel operating at 10^{-6} mbar, as used on the new VMXm beamline at Diamond Light Source. Vacuum testing the vessel has demonstrated that this manufacturing technique has the potential to produce vessels that are capable of holding 10^{-10} mbar.

FDM PEEK

FDM Technology and Material Development

FDM technology has increased in popularity over the last 10 years since the launch of the RepRap self-build hobby machines in 2005. These cheap machines with open source software has allowed hobbyists and engineers to invest in the technology at home and in small offices.

The boom lead to a number of competitors copying the technology and then an increased number of materials on offer. Initially limited to thermoplastics such as PLA (Polylactic acid), ABS (Acrylonitrile Butadiene Styrene) and Nylon, now materials include high percentages of fillers such as wood and metal to generate different material finishes and properties. In 2015 the German company INDMATEC [1] (now Apium) produced the first FDM PEEK material.

FDM PEEK

PEEK is a popular material to choose when looking for a vacuum compatible plastic; it has low moisture absorption, good stability and is very strong compared with other plastics. Its most useful property is the high temperatures it can withstand, thus enabling PEEK components to go through the vacuum bake out process.

Having the ability to produce complex parts locally and quickly would clearly be a benefit. However, the common low cost FDM machines cannot reach the temperatures required for the production of PEEK parts.

Specialised FDM machines have been produced to combat the issues with high temperature heads, heated beds and enclosed build areas.

Vacuum Testing FDM PEEK

The vacuum group at Diamond tested 19 samples supplied by Apium. The samples were specified by Apium as 100% build density and were in the form of flat tensile test samples with a surface area of 1.42 cm^2 each.

Testing the samples uncleaned, as delivered direct from the supplier, the outgassing rate reached 1.33 x 10^{-6} mbar l s^{-1} cm^{-2}. Ultrasonic cleaning in IPA (Isopropyl alcohol) made the outgassing increase to 1.7 x 10^{-6} mbar l s^{-1} cm^{-2}. After baking at 150° C for 12 hours the outgassing rate improved significantly to 3.98 x 10^{-11} mbar l s^{-1} cm^{-2} meeting our specifications for use in UHV.

These results compared favourably to machined PEEK components and it is possible that they could be baked longer to improve outgassing rates.

Forming Components Using FDM PEEK

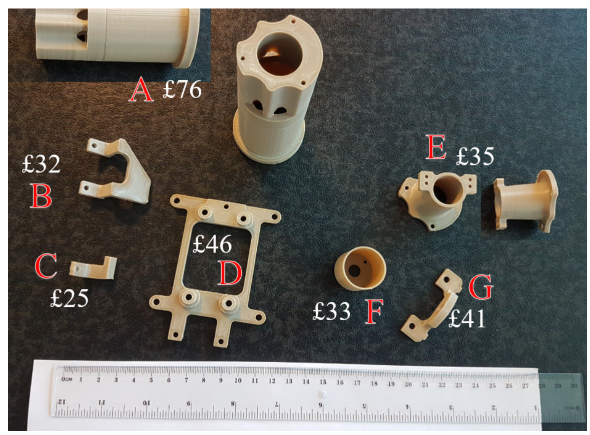

Figure 1: PEEK components produced using FDM, with costs in sterling 2017.

Seven components were ordered from Apium and a visual and dimensional inspection was carried out on five of them (A-E).

The visual inspection clearly showed some build issues:

- Poor surface finish
- Unpredictable distortion
- Unpredictable component shrinkage

Detailed inspection reports were carried out on the components using a CMM. Although many feature dimensions were within tolerance, components B, C and D (Figures 1 and 2) were distorted and warped by up to 1 mm in the extremes. Component E showed no signs of warping and most dimensions within ±0.1 mm. Component A showed no signs of warping, but the internal diameter was 1 mm undersize and the outer flange diameter 0.5 mm oversize.

Surface finishes also varied considerably; the base plate build surface came out polished while all other external

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surfaces were rough and had cavities - adding doubt to the 100% build density.

Hole sizes under 5mm diameter tended to be produced undersize.

Figure 2: Component D, shown with base plate build surface facing upwards. Clear warping can be seen in the reflections.

Cleaning and Baking FDM PEEK

No issues were discovered through the washing and baking process.

DMLS VACUUM VESSEL

Reasons for Considering DMLS

The 2^{nd} use of AM technologies on the VMXm beamline was the sample vessel. This vessel is complex, as many sensors and detectors converged at the sample position as well as an exit window large enough to cover a 100^{o} inclusive diffraction cone (Figure 3).

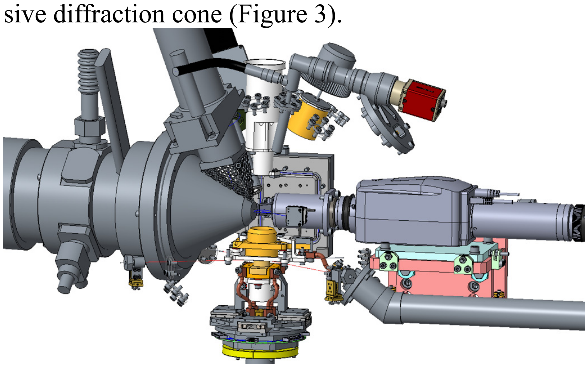

Figure 3: Equipment converging at the sample position on the VMXm beamline at Diamond Light Source.

At this time, the specification for base pressure was 10 mbar (this specification later changed to 10^{-4} mbar). DMLS suppliers were advertising 100% build densities, and existing applications already used the manufacturing process to contain fluids and gasses above 1 bar pressure differential.

A vessel design was created that could be fabricated using standard manufacturing techniques (Figure 4). This was quoted using fabrication in stainless steel and DMLS in aluminium. Note; fabrication was not available in aluminium due to welding restrictions.

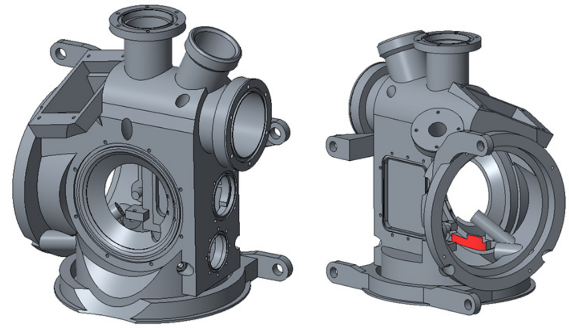

Figure 4: VMXm fabricated sample vessel design.

Finding a Supplier and Choosing the Material

Although DMLS is now an established technology there are still only a small number of suppliers and their responses varied enormously. Our chosen supplier CA Models [2] agreed to take on the work and finish the component to our specification with minimal changes, that we could implement ourselves.

The material chosen was aluminium as we only required O ring seals, the build times are quicker and the clean-up and 2^{nd} op machining operations are easier. A stainless-steel version of this vessel would double the cost.

Price comparison showed the stainless steel fabricated vessel would be £19,750-£22,600 and the DMLS vessel in aluminium with secondary machining operations to be £12,350. The decision was made to progress with the DMLS solution.

Design Freedom

Once the decision to go ahead with AM technologies had been made, the design could now be revised to suit the manufacturing technique (Figure 5). Flowing curves and gradual changes in wall section suit this manufacturing process much better than sharp edges and ninety degree wall changes.

With this in mind, a sphere was chosen as the base shape. From this all features were either cut into, or extruded out, with generous fillet radii added at all wall intersections. The wall sections varied from 3 mm to 12 mm.

This method of manufacture also allows for undercuts and hard to access internal cavities. Whilst these features can be designed into the vessel, access for tools needs to be considered for the removal of the support material after build.

Another advantage is that many additional features can be added to the vessel, effectively free of charge, as part complexity does not change the price. Many more brackets, view ports and other features were added in to the DMLS version compared with the original fabricated design.

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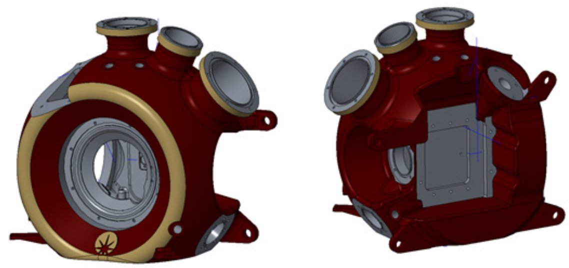

Figure 5: VMXm sample vessel designed for DMLS.

Build Errors and Issues

With a vessel of this complexity, regardless of the manufacturing method, errors are likely to occur. At the start of the project it was decided to create a prototype which could later be used as an off-line test vessel. A second vessel would then be built for use on the beamline.

An AM plastic vessel could have been produced to test for fit, but this would not have proven the technology as a vacuum vessel.

After delivery, inspection and leak testing the list of errors on the prototype vessel were as follows:

- Failed build due to power cut– *supplier remade the part free of charge*
- Thread breakthrough – *supplier locally welded*
- Some 2nd Op machining was omitted from the drawing – *Our technician carried out the machining*
- Missing O ring groove – *Vessel sealed with sealant*
- Internal clash SEM secondary detector – *Technician filed vessel*
- External clash (slits) – *Technician filed part*
- Fluorescence detector hole not machined – *Technician machined hole*
- Access to internal polishing and support removal – *Supplier observation; new vessel had re-entrant bores fabricated*
- External painting prevented bakeout – *New vessel was unpainted*

Testing and Vacuum Performance

The prototype vessel after being modified, glued and welded, achieved a vacuum pressure of 10^{-5} mbar, well exceeding the initial specification of 10 mbar and now exceeding the new specification for the vessel of 10^{-4} mbar. This vessel had only been wiped clean with alcohol as a pump and bake was not possible with the painted surfaces.

We also tested the vessel that failed during build. This had not been painted and could go through a thorough cleaning process with ionised water. The vessel was then pumped and baked and placed inside larger vessel to check outgassing rates.

Results showed no difference detected from standard aluminium with 3.9×10^{-12} mbar L s^{-1} cm^{-2}.

Current Situation

The production vessel was installed onto the VMXm endstation in May 2018 ready for the first experiment (Figure 6). No issues have yet been discovered and the vacuum has reached 10^{-6} mbar comfortably.

The prototype vessel is used as an off-line testing vessel for new beamline equipment and upgrades.

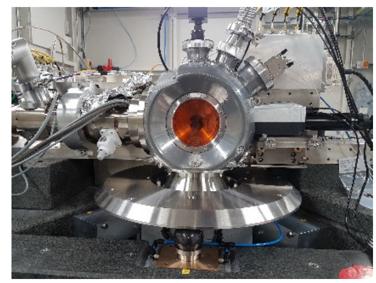

Figure 6: VMXm Sample vessel installed into end station.

Final Version Specification

- Manufactured by CA Models
- Material: Aluminium
- Mass: 4 kg
- Machine: SLM 500HL
- Build time: 60 hours
- Dimensions HWD: 262 mm x 300 mm x 200 mm
- Wall section: 3 – 12 mm
- 17x Equipment ports
- 3mm X-Ray input hole and 100° diffraction cone
- Internal and external features for mounting additional equipment
- 70 Tapped Holes
- Polished internal surfaces

CONCLUSION

AM technologies have come along way in the last 10 years, but it is not always the solution that it is cracked up to be. The FDM PEEK sounded great but in reality, the quality of the components is not up to scratch for many applications. Overall, this process is cheap and offers a quick turnaround. Components are vacuum compatible and survive the cleaning process. Complex geometries can be produced but the end results can be unpredictable.

Not yet ready to be used as a substitute to machined PEEK components but works as a quick replacement when geometry is not critical.

On the other-hand DMLS offers the ability to produce a very complex vacuum vessel in aluminium quicker and cheaper than conventional methods suitable for HV. Changing the material to stainless or coating the seal faces will allow for metal seals to be used and the vessel has the capability of being used for UHV applications 10^{-10} mbar.

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REFERENCES

[1] INDMATEC 2015, renamed to Apium Additive Technologies GmbH, Willy-Andreas-Allee 19, 76131 Karlsruhe, Germany, https://apiumtec.com/en/home

[2] CA Models, AFS (Scotland) Limited, 15 Borrowmeadow Road, Springkerse Industrial Estate, Stirling FK7 7UW, http://www.camodels.co.uk/