The scope of additive manufacturing in cryogenics, component design, and applications

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The scope of additive manufacturing in cryogenics, component design, and applications

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Abstract. Additive manufacturing techniques using composites or metals are rapidly gaining momentum in cryogenic applications. Small or large, complex structural components are now no longer limited to mere design studies but can now move into the production stream thanks to new machines on the market that allow for light-weight, cost optimized designs with short turnaround times. The potential for cost reductions from bulk materials machined to tight tolerances has become obvious. Furthermore, additive manufacturing opens doors and design space for cryogenic components that to date did not exist or were not possible in the past, using bulk materials along with elaborate and expensive machining processes, e.g. micromachining. The cryogenic engineer now faces the challenge to design toward those new additive manufacturing capabilities. Additionally, re-thinking designs toward cost optimization and fast implementation also requires detailed knowledge of mechanical and thermal properties at cryogenic temperatures. In the following we compile the information available to date and show a possible roadmap for additive manufacturing applications of parts and components typically used in cryogenic engineering designs.

1. Introduction

Additive manufacturing or also earlier called 3D printing is gaining rapid momentum in the medical, automotive, astronautics, aerospace and the renewables industries creating new business sectors (GE Additive recently disclosed the world's biggest 1 m cubed 3D printer). Benefits are speed of manufacture with short lead times, reduced material waste and being able to design, shape and produce custom-tailored, complicated and intricate individual components for many critical high-tech applications. Furthermore, multi-axis oriented printing machines significantly reduce the product time to market. On this development path, additive manufacturing has left the stage of prototyping starting in 1983 (3D systems) and is now embracing the volume market. In the following, we will briefly touch on how cryogenics and in a broader sense superconducting technology can benefit from this latest design and manufacturing development.

Additive manufacturing allows the designer to start with a clean sheet of paper and requires a mindset with an "openness" for new ideas and entirely new design approaches. We commonly hear the word "forget all you know of today" or "everything is possible". Designers are now even using

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algorithms to assist them in taking full advantage of the additive manufacturing benefits through software that optimizes component topology and shape (topological optimization (TO)). On the other hand, following a classical design means creating designs that are oriented on conventional manufacturing strategies underwritten by experience, design catalogues and well established norms and standards.

In cryogenics, the conventional metal-manufacturing processes commonly used are:

Forgings, sheet metal forming, extrusion methods (impact and hydrostatic), wire drawing, cladding/bonding (bimetals), tube drawing and their associated fabrication, such as, bending, bulging, die and deep drawing, rolling, spinning, exploiting friction phenomena, and pressure bonding, etc. However, the currently emerging industrial trend points towards making larger parts for bigger machines but with reduced component mass, if possible, by using high-strength materials or if applicable, by using light-weight superalloys, specialty alloys and zirconium and other related alloys or by choosing a metal forming process that allows one to maintain the desired physical and mechanical properties for the design approach.

It is now safe to say that additive manufacturing will be targeting the volume production of making metal parts and components that to date have not been possible using the conventional technologies mentioned above [1]. We now have the capability of using a layer by layer material build up strategy with the following methods:

- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Fused Deposition Modelling (FDM)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Electronic Beam Melting (EBM)
- Pointwise Spatial Printing (PSP)

(further processes are in preparation by industries).

Different processes are now available depending on the specific design task. Additional thermal and/or deformation methods may also be employed to enhance the additively manufactured component properties (e.g. Hot Isostatic Pressing (HIP) or heat treatments/annealing/sintering).

It also needs to be mentioned that some of these processes require the support from the gas industry to ensure material integrity/quality. The reason is that in most cases, protective gases are required during printing and gas purity in the chamber may play an important role. Laser Metal Deposition (LMD) for example, is used for cladding and for structural repairs and requires the use of gases like argon, helium and nitrogen. The level of oxygen and/or the humidity in the production chambers can play a very significant role in maintaining the designed material properties [2].

2. Cryogenic component design with additive manufacturing – scope of applications

Recently, additive technology widened the application scope by targeting metal structures that range from the micrometer scale up to gigantic structures with diameters of up to 10 m. The production machines for that are currently under development. What metals or plastics based components do we use in cryogenics that can now be manufactured additively?

- Tubes and shells
- Cryogenic suspension and support systems
- Bimetal structures
- Structures for impellers or pumps, valve stems
- Cooling tubes, vials, seals and heat switches
- Heat pipes
- Thermal batteries / salt structures
- Thermal insulation designs, e.g. for HTS structures

- Micro heat exchanging structures / microchannels
- Salt pills and special structures for ADRs
- Porous plugs
- Gas storage in high porosity structures
- Squid insets [3]
- Superconducting wires / superconducting coils / magnet / cold mass support

To apply additive manufacturing technology to cryogenics we need to have a deep understanding of how these materials behave at cryogenic temperatures and validate their suitability for use in vacuum, e.g. with respect to outgassing. But we also need to know which available materials are best for the application as well as from the materials processing point of view. Designing for cost will be different from what we know it today. Furthermore, reliable computational modeling techniques need to be developed so that our design goals are met. Apart from the standard metals, the scope now also includes ceramics, rare earths, most likely the hard materials of carbide structure, light weight alloys and in the future, some superconducting bulk and wire shapes. What is urgently needed about additive materials, for them to be accepted is shown in brief below:

- General material characterization
  (strength, degradation, fatigue, outgassing, stress relief, porosity, etc.)
- Revisiting and defining inspection and methods, e.g. CT
- Repeatable / certifiable properties, porosity control, surface finish
- Structural repairs of printed structures
- Thermal cycle testing
- Metal joining methods (gluing / welding etc.), dissimilar materials
- Sustainability of materials
- Creation of new cryogenic superalloys
- Development of thermal barrier coatings
- Development of surface structures with high reflectivity

3. What we need to know for cryogenic applications

From the global material research teams test results are required for:

Physical parameters: Electrical resistivity, specific heat, thermal conductivity, thermal expansion and magnetic susceptibility, magnetic characteristics in general, and for plastics, high voltage insulation properties and outgassing, etc.

Mechanical parameters: Ultimate tensile strength, yield tensile strength, compressive strength, elongation, elastic modulus, impact strength, fracture toughness and fatigue strength, etc.

Besides machining, metal joining questions need to be answered as well, in particular how to make welded joints, how reliable are those e.g. with respect to fatigue. Another more specific example would be to better understand the anisotropy of properties due to the layer build up directional effect. Micro and macrographs are needed to qualify the process. This raises the question on which labs and institutions are available to characterize those materials. It may be necessary to run the latter through international round robin testing labs, as we did for SS 316 LN and develop new standards.

Most commonly used are the titanium alloys (TiAl6V4 and ELI), the aluminum alloys (AlSi10Mg / Al6061) and Inconel 718 / 625 (nickel based superalloys), Stellite, the stainless steel 316 and 304 family etc., as well as refractory materials, e.g. MoRe, of Alumina.

The manufacturing tolerances that can be achieved mainly depend on the size of the component, whereas smaller components can be produced to tighter tolerances. Since rapid melting paired with thermal expansion and following solidification is involved in the process, the component will change its shape due to the resulting large stress build up that is difficult to control. As digital insight on the manufacturing process becomes more readily available, tolerances can be further tightened.

Components, for example made by selective laser melting show a tolerance range between 50 to 100 µm or lower, provided machine parameters and stress build up is the same for each production run. For larger components, the initial stress induced deformation after printing may be about 0.2 to 10 mm, but as mentioned, this value can be reduced to the µm level once the process parameters are well defined.

A further process variable is the particle size. This needs to be chosen carefully and depends on the available machine parameters and on supplier information (usually in the 20 µm range). When targeting microarchitectures, particle sizing ranges from 30 to 50 nm are possible [4]. The following two examples show what to expect.

3.1. Metals, example: thermal conductivity of additively manufactured TiAl6V4

We measured the thermal conductivity of an additively processed part of TiAl6V4 alloy made by Selective Laser Sintering in the range of 300 to 3.27 K. The graph in Figure 1 shows a family of curves comparing bulk to additively manufactured alloy. For reasons of comparison, bulk Inconel 718 is included in the figure since Inconel is well-suited for additive manufacturing and cryogenic applications, as mentioned. The additively manufactured alloy shows a clear difference to bulk. There is no explanation yet possible on why the shape of the curve departs from bulk as shown in Figure 1. However, it is quite obvious from the way the alloy is formed that grain boundaries would tend to inhibit thermal conductivity at very low temperatures. At 3.27 K the measured thermal conductivity is nearly half of bulk. This is advantageous if the component is intended for use in the temperature range it is designed for, for example, when using it as a typical Titanium support rod with typically 4 mm diameter and length of 150 mm with threaded ends. On the other hand, the alloy may show higher heat loads at temperatures above 140 K. As compared to the difference to bulk, it is known that the thermal conductivity during the layer build up depends on many factors, e.g. grain size, anisotropy and boundary penetration etc. The measurements were executed with the routine and expertise of Y. Yang at the University of Southampton [5].

With regard to high strength materials and lower thermal conductivity it seems to indicate that those structures would reduce the thermal load on a component or cold mass when additively manufactured. The density of TiAl6V4 bulk material is typically approx. 4430 kg/m^3 which is nearly the same at 99.9% when made by a laser sintering process.

Additive manufacturing standards for feedstock materials, process/equipment and finished parts are being developed by ASTM/ISO/NIST etc. Cryogenic engineering still does not have any reference data yet on achievable mechanical properties. Initial room temperature test results however suggest that the material strength may be high and somewhere in between of what we get for conventional casting and forged bulk. Although we often do not exploit the material strength improvement at cryogenic temperatures, we still need to know the safety margin we can factor in. How does that compare to the additively made plastics?

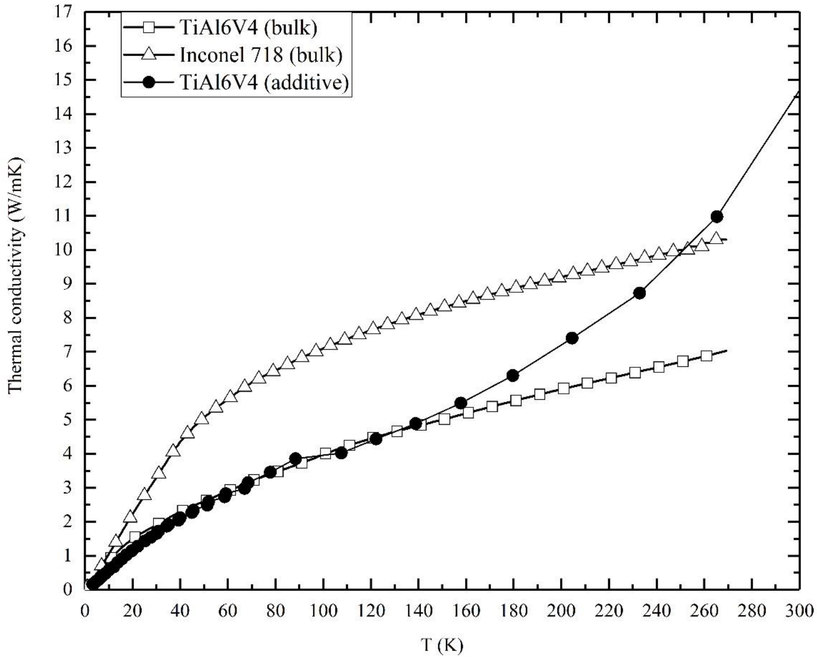


Figure 1. Thermal conductivity comparison of additively manufactured TiAl6V4, normal interstitial, T-range 1 to 300 K with TiAl6V4 bulk [6], [7] and Inconel 718 [6].

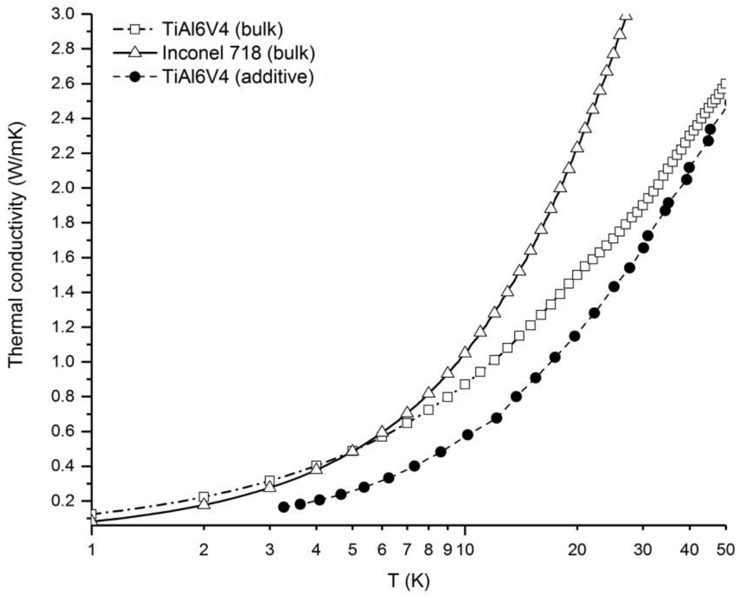


Figure 2. Thermal conductivity in the T-range 1 to 50 K.

3.2. Cryogenic properties of plastics materials

It was the team at KIT (ITP-Institute for Technical Physics) that first looked at the physical and mechanical properties of polymers at cryogenic temperatures [8, 9]. The main drivers for that effort were to arrive at a better understanding on how those additive polymers can be used with HTS components and for space and aerospace applications. As was expected polymers in cryostats have to be used with caution. In the KIT tests, component design modelling was done in 2 ways, using Fused Deposition (ABS (Acrylonitrile-butadiene-styrene)) and Polyjet modelling, using an acrylate photopolymer (VeroWhite®). The current test results of the material properties (tensile / compression / thermal expansion) for different specimens with those two printing methods is given below in figures 4 and 5. KIT/ITP routinely measures material properties from room temperature down to cryogenic temperatures. Figure 3 shows the 3D printed specimen geometries for tensile (left), compression (middle) and thermal expansion tests (right).

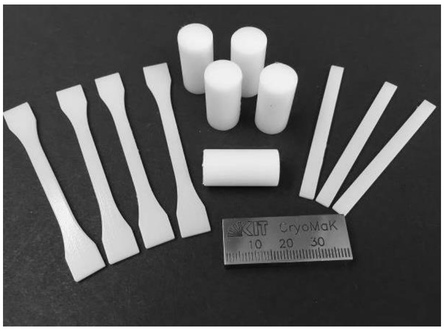


Figure 3. 3D printed test samples.

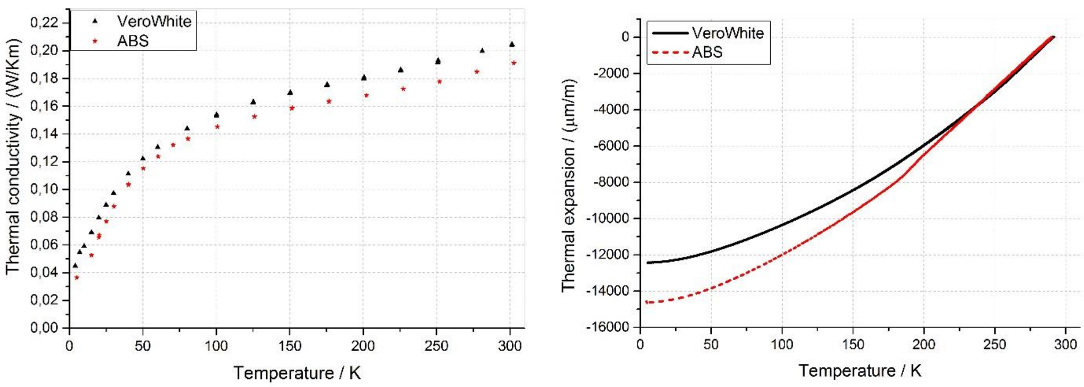


Figure 4. a) thermal conductivity in W/mK, b) thermal expansion in µm/m of VeroWhite / ABS.

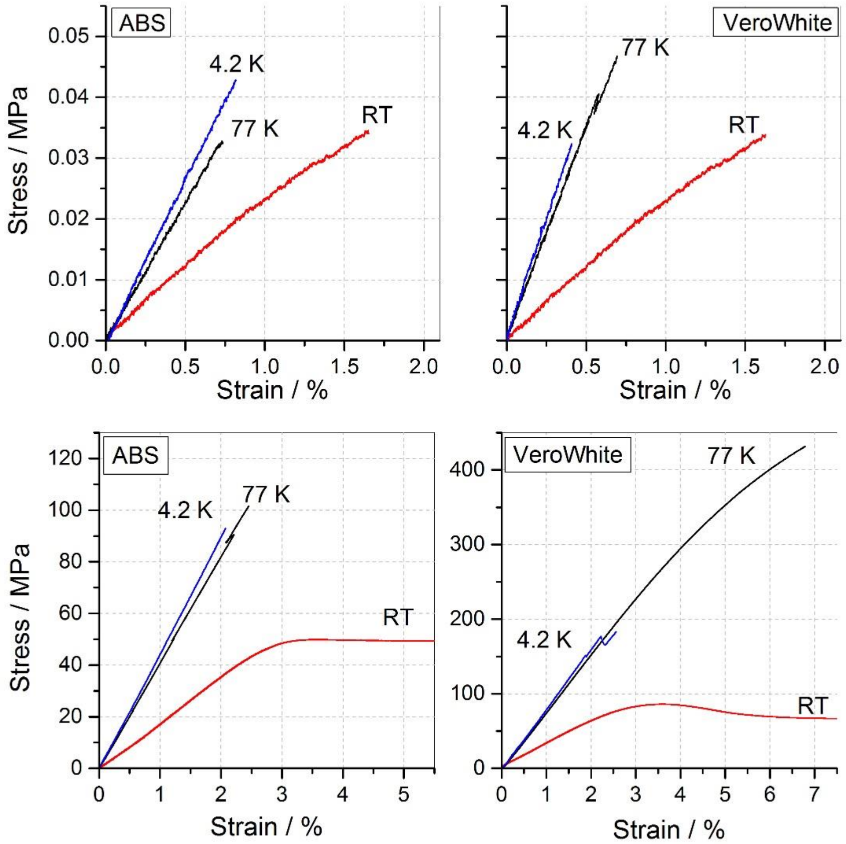


Figure 5. tensile (above, same scale) and compression (below) test results in MPa for 2 different processes.

Compared to room temperature the tensile stresses increase significantly at cryogenic temperatures at 77 K with less effect below 77 K. Note the striking difference in compressive strengths between ABS and VeroWhite.

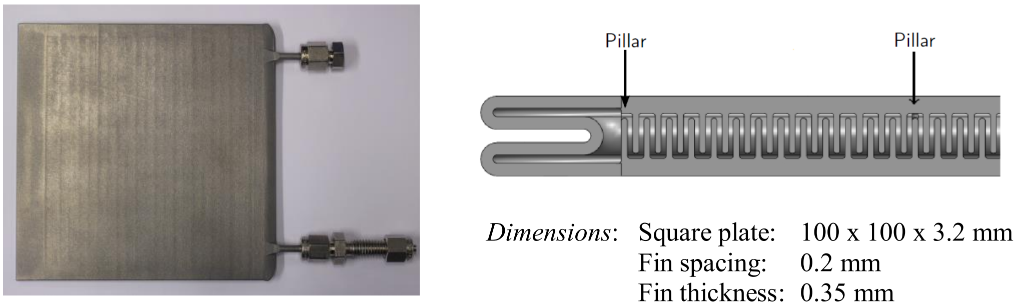
4. Design examples - execution

Although knowledge of the material properties of additive manufactured components is still very limited as mentioned, first components have been built successfully for cryogenic applications.

4.1. Example: A flat-panel gas gap heat switch

The compact flat-panel gas gap heat switch developed by Vanapalli for ESA is an excellent example how additive manufacturing will make its way into cryogenics [10, 11].

Gas gap switches require a very tight fin spacing whereas the high purity copper fins are usually trapezoidal shaped and enclosed by a thin-walled stainless steel tube to increase the ON/OFF ratio. Switches need to be vacuum brazed and are very expensive since many different manufacturing steps are required.



Dimensions: Square plate: 100 x 100 x 3.2 mm
Fin spacing: 0.2 mm
Fin thickness: 0.35 mm

Figure 6. TiAl6V4 gas gap switch with printed gas entry and exit tubes [11].

Several design iterations were necessary to be able to arrive at a configuration for maximum efficiency. To achieve the design goals for example, the structure had to be made with an elongated, convoluted heat path at 3 of the 4 sides of the plate. Further design refinement showed that it was possible to manufacture and maintain a gap spacing of 0.2 mm between the fins. To prevent top and bottom plate from buckling, special pillars were modeled in that allowed for increased structural strength.

4.2. Example: A superfluid helium heat switch for the 1 K temperature range

Figure 7 shows the test setup of the same switch for ON/OFF conductance ratio measurement between 2 copper plates attached to a cold bus that is in direct contact with a 4 K cryocooler. The test switch is prepared to work with liquid helium and continually remains in the ON state and occasionally needs to be OFF. The switch is helium leak tight and has additional, long fill tubes (Ti grade 2 type) welded onto the 3D printed TiAl6V4 tubes as shown in Figure 6. After successful testing and performance characterization with different spring preloads a modified switch will be used as an VTI insert for NMR applications [12] and operating at 1 K.

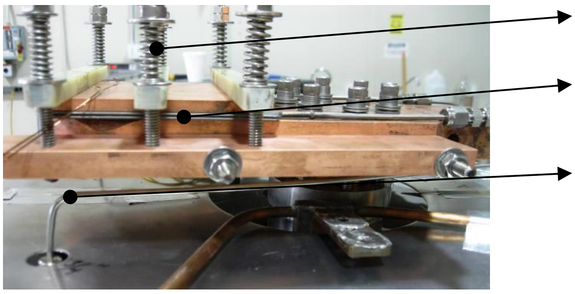


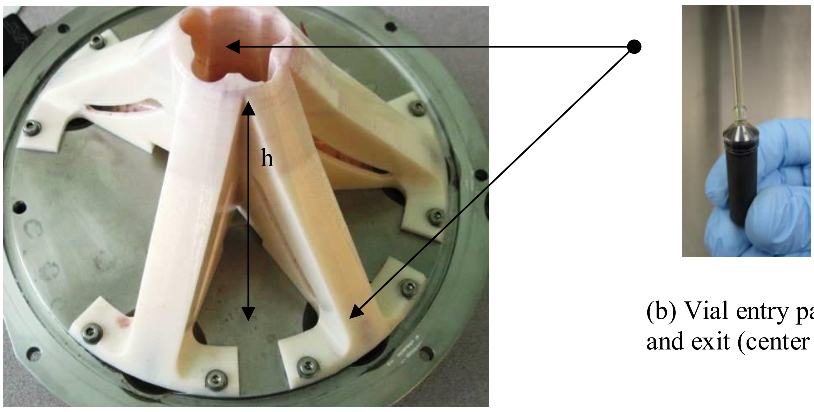
Figure 7. Thermal switch mounted on 3 K cold plate.

One main problem was to minimize the contact conductance between 2 dissimilar materials, TiAl6V4 and copper. Recent experiments with a special thermal interposer material have shown a way in which dT is too small to be measurable [13].

4.3. Example: Cryocooler regenerator packing with additively printed rare earth material
It is now possible to print defined structures using rare earth materials commonly used in cryocoolers. The perfectly packed matrix usually approaches a maximum porosity limit of 30 % for optimally packed sphere beds. It may now be possible to further optimize flow and heat exchange through a packing using additive manufacturing techniques.

4.4. Example: Support structures
The thermal conduction path of supports and suspensions can be greatly increased, reducing the heat burden and at the same time increase the overall stiffness and weight of a component even for large structures, e.g. a torque tube. Further improved designs of the support posts commonly used in accelerator technology seem feasible.

4.5. Example: Complex 3D printed component for use in a cryostat
Shaping complex geometries for cryogenics out of one piece is challenging or cost prohibitive using conventional methods. Additive manufacturing can lead to better ways of shaping those complicated structures. Amongst other 3D printers at GE GRC we use a Stratasys 3D printer with the ABS family based material, e.g. ABS+-P430. However, many other plastics based components can be used like Nylon, Polyetherimides (Ultem®), Polyphenylsulfones (Radel®), or polycarbonates as mentioned. Figure 8 shows a 3D printed vial guide assembly with convoluted insertion shape to ensure cryogenic vials can follow a targeted travel path. Initial worries about contaminating the vacuum because of material outgassing were unfounded.



(b) Vial entry path and exit (center hole)

Figure 8. (a) Vial guide mounted at cryostat top plate bottom, Ø = 250 mm, h = 100 mm, (b) vial.

5. Design challenges and rules with additive manufacture
Unlike with conventional machining, a flat thin plate needs a specially designed support to keep its shape after the material build up. Buckling can be observed after the part goes through a heat treatment/stress relief process. The designer needs to know where to place support structures, how many are needed and of what size to prevent deformation after completing the component build, see figures 9 and 10. The following exemplary figures below from Vanapalli show how to cope with thermal gradients during the stress relief process and why stress build up needs to be understood. 3D printing may require more extensive thermal modelling. In summary, the cryogenic engineer needs additional, specific design guidelines for the use of additive manufacturing of components.

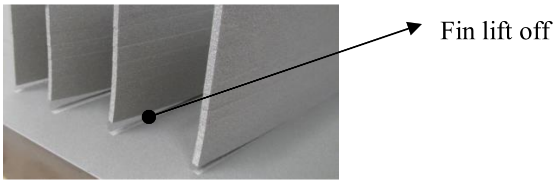
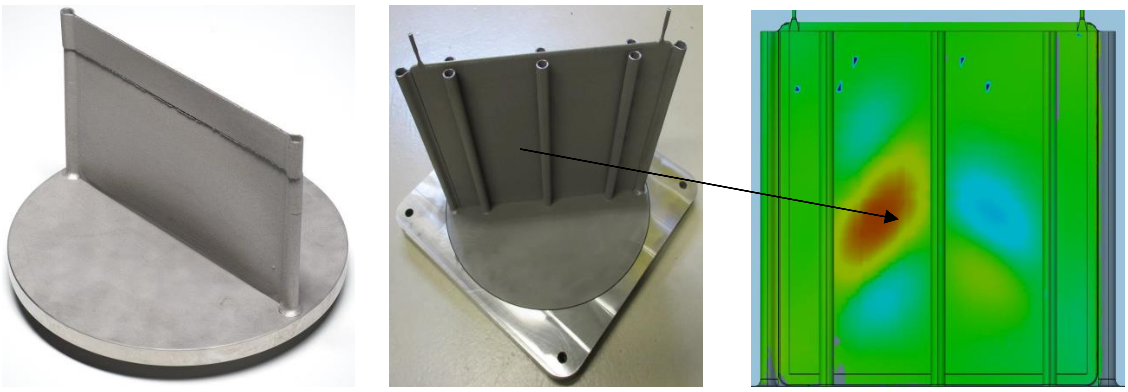


Figure 9. Thin plates (high risk of fins separating from support structure).



(a) (b) (c)

Figure 10. (a) Buckling of product, (b) with added reinforcing pillar structure around part to reduce stresses, (c) analysis.

No buckling of the component was observed before heat treatment. Slight bulging (red section) of the flat surface was observed after completing the stress relief process which revealed that more structural support is needed. When designing for flat surfaces one powder can be entrapped during the manufacturing process at thick to thin transitions. Especially angles can be tricky, while sharp corners may show the tendency to crack.

6. Summary

So far very little only has been done in cryogenics and superconducting technology to design for additively manufactured components [14]. Reduced time and cost to product paired with specific, complicated and novel designs we can't even think of today and reduction of waste should be more than enough incentive. Apart from the flexibility to change designs on the fly there are surprisingly clear and outstanding design benefits that will continue to emerge as industrialization of additive manufacturing accelerates and material characterization progresses. However, possible material anisotropy effects during manufacture need to be understood. This raises the question as to which labs and institutions are available and willing to help out.

References

[1] Frazier W E 2014 Metal Additive Manufacturing: A Review *JMEPEG* **23** pp 1917-1928
[2] Forêt P 2017 If you can imagine it, you can make it *Gasworld* **55** no 4 pp 24-25
[3] Bartolomé E, Bozzo B, Martínez-Pasarell O, Puig T and Granados X 2017 ABS 3D printed solutions for cryogenic applications *Cryogenics* **82** pp 30-37
[4] Saleh M S 2017 Three-dimensionial microarchitected materials and devices using nanoparticle assembly by pointwise spatial printing *Sci. Adv.* **3** e1601986

[5] Yang Y 2017 Rifi (Research Institute for Industry) Faculty of Engineering and the Environment University of Southampton UK
[6] Cryocomp V 5.2 2012 Eckels Engineering USA
[7] Ziegler W T, Mullins J C and Hwa S C P 1963 Specific heat and thermal conductivity of four commercial titanium alloys from 20 to 300 K *Adv. Cryo. Eng.* **8** pp 268-277
[8] Weiss K-P, Bagrets N, Lange C, Goldacker W and Wohlgemuth J 2015 Thermal and mechanical properties of selected 3D printed thermoplastics in the cryogenic temperature regime *IOP Conf. Series: Materials Science and Engineering* **102** doi:10.1088/1757-899X/102/1/012022
[9] Fink S, Fuhrmann U, Lange C, Müller R and Zwecker V 2016 3D Printed Cryogenic High Voltage Devices *IEEE Transactions on Applied Superconductivity* **26** 37700104
[10] Vanapalli S, Vermeer C H and Tirolien T 2016 Additive manufacturing of a compact flat-panel cryogenic gas-gap heat switch *1st International Conference IIR of Cryogenics and Refrigeration Technology* pp 134-142
[11] Vanapalli S, Keijzer R and Buitelaar P 2016 Cryogenic flat-panel gas-gap heat switch *Cryogenics* **78** pp 83-88
[12] Stautner W and Budesheim E 2017 (patent pending)
[13] Stautner W, Chen R, Comment A, Murray J, Ardenkjaer-Larsen J-H and Chen A 2017 (patent pending)
[14] Weiss F, Binz H and Roth D 2016 Conception of a design catalogue for the development of functionalities with additive manufacturing, DS 85-2: *Proceedings of NordDesign*, **2** Trondheim, Norway

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