# Heat Exchanger Design and Manufacture using 3D Printing Technologies

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Abstract – As part of the 3D Printing (3DP) Exploration Program at KLA-Tencor, where the production-related applications and associated benefits are being investigated, one particular use case is being presented in this paper to highlight one major 3DP benefit: the freedom of design which allows the production of parts otherwise impossible to make using traditional techniques. The E-Beam optical column's heat exchanger features inner channels which limit its heat dissipation performances, making it a great candidate for this study. Hence, we used metal 3DP technologies to allow for an increase in structural complexity of the inner cooling channels, rendering a much higher heat transfer dissipation while using a lesser conductive material. In this paper, the challenges, design strategies, printing and test results, as well as main lessons learned will be presented, paving the way to the next generation heat exchanger designs.

## I. Introduction

In the fabrication process of a complex part, in particular those who feature internal channels and void structures, several manufacturing techniques can be used, such as surface machining, milling, EDM, brazing, molding, water jetting, etc. Due to the complexity of such parts, most of the current manufacturing techniques involve also an assembly process, which increase the machining and metrology tools touch-time on each sub-assembly part, leading to an overall impact on part cost and lead time.

One additional consideration when dealing with assemblies are the points of failure which can be introduced at interfaces and joints.

More specifically, internal channels are used for many applications at KLA-Tencor. A few examples are:

1. Vacuum manifolds *(e.g.: wafer chucks, handler manifolds, IC handlers, etc.)*
2. Cooling channels *(e.g.: heat exchangers, chuck heat dissipation, etc.)*

It is also important to note at this stage that the use of 3D printing does NOT preclude the use of conventional machining techniques. In fact, in most use cases, the latter will be used in conjunction with the 3D Printing in order to yield the best overall part performance. We will return on this topic later in this paper.

As part of the KT 3D Printing Exploration Program, we selected a few use cases in order to illustrate the production benefits of 3D Printing for these challenging structures, for which we optimized the design for best thermal performances, as opposed to being optimized for best manufacturability. One of those use cases is presented below.

## II. Use case: e-Beam Optical Column Heat Exchanger

### A. Challenges

In electron microscopy, thermal control plays a vital role in accurate imaging. The imaging of electrons is only possible if the lens remains stable over time at sub-micron level. This is only possible if the interacting machine parts are conditioned under the strictest control of the temperature. This is done by cooling of parts at predetermined locations, through channels filled with a cooling agent (mostly a liquid like water).

Typically, a heat exchanger is a combination of a bottom half with milled cooling channels and a lid which is welded or brazed on top of it. The channel location and dimensions are limited by manufacturing constraints, like tool size and machining vibrations, and also by brazing or welding constraints. In most cases, these constraints lead to sub-optimal cooling performance, in maximum cooling power as well as in uniformity. It also has the potential of adding leaking points at the joints locations, leading to part reliability and customer satisfaction issues.

## B. Objectives

The "quasi-unlimited" geometrical design space of Additive Manufacturing (AM) offers freedom in the location and geometry of cooling channels. As a result, the exchange of heat can be optimized by varying the layout and cross sections. We illustrated this by redesigning a conventional Heat Exchanger, (HEX1, see Figure 1), that is part of an existing electron microscope column.

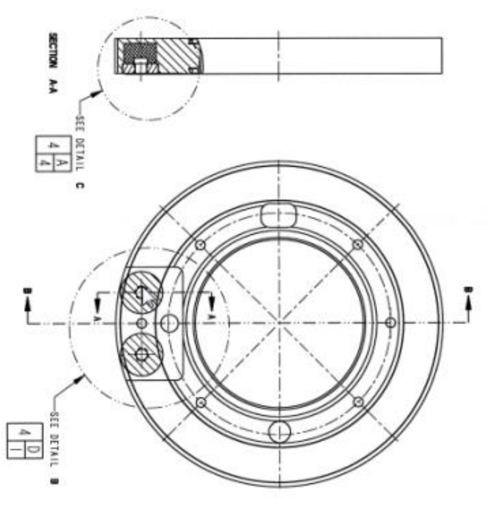

**Fig. 1**: Drawing of the current (reference) Heat EXchanger **HEX1**, made of Aluminum (Al), with ONE cooling channel.

HEX 1 will serve as our benchmark reference. However, as part of an improvement design (not a released revision), a THREE channels Copper (Cu) heat exchanger (HEX2) was designed to increase both surface areas as well as thermal conductivity of the material. Although HEX2 has never been released due to the "dirty" nature of Cu for semiconductor contamination-free applications, this improved design served for this study as an ultimate performance target for this part. In summary, our goal was to improve on HEX1 performance, while keeping the material the same (Al). Matching or exceeding HEX2 performance was considered as a "bonus".

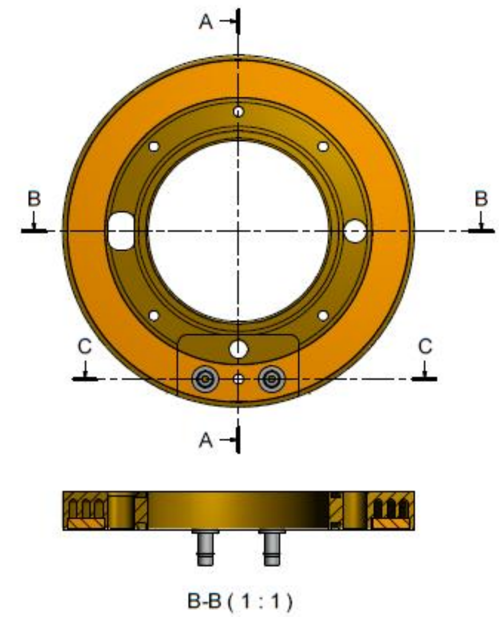


**Fig. 2**: Drawing of the improved Heat EXchanger **HEX2**, made of Cu, with THREE cooling channels. HEX2 is made from solid Cu through various milling, turning and brazing steps. Drawing dimensions also apply to design of **HEX3** (see below).

The first objective was to duplicate the HEX2 design (not performance) using 3D Printing using Selective Laser Melting (SLM) process, leading to HEX3, and to match the form and fit of HEX2. However, since SLM does not allow (yet) to print Cu, we chose to print HEX3 in Al alloy. Therefore, the thermal dissipation for HEX3 was expected to be worse than for HEX2, but better than HEX1.

Both HEX2 and HEX3 have three internal circular channels (Figure 2), flowing in the same direction. The outer diameter is 200mm and it has thickness of 12.7mm with a tolerance for parallelism of 0.02mm. The required roughness (Ra) at the interfacing areas (outer surfaces) is 0.4 µm.

The second objective was to push the design further, and to improve the thermal performance (heat transfer and distribution of heat) of HEX3 despite the use of a lower thermally conductive material (Al vs Cu). The redesign (HEX4, see Figure 3) was also done in Al, using SLM Additive Manufacturing (a.k.a. 3D Printing)

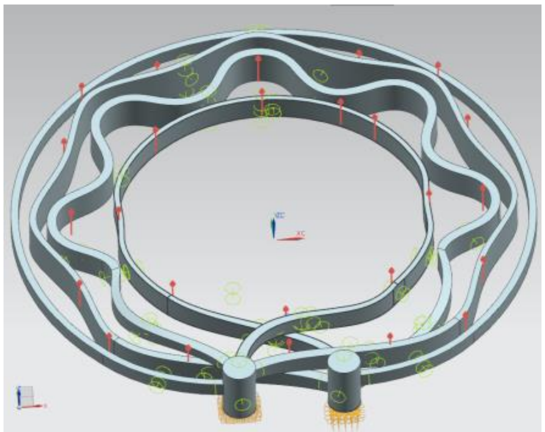

**Fig. 3**: Drawing of the AM re-designed internal channels of **HEX4**, showing channels optimized in width, height, linearly varying cross-section, distribution, as well as flow direction to enhance the heat dissipation.

## C. Simulations

The thermal performance of HEX1, HEX2, HEX3 and HEX4 were simulated using an internal flow of 0.8 l/min and a heat source of 45 W applied to the bottom surface of the heat exchanger. A heat transfer coefficient of 117 W/m/K was used for Al. The average temperature of the heat exchanger was about 1.1K above the cooling water temperature, which is not considered relevant for the electron column performance. However, the tangential temperature gradient of 0.55K is clearly visible in Figure 4 for HEX2 & HEX 3.

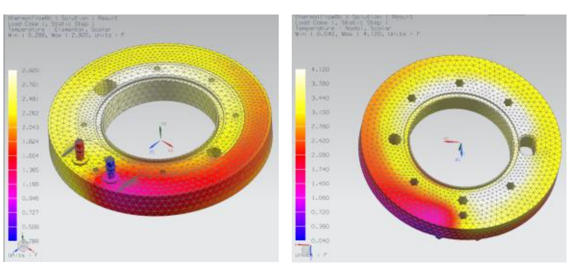

**Fig. 4**: FEA results of thermal inhomogeneity for: LEFT: HEX2(Cu) and: RIGHT: HEX3 (Al). Note HEX2 is shown looking upward while HEX3 is shown looking downward.

At a microscopic level, this inhomogeneous distribution may lead to:

1. Sub-optimal image quality.
2. Longer stabilization (=waiting) time during startup of the machine.
3. Longer downtime during exchange of lens elements in the field due to thermal stabilization during assembly and re-initialization.

Simulations for the re-designed HEX4 (Al) showed very good improvement over the other designs, despite its lower thermal conductivity coefficient material (vs HEX2-Copper).

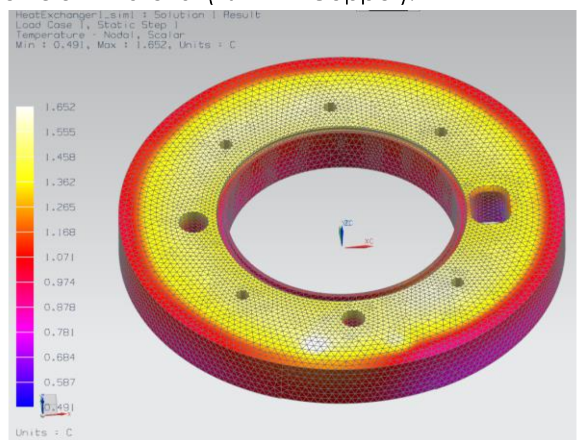


**Fig. 5**: FEA results of thermal inhomogeneity for the AM re-designed HEX4 (Al)

**Table 1**. Summary of the FEA results on temperature inhomogeneity across the top surface of the HEXs.

| FEA Analysis | HEX1 | HEX2 | HEX3 | HEX4 |
|---|---|---|---|---|
| Material | Al | Cu | Al | Al |
| # of channel | 1 | 3 | 3 | 4 |
| 3D Printed? | NO | NO | YES | YES |
| Inhomogeneity [K] | 3.6 | 1.8 | 3.1 | 1.1 |
| Inhomogeneity [% from HEX1 (Current)] | N/A | -50% | -14% | -70% |

The FEA results will be compared to the test results later on.

## D. Manufacturing

Both HEX1 and HEX2 were existing designs, which served as benchmarks for this study. We used HEX 1 from stock inventory for testing. We did not machine HEX2, but simulated its performance.

HEX3 and HEX4 were both 3D printed using SLM technology (Fig.6 Top) which consist of melting successively, layer by layer (10-16μm thick) fine metal powder (5-6μm beads) using a high power fiber laser (Fig.6, Bottom).

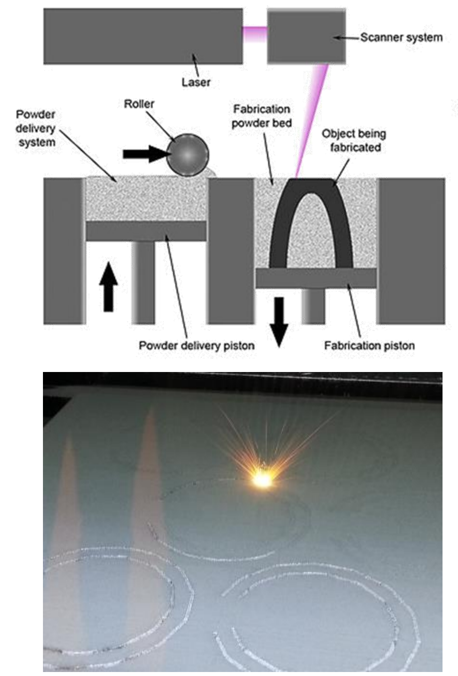


**Fig. 6:** TOP: Illustration of the SLM printing technology. BOTTOM: Picture of laser melting process on a Titanium powder layer.

Just like any other manufacturing process, SLM has limitations concerning design. The main limitations regarding the redesign of HEX4 in Al were:

1. Smallest wall thickness: 0.3 mm *(to avoid leakage)*.
2. Biggest channel diameter: 5 mm *(to avoid sagging of channel roof during the printing process)*

As mentioned in the introduction, the finished part will benefit and require the combination of both machining and AM (SLM) techniques to fully meet the dimensional requirements. Indeed, SLM manufactured parts have several typical characteristics that require post-processing to meet the requirements for a heat exchanger. These are:

1. Internal stresses leading to a surface flatness not suitable for optimal heat exchange.
2. High surface roughness/quality (Ra ~ 3-5 μm), typically insufficient for critical surfaces.


**Fig. 7:** LEFT: Picture of HEX3 straight out of the printer after shot peening (cut outs machined to see internal features). RIGHT: Picture of HEX3 after post machining of critical interface surfaces

As part of the study, we verified the result of the printing process for both HEX3 and HEX4 by opening the enclosed cooling channel in sacrificial parts. It revealed intrinsic challenges of the SLM printing and post printing processes required to ensure cleanliness of the channels from non-sintered/melted powder.


**Fig. 8:** LEFT: Picture of HEX3 channel cut-outs, showing cleared channels with Ra~6 μm. RIGHT: Picture of HEX4 channel cut-outs, showing clogged sintered powder due to post-print annealing process while powder was still left inside the channel after printing.

Another demonstration of the enhanced manufacturing capability offered by the use of both conventional and AM techniques was used for this part, where 3 HEXs were printed at once, stacked on top of one another. Wire EDM was used thereafter to slice the units apart for post processing.

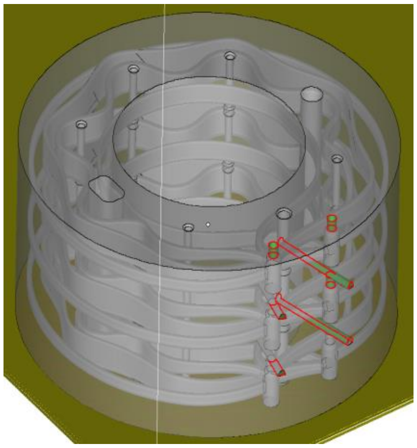

**Fig. 9:** CAD rendering of 3x HEX4 printed together, allowing efficient and cost effective SLM manufacturing. Note that an experienced 3DP manufacturer/contractor will know the additional material to add to the designed part in order to allow for post-processing of the critical surface/features.

### *E. Results*

The following tests were performed on HEX1, HEX3 and HEX4 to validate the FEA simulations.

1. Dimension accuracy
2. Cleanliness (VOC, particle)
3. Leak testing (He)
4. Thermal performances (50W heat load and thermal sensors applied at different locations, with constant and monitored water flow)

The key results are shown in the following table:

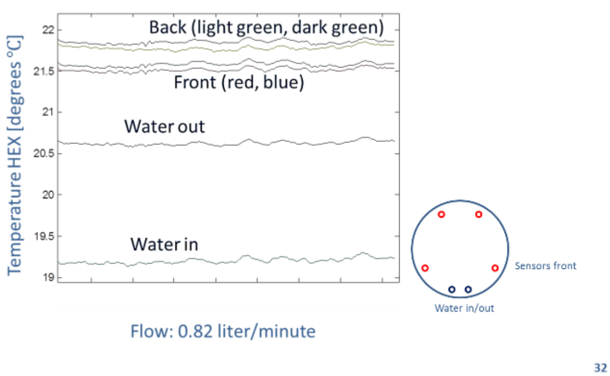


**Fig. 10:** Sample test results from thermal sensors on each HEXs.

**Table 2**. Summary of the test results on temperature inhomogeneity across the top surface of the HEXs.

| Test Results | HEX1 | HEX2* | HEX3 | HEX4 |
|---|---|---|---|---|
| Material | Al | Cu | Al | Al |
| # of channel | 1 | 3 | 3 | 4 |
| 3D Printed? | NO | NO | YES | YES |
| Leak rate (He) | $<10^{-10}$ | N/A | $<10^{-10}$ | $<10^{-10}$ |
| Inhomogeneity [mK/W] | 10.7 | - | 7.2 | 2.0 |
| Inhomogeneity [% from HEX1 (Current)] | N/A | - | -33% | -81% |
| Cost/unit** | $1100 | $1185 | $1420 | $1420 |
| Lead time** | 10wks | 10wks | 5wks | 5wks |

**** Not fabricated nor tested ** Assuming batch pricing***

Note that, compared to the FEA results presented above, the thermal performance relative to HEX1 are better than expected. We can explain this by the increase in surface roughness of the inner channels for the printed part Vs to the simulated perfect surface finish part.

One important consideration in this study was the assessment of cleanliness of the part, both for outgassing and particle contamination. VOC, and particle release rate tests are pending. Since cleanliness is a hard prerequisite for semiconductor applications, we explored on other parts already existing cleaning process for Ti ISO class 1, and similar process are being developed for AL and SS316 and SS304.

## III. Lessons Learned

### *A. Design Rules*

Based on our work with this use case, we have learned the following specific rules which can help the design of other similar enclosed channel parts:

1. Always minimize printed (bulk) material while keeping functionality & integrity.
2. Complexity is free, but considerations are needed on overhanging and self-supporting angles.
3. For heat transfer, maximize surface area by surface rendering and/or layout complexity while keeping structural integrity which does not impact printability.
4. Structural mass can be designed and

variable across the part in order to tune its natural frequencies if needed (e.g.: by adding lattices structures at specific locations)

5. Respect minimum wall thickness for He-leak tightness (e.g.: 1mm for Al, 0.3mm for Ti)
6. Respect minimum channel width to avoid semi-sintered powder and difficulties to clean.
7. Avoid overhanging roof width which may sag during the printing process. Instead, use tapered apex with self-supporting angles
8. Always consider in the design the printing orientation, as well as the powder evacuation routes/path/channels (not sintered powder beads).

### B. *Printing Strategies & Process*

Similarly, some considerations to the printing process should be taken:

1. Ensure proper way to evacuate (blow out) residual non-sintered metal powder from the enclosed channels.

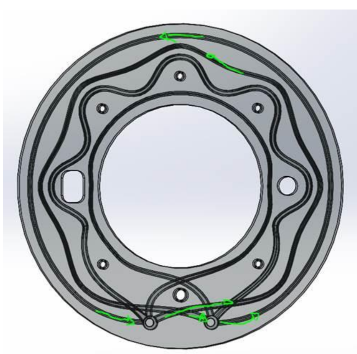

**Fig. 11:** Illustration of a challenging channel orientation which prevents powder from being blown out from the same port since they are on axis from one another. Also, grey areas represent STILL very bulky printed material which increased significantly the cost of the printed part. Tradeoff between mass and heat transfer was made.

2. Consider stacked printing when possible, to save on printing cost and take advantage of the printing volume available (~1 cubic feet)
3. Although still very useful for the post-processing portion of the part, it is possible to avoid the production of 2D shop drawings. Instead, always identify clearly the critical surface requiring specific surface finish, hole taping/tolerances, and other critical dimension tolerances requirements. The printing vendor will figure out the added material required to be printed to account for post-machining/processing. This will be part of the NRE.
4. .STP files and .STL files are generally required at a minimum when requesting a 3DP part to a service bureau.

## IV. Conclusion

Additive Manufacturing provides new manufacturing capabilities that increase the average cooling performance as well as the thermal uniformity of a heat exchanger. We can see, as expected, that the Al-printed HEX3 already presents a 50% improvement over the current single-channel HEX1. But the important "bonus" achieved in this study is to surpass by 25% the thermal performance of the Copper HEX2 while using 2x lesser thermally conductive material. This was achieved through bidirectional flow and free-form meandering of internal channels.

Hence, the current redesign is expected to improve electron column performance, although no tool test has been performed (out of scope) yet. As such, this result confirms the potential of AM to improve thermal functions of key KT parts. It also confirms the enhanced manufacturability power it provides to the conventional machining techniques.

One major benefit clearly identified in this study is the enabling design capability of Additive Manufacturing, allowing the fabrication of structures previously impossible to make. Additionally, beyond the foreseeable cost savings that a more mature AM industry will provide, another major benefits is the lead time reduction (2x shorter), which we can associate to time-to-market for our product applications and solutions. To this end, manufacturing quality and reliability should be developed and explored further, to make AM a feasible and common manufacturing technology for high-tech equipment.

## Acknowledgment

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## Bibliography

[1] F-W Goudsmit, J. Vogels, G.-J. Verstralen, D. Dams and F. Koopman, " AM redesign of a heat exchanger," VDL-ETG Technology and Development BV, March 2015. ASPE 2015.[(Not submitted]