Flexible Thermal Link Assembly Solutions for Space Applications

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ABSTRACT

Absolut System is designing and producing Thermal Link Assemblies (TLA) to be used on space observation programs including CNES IASI-NG and MTG ESA programs.

TLA have the following main functions: to ensure a high conductive coupling between both cryocoolers' cold tips (nominal and redundant) and detectors or cold optical bench, to have a reduced stiffness allowing misalignment and relative dynamic displacement between cold tips and detectors, and to filter micro-vibration coming from cryocooler cold tips to the detectors. The TLA should also be compliant with stringent constraints which are common for space products as follows: to have a reduced mass, to stay inside the static and dynamic Interface Requirement Document (IRD) reduced volume, to be compliant with the cleanliness requirements imposed by the detector proximity, and to survive without performance degradation from the launch loads and thermal cycling.

This paper will present different technical trade-offs performed on the material candidates and production constraints. Current thermal, mechanical, and cleanliness performance of TLA FMs (Flight Model) made of 5N (99.999) high purity aluminum foils and OFHC copper foils. Several on-going TLA designs and performance will be presented, including a TLA made of Pyrolytic Oriented Graphite (POG) foils developed for a 2-stage cryostat (presented in a companion paper [1])

INTRODUCTION

Absolut System is producing cryogenic Thermal Link Assemblies (TLA) for European space observation missions flying pulse tube cryocoolers. TLA are critical equipment in the overall cryostat performance as they shall provide the main following functions:

- Ensure a high conductive coupling between both cryocoolers cold tips (nominal and redundant) and detectors or cold optical bench.
- Have a reduced mass.
- Allow misalignment and relative dynamical displacement between cold tips and detector.
- Stay inside the static and dynamic volumes of the IRD.
- Filter micro-vibration coming from cryocooler cold tips toward detectors.
- Be clean.
- Survive without performance degradation to the launch loads and to the thermal cycling.

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	Thermal conductivity (W/m:K)				
	Aluminum grade				Copper
T (K)	1100	1050	4N	5N	OFHC
50	369	425	948	1087	1173
60	338	389	645	695	816
70	308	354	484	507	646
80	283	326	390	401	558
Purity %	99	99.50	99.990	99.999	99.99

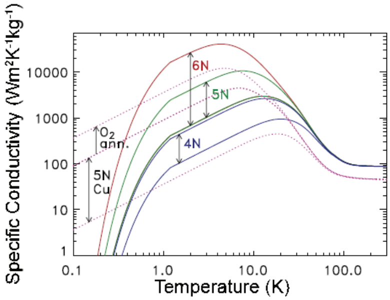

Figure 1. Thermal conductivities (left) and thermal conductivity versus density ratio (right) of OFHC copper and various grades of aluminum as function of the temperature.

MATERIAL TRADE-OFF FOR 50-80 K CRYOGENIC APPLICATIONS

For cryogenic applications of TLA below 80 K, two materials can be selected: high purity aluminum or OFHC copper. As shown in the Figure 1 [2], in the 50-80 K temperature range of interest, OFHC copper offers the highest thermal conductivity.

However, looking at the ratio of thermal conductivity to density, pure aluminum gives a considerable advantage over copper material for on-board applications. High purity aluminum appears the best candidate for TLA attached to the cryocooler cold tip where the mass constraint is very stringent.

Furthermore, in the 50-80 K temperature range, the thermal conductivity of aluminum is less sensitive to the purity, and thus, Al4N or Al5N grades can be selected (Al6N being less common and quite expensive).

Thin foils of Al5N can be sourced with thickness ranging from 50 to 100 µm. The procurement can be made with several hundred meters long foil wounded in coil format.

Since aluminum is more difficult to assemble than copper, high vacuum Electron Beam (EB) welding process is selected (Table 1) because it induces a perfect mechanical and thermal continuity between the foil material and the end-fittings without the use of external filling material, that are generally a source of additional thermal resistances.

Table 1. Feasibility study of assembling processes according to the foils and fittings materials.

Processes available for foil assembly	Aluminum foils and aluminum fittings	Copper foils and copper fittings	Copper foils and aluminum fittings
TIG/MIG	**Good** but not critical on foils	**Good**	**Not feasible**
Press-welding	**Not feasible**	**Very good** no thermal resistance between foils	**Not feasible**
Diffusion welding	**Feasible** with force applied during process	**Good** no deformation and good performances	**Feasible** with force applied during process
Laser welding	**Feasible** but spot welding only	**Feasible** but spot welding only	**Not feasible**
EB welding	**Very good** no thermal resistance between foils	**Very good** no thermal resistance between foils	**Not feasible**
Brazing	**Good** with additional thermal resistance	**Good** with additional thermal resistance	**Good** with additional thermal resistance
Swaging	**Good** with additional contact resistance between foils	**Good** with additional contact resistance between foils	**Good** with additional contact resistance between foils

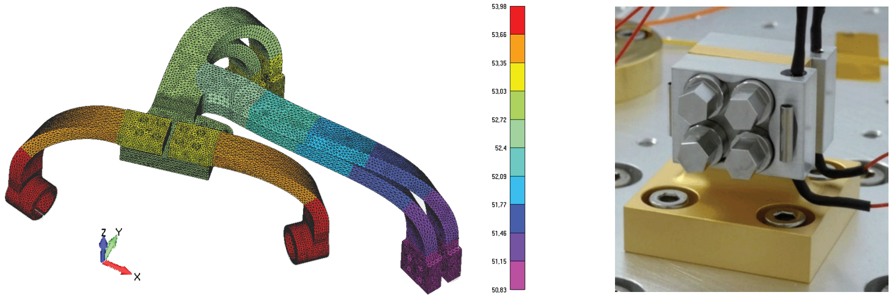

Figure 2. Illustrations of a FEM thermal model (left) and thermal contact conductance characterization at cold tip interface (right).

THERMAL AND MECHANICAL ANALYSES DURING DEVELOPMENT PHASE

Thermal and mechanical performances of the TLA always result in a trade-off of competing requirements. Thus some compromises shall be performed between the thermal performance (primary aim of the TLA) and other mechanical requirements such as stiffness, mass, and robustness to the loads which all depend on the routing of the TLA foils.

Thermal Analyses

An iterative thermal modelling phase is performed taking into account the thermal conductance and AIT requirements for various routed designs. For the thermal analyses, we use FEMAP software with TMG thermal module (MAYA). Thermal analyses are coupled with prototyping mainly performed on the thermal contact conductance measurements at cold tips and detector dismountable bolted interfaces (Figure 2). Thermal contact conductances are then characterized as function of the cryogenic temperature, screws tension, fillers (such as gold foils), mounting and dismounting and thermal cycling impacts.

Mechanical Analyses

The support of FEM analysis is limited during the development phase due to the difficulty to model the mechanical behavior of the flexible TLA composed of a stack of hundreds of foils. For the stiffness optimization, we use prototyping for various routings of the foils stack as illustrated in the Figure 3.

Dynamic displacement tests are also performed to complement the stiffness characterization. During this test, one extremity of the thermal link is fixed while the others are submitted to dynamic displacement in the three axes, from few tenths of a millimeter up to several millimeters. This dynamic test is quite easy and is performed in house due to the low shaker capacity required. This allows for fast reactivity during the design phase.

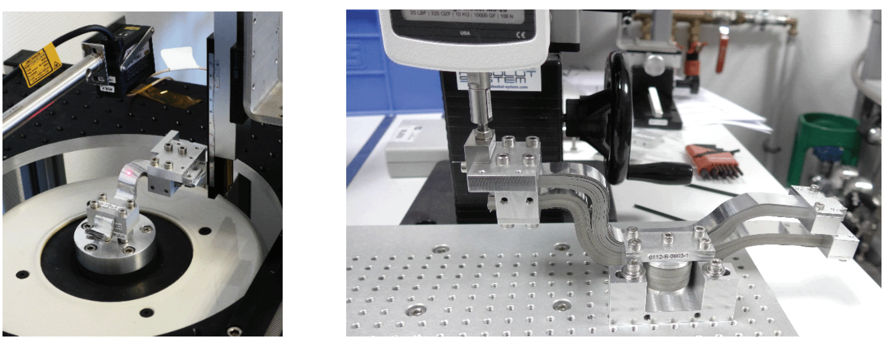

Figure 3. Illustrations of a cumulated dynamic relative displacements tests (left) and stiffness characterization (right) on prototyped routing of foils stack.

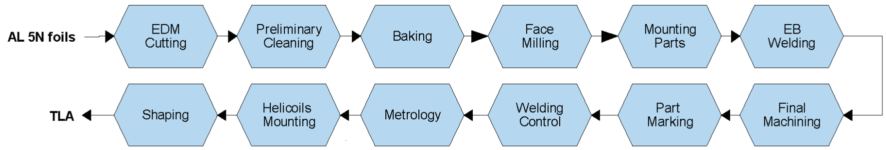

Figure 4. Manufacturing flow chart of aluminum TLA

TLA PRODUCTION

Aluminum TLA Manufacturing

The manufacturing of an aluminum TLA consists of a succession of several processes as presented in the schematic manufacturing flow chart attached in the Figure 4. A brief summary of the processes is given as follows:

- Aluminum 5N foils are cut to the dedicated shape by Electron-Discharge Machining (EDM) process. To do so, a stack of foils is pressed between two masks made of thick stainless steel. The masks are reused for the mass production. The cutting is performed by an external supplier with an extra length at the end fitting sides.
- After the cutting, the foils are cleaned one-by-one in a bath with isopropanol alcohol.
- The cleaned foils are baked at 140 °C in a furnace under vacuum environment.
- Al5N cut foils with extra length are mounted in dedicated U shaped Al1080 support and the stacking is ensured by a dedicated bolted assembly. In-house high speed face milling process is used to remove the extra length of the Al5N foils so that a perfectly planed surface is produced in the weld joint.
- Then perfect contact is ensured between the machined face of the Al5N foil stack and the massive Al1080 block prior to the welding step.
- An external qualified EB welding process is used to weld the Al5N foil stack to the Al1080 blocks.
- The final end-fitting interfaces (cold tips, detector assembly or optical bench interfaces) are machined into the massive Al1080 blocks.
- All the parts are marked for identification. The marking is a machining process performed by the supplier insuring also the final machining.
- After the production tests described below, helicoils are implemented, if required, on dedicated machined end-fittings.
- Finally, the produced TLA is shaped by Absolut System according to dedicated manufacturing drawings (example of shaping is attached in Figure 5).

Copper TLA Manufacturing

The manufacturing of an OFHC copper thermal link is performed with a similar process to the aluminum material thermal link. The technology is the same because thin copper foils are stacked together, cut to shape and welded at end-fittings interfaces.

The main difference is that the press-welding process is used instead of EB welding. With aluminum, the foils are welded on a massive end-fitting made with Al1080 while with press-welding process, the end-fittings are constituted directly with the foils themselves.

The foils are pressed and a current is applied into the foils in the contact area. With the resistivity of the copper, the current heats up the material near the fusion point (in the range of 965°C) and the foils are welded together without contact resistance or additional filling materials. This process is performed under an inert gas environment to prevent oxidation of the copper. Figure 6 shows an overview of the press-welding process during operation. The press-welding process is very good for the thermal performance (no thermal resistance between the foils) and for mechanical homogeneity (conservation of the material properties in the junction area) due to molecular connection reached after press-welded process. In our case, after the cutting of the foils to the required shape, the foils are stacked and placed between two OFHC copper plates increasing the thickness of the end-fittings. This stack is press-welded and the final shape of end-fitting is realized after the final machining.

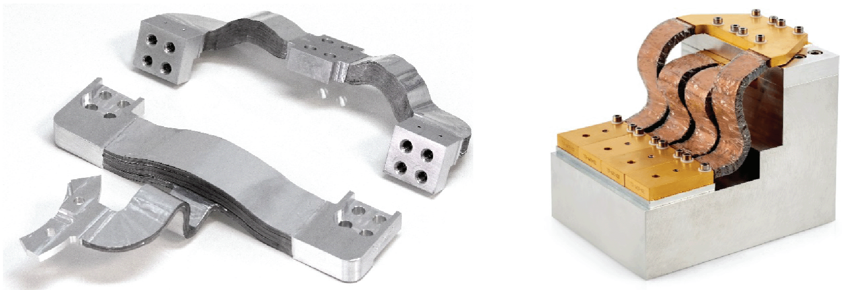

Figure 5. Examples of Al5N and OFHC cooper TLAs produced by Absolut System.

Production Testing

For the EB welding control a nondestructive inspection (NDI) tomography process is used. This control consists of an X-ray source to visualize the internal material characteristics of the end-fittings at the weld location. This control is used to validate the integrity of the welding. The definition is in the range of 100µm, and it is possible to estimate with this method a maximal porosity of the welding. In order to maximize the definition, this process is performed after the final machining of the welded end-fittings.

The metrology control is a standard metrology process used in order to ensure the tolerances of the machined interfaces according to the manufacturing drawings are respected. Depending on the manufacturing flow chart, some protective tubes tool are used after this step to protect the machined interfaces to accomplish the following steps.

Qualification and Acceptance Testing

A typical flow chart of an acceptance test is attached in the Figure 7. Cleanliness control is measured during the test sequence. Physical properties (such as mass), electrical resistivity, mechanical stiffness, and static/dynamic displacements measurements are performed under ISO 5 class laminar hood at Absolut System premises.

For the thermal conductivity measurement, TLA specimens are mounted and encapsulated in metallic housing under ISO 5 environment (Figure 8). Protective housing set-up are implemented prior to integration in the thermal test bench and are removed after test also under ISO 5 clean hood. The same test bench and precautions apply for the thermal cycling tests.

For the sine and random (and shock if applicable) tests, the TLA specimens are mounted on JIGs under ISO 5 clean hood and encapsulated in polyester housing closed by Kapton tape. Those mechanical tests are performed externally to Absolut System. Protective housing are removed after mechanical tests under ISO 5 clean hood.

Particularly for the TLA Qualification Models, thermal conductivity and stiffness measurements are performed before and reproduced after the application of stresses (sinus, random, accumulated displacements, thermal cycling) to track any change in performance.

Figure 6. Example of press-welding process.

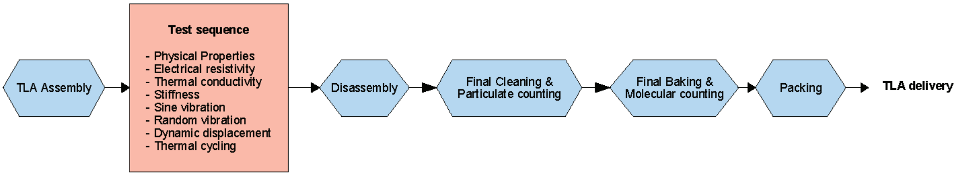

Figure 7. Typical acceptance flow chart of TLA.

The final cleaning process is performed after the completion of the complete test sequence, before the contamination measurement. This process is performed in ISO 5 environment by Absolut System. This process consists of:

- Ultra-Sonic (US) bath with Isopropanol (IPA),
- US bath with de-ionized water,
- Cleaning with particulate counting with de-ionized water.

After final cleaning, a sample extraction is made by running the TLA specimen entirely in a filtered bath of IPA with manual agitation. This bath is then analyzed internally by a specific HIAC 8011+ type analyser from Beckman Coulter able to count particles from class 5 (> 100 µm) down to class 1 (5 µm – 15 µm).

After the final cleaning with US bath using IPA and de-ionized water, a bake-out procedure is applied in order to remove all volatile components present on the specimen's surface. This bake-out process is done in a specific furnace able to heat the system up to the required value during a long period (min. 72 hours) in vacuum (typically < 10^{-5} mbar).

For the molecular counting, the analyses are performed with a Gas Phase Chromatography coupled with mass spectrometry (GC / MS). The sample is extracted by wiping process (according to ECSS-Q-ST-70-05C). Tissue is wetted by methanol and wiping is performed on the TLA surfaces. This sample extraction is done at Absolut System premises under ISO 5 environment and then sent to external laboratory for molecular analysis.

For the packing, a double bag approach with nitrogen flushing is used. This double packing is performed under class ISO 5 and flushed with dry Nitrogen. Desiccant is used in the second bag. Along the MAIT process, components are stored in a dry cabinet (humidity controlled to a value lower than 1 %).

TYPICAL TLA PERFORMANCES

Each project flying TLA comes with its specific set of user requirements, so only typical performances can be listed here. As primary function of the TLA, the thermal conductance shall be maximized giving the overall dimensions and mass constraints. Typical conductance of aluminum

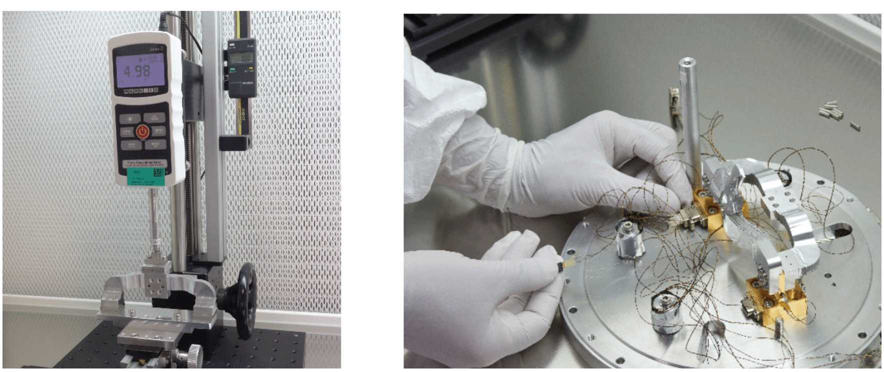

Figure 8. Picture of TLA during stiffness measurement and TLA installation on dedicated cold plate for thermal conductance characterization.

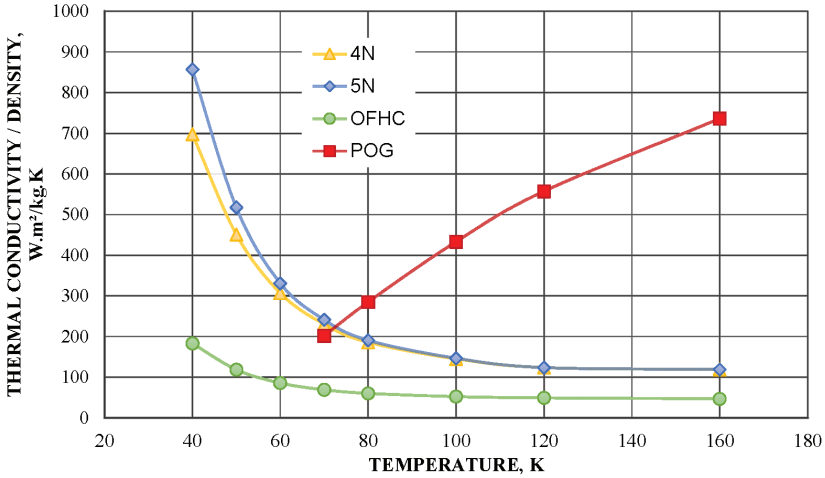

Figure 9. Ratio between thermal conductivity and density for pure aluminum, OFHC copper and POG

FM TLA, including contact interfaces, are in the range of 0.5 to 0.9 W/K in the 50-70K temperature range. Thermal performance achieved are now predictable within less than 10%. Typical overall mass budget allowed is in the range of 200 to 400 grams. The more stringent budget specified for the mass is linked to the limitation of the mass suspended to the cold finger cold tip of less than 75 grams. For the mechanical environment, typical figures are 20-50 g for quasi-static and launch sine vibrations qualification levels in the [5-100 Hz] bandwidth and 0.5 to 1 g^2/Hz power spectral density in the [100-500 Hz] bandwidth for the random vibration qualification levels. Depending on the mechanical launch vibration levels and TLA shape (imposed by the stiffness and routing requirements), the flexible foils stack of TLA can be wrapped in a PET polyester tube of 100 µm thick which is heat shrunk around the foils with a dedicated process. The PET shrink tube allows the TLA to support high mechanical levels without delamination of the stacked foils and with very limited impact of the overall stiffness of the TLA. With respect to flexibility, typical stiffness requirement is in the range of few N/mm at cryogenic temperature. This requirement applies for displacements up to 5 millimeters to accommodate the misalignments of detector and cold finger and relative displacements under mechanical and/or thermal load. The stiffness measured at room temperature is corrected by an amplification factor to take into account the Young modulus variation of the foil material. Finally, the TLA cleanliness is in accordance with standard $5x(10)^{-8}$ g/cm² and 100 ppm respectively for molecular and particulate cleanliness requirements.

TLA UNDER DEVELOPMENT

For flight applications, the mass and thermal conductance need to be improved. OFHC copper thermal link can be used in application not sensitive to mass, but in most of the applications, the volume of the thermal link and its perfosrmance are critical for instrument performance and thus need to be optimized. As we can see on Figure 9, the Pyrolytic Oriented Graphite (POG) is the best candidate in the 75-160 K temperature range while the 5N aluminum is the best candidate in the 40-75 K temperature range. Both materials offer very low Young modulus which will make those the optimized choice for our application.

For this reason we adapted the thin foils thermal link technology to POG material which represents an excellent candidate for performance optimization. The POG thermal link is made with thin foils of POG which are stacked and connected at extremities on Al1080 end-fittings. The foils are swaged on the end-fittings to insure the thermal contact between POG and Al1080. On paper, the performance of such a thermal link is very high due to the high POG thermal conductivity which exceeds the OFHC copper with a factor of 3 at room temperature. However, several issues need to be solved to be able to exploit the material capability.

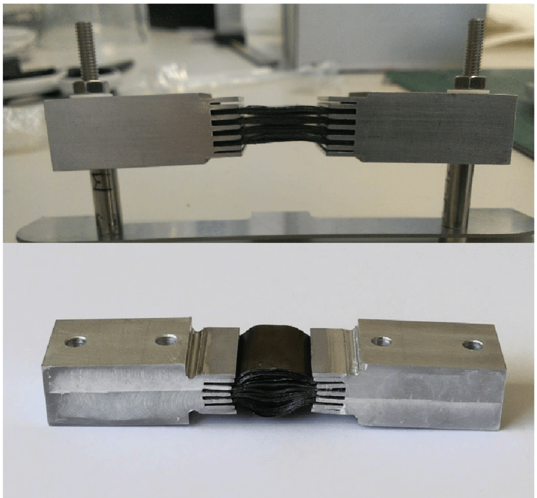

Figure 10. Pictures of a breadboard thermal link used to validate the FEM modelling. Before swaging on the top and after swaging on the bottom.

Management of the Contact Conductance on End-Fittings

The contact conductance is a key characteristic of the POG thermal links. To benefit from the high POG thermal conductivity, the contact resistance between foils and aluminum end-fitting needs to be optimized as well. Furthermore, the POG has the attribute to offer a very high thermal conductivity in the plane but a poor thermal conductivity out of the plane (thermal conductivity 50 times lower out of the plane than in the plane).

To optimize this interface, FEM modelling has been performed, supported by breadboard tests' (Figure 10) to determine the most efficient design for this junction. If the thermal link is made with a single stack, the contact conductance across the POG foil will be very low due to the poor thermal conductivity of the foils out of the plan. So the number of slots in the aluminum block and their height has been optimized to lower the thermeal conductance through the complete end-fitting. After several iterations and correlation with tests, we defined an optimal configuration for this interface with specific dimensions for the slots for an optimal elementary stack thickness.

Contamination Due to Particles Release

The contamination is a driver in the production of our flight cryogenic thermal links. Most of the time, these thermal links are integrated between the detector and the cryocooler, and thus, the thermal links need to offer a perfectly controlled contamination. With aluminum and copper, this issue is managed with the implementation of several cleaning steps along manufacturing process and the performance tests are performed in clean environment. However with POG, the problem is to avoid release of foil material particles during its life. It is particularly critical during integration where particles can scratch the foils. To solve this issue, a thin membrane will encapsulate the foils. The membrane will surround the complete flexible part of the thermal link in order to trap particles. To do so, a PET membrane is used. This membrane has been qualified in the frame of other projects down to 50 K. The membrane is very thin (about 20 µm) and thus doesn't impact the stiffness of the foils.

Example of POG Thermal Link

Following this development, several POG thermal links are under production. The one presented in Figure 11 is made to connect the first stage of a Pulse tube cryocooler to an optical bench. This thermal link is able to provide a thermal conductance of 1.1W/K @ 110K for a mass of less than 50 g.

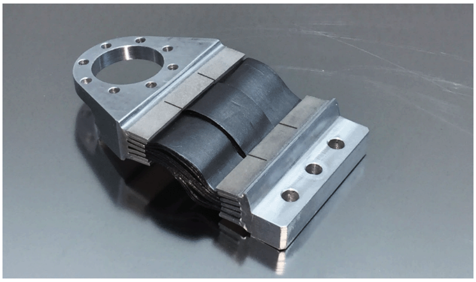

Figure 11. Overview of POG thermal link

CONCLUSIONS

Following the different developments and qualification phases performed by Absolut System for European projects, we are now able to provide flight qualified high performance thermal links using aluminum and OFHC copper. Flight hardware has been delivered in Europe and several other components are under production. In complement, the thin foils thermal link technology is tailored to POG material to offer thermal and mechanical architects an efficient alternative to aluminum and copper between 75K and room temperature.

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