First Steps in the Development of High Thermal Conductivity Hybrid Structures (HiDuct)

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We intend to develop hybrid structures, where besides structural strength also high thermal conductivity is required. These high conductive structures can replace conventional metallic elements, which are heavy due to their limited thermal conductance, and in selected cases even two-phase heat transportation systems. Outstanding weight and cost reduction may be achieved for example in spacecraft radiators, since the use of heat pipes can be avoided or reduced. The compound can also be envisaged to reduce weight in spacecraft thermal management systems, which are typically constrained by thermal limitations. Examples are passive deployable radiators, thermal doublers and housings of electronic units. The paper describes the principle of the hybrid structure and results of sample testing. Performed thermal analysis of a typical heat pipe radiator shows that the use of the high-conductance hybrid structure could delete the entire heat pipe network.

I. Introduction

THE final heat sink available in a spacecraft is heat radiation into the space environment. For GEO communication satellites, as an example, the North / South spacecraft panels are generally used as thermal radiators, since the background temperatures of these surfaces are lower than surfaces pointing in other directions. Waste heat, generated in most cases by electronic units of the spacecraft, need to be transferred to these radiators. These can be accomplished by internal thermal radiation from the warmer units to the inner surface of the radiators (less efficient) or by heat conduction (more efficient).

Since heat radiation from the radiator surfaces into space takes place proportional to the forth power of radiator temperature, the main requirement of a thermal control system is therefore to minimize the temperature difference between heat source and radiator, in order to provide the highest possible radiator temperature. Effective radiation heat transfer within a spacecraft closure requires high temperature differences and is therefore less efficient than conductive heat transfer. All improvements in the efficiency of a thermal control system are therefore related to either shorten the heat conduction path between heat sources of electronic components and the radiator of the spacecraft or to increase the thermal conductivity of the elements between heat source and radiator including their interfaces.

There are two reference scenarios, which covers most of the subsystem design tasks:

1. Connection of dissipative equipment on the radiator itself. This is currently the simplest method to shorten the heat transfer path for equipment, which do not have specific requirements with respect to their location, i.e. repeater equipment, high power boxes, etc.

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2. Design the heat path to the radiator with high conductive elements and to improve interface conductance between conductive interfaces, located within this path. These solutions are applied to equipment, which needs to be placed at specific locations of the spacecraft as to support their unique functions, i.e. star sensors, reaction wheels, direct radiating antenna, etc.

All solutions to increase thermal conductance in the heat transfer paths need to fulfill general requirements, which can be summarized as follows:

- High thermal conductance to mass ratio
- Fulfillment of mechanical, electric, outgassing, aging requirements
- High reliability throughout spacecraft life
- Ease of integration and testability at system level

We propose an innovative hybrid structure with high thermal conductivity in order to improve thermal conduction in the path between heat source and radiator, and which would meet at the same time necessary mechanical requirements.

We identified possible application fields in a spacecraft for high-conductance hybrid structures as follows:

- In conjunction with current technology such as heat pipe, LHP and mechanical pump
- Heat pipe radiator
- Highly dissipative components
- High conductive interfaces
- Tubular boom structures
- Optics terminal housings
- Telecom battery housing
- High-power electronic housings

II. Hybrid Structure Concept

Hybrid structures, as used in several industrial domains, are most often a combination of dissimilar materials in order to combine their advantages and to obtain consequently weight and fabrication cost reduction. In all known applications the material is used to improve structural strength such as high specific stiffness.

In our project we intend to develop solutions, where besides necessary structural strength also high thermal conductivity is required. In an ideal case a material with high strength, but limited thermal conductivity (A), is combined with a material of high conductivity, which may have typically low conductivity (B), in order to arrive at a compound A/B, which combines the properties of the separate matters (Figure 1).

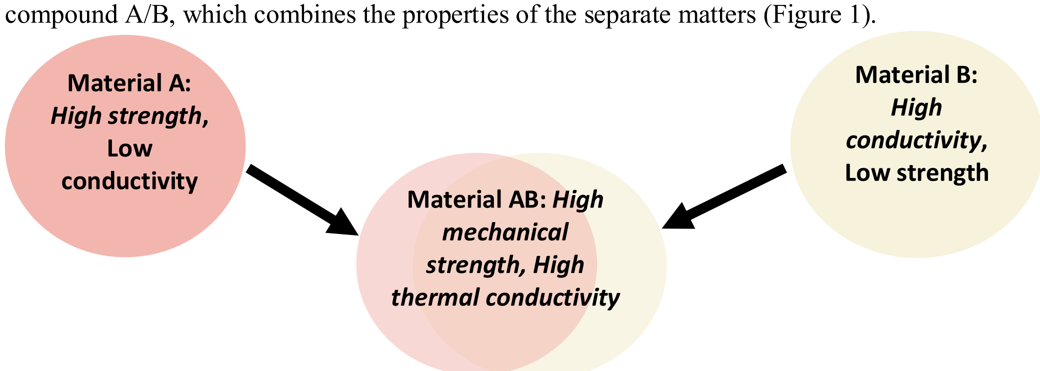


Figure 1. Principle of hybrid structure

These high-conductive structures could replace in thermally demanding cases conventional metallic elements, which are heavy due to their limited thermal conductance. Outstanding weight and cost reduction are achieved for example in spacecraft radiators, since the use of heat pipes could be avoided. The compound will also reduce weight in spacecraft and terrestrial thermal management systems of high-power electronics, which are typically constrained by thermal limitations.

The proposed hybrid structure is based on a high conductive layer, which is encapsulated by two aluminum face sheets with integrated, small hooks, which are machined into the surface (Figure 2). The height of the hooks can be varied between 0.3 and 2.4 mm (depending on the sheet thickness) as well as the density of hook distribution. The integrated hooks provide interlocking between the high conductive layer and metal face sheets, which not only improves the structural connection, but also protrude through the entire high conductive layer in order to conduct the heat directly into the high conductive material. In addition, the aluminum face sheets allow known and validated joining techniques to adjacent metallic spacecraft parts.

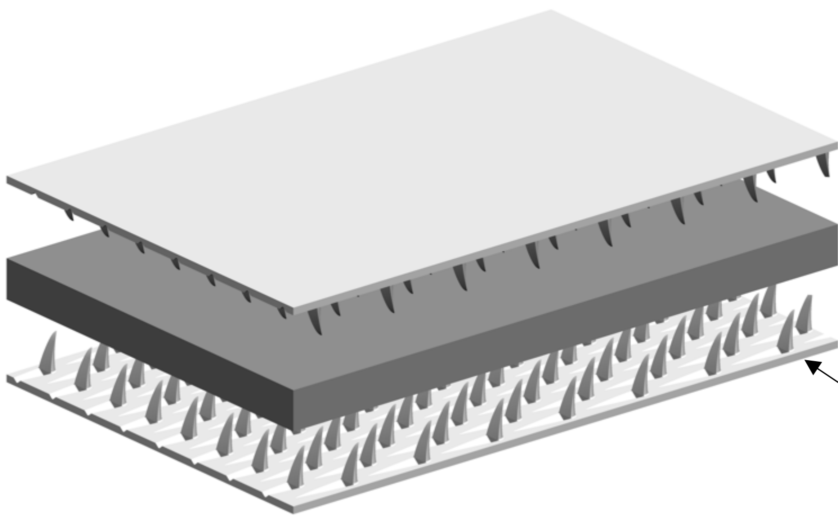


Figure 2. Build-up of high-conductance hybrid structure

III. Selected application

Structural elements in spacecraft designs are often from aluminum alloys due to the high strength to weight ratio. The relatively high thermal conductivity of aluminum alloys (compared to Titanium, Steel) is another asset of these materials.

However, in many cases the thermal conductivity of used aluminum alloy with about 150 W/(mK) is not sufficient for demanding thermal solutions and the idea to increase the thickness of structural parts as to increase the thermal conductance would add mass to the spacecraft design in a not acceptable way. For these reasons it is state-of-the-art to enhance demanding thermal designs by active conductive elements, which feature a high conductance to mass ratio. Examples are heat pipes, loop heat pipes and mechanical pumped two-phase flow devices.

The thermal spacecraft radiator can be seen as a typical example for a low-mass construction, which uses heat pipes as active thermal elements to improve the thermal conductance. Dissipative electronic elements are mounted on the inner surface of a radiator, as shown in Figure 3. Waste heat of the electronics is conducted and distributed in the radiator plate. Since the efficiency of the radiator increases with the uniformity of the temperature distribution in the radiator, heat pipes are embedded into the sandwich structure, which uniformly distribute the heat along the pipe axis. In many cases a second set of heat pipes is arranged cross-wise in order to improve conductance perpendicular to the first set of heat pipes.

The disadvantages of using large arrays of heat pipes within a radiator are:

- High mass of the heat pipes
- High manufacturing and integration costs for heat pipes
- Long lead time
- Constraints in system testing (only horizontally oriented heat pipes work on ground or heat pipes in reflux mode)
- Constraints in the layout of electronic equipment on the radiator (mounting bolts shall not interfere with heat pipes)
- High safety regulations due to the ammonia content in heat pipes

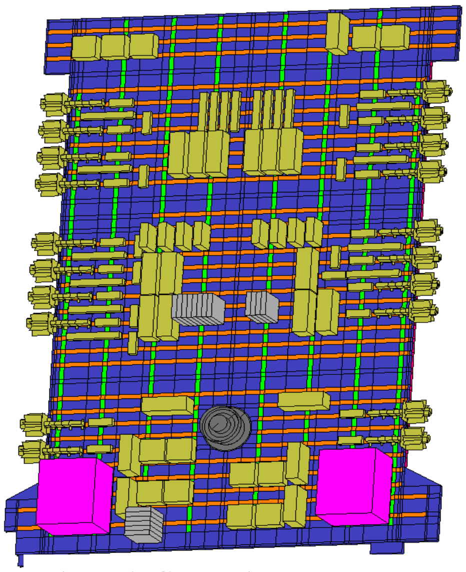


Figure 3. Cross-wise arrangement of heat pipes in a radiator panel

To visualize the high mass of a heat pipe network in a typical telecom satellite, the mass budget in Table 1 is given for one radiator plate. It can be seen that the heat pipe network weight of 71.7 kg amounts to about 64.8% of the total radiator mass of 110.6 kg.

Radiator Item (1 radiator)	Mass / kg
Face sheets (6.5 m^2, 2 x 0.5 mm thickness)	18.1
Honeycomb core (26mm thickness) including high density core	8.5
Foil Adhesive	1.3
Inserts / Potting	11.0
Subtotal:	**38.9**
Heat Pipe Network	71.7
Total:	**110.6**

Table 1: Typical mass budget of a heat pipe radiator for Telecoms

Our aim is to demonstrate that the proposed hybrid material concept can reduce the amount of heat pipes or, preferably, delete the entire heat pipe network.

IV. Material and process selection

A. High conductive foil

Only materials with very high in-plane thermal conductivity may compete with current advanced, fluid based thermal control configurations. We evaluated possible materials and found that structural panels built-up with pyrolytic graphite foils (Figure 4) could serve as a suitable solution to meet the requirements of present heat pipe radiators.

The fabrication method of graphite foils, which are commercially available from KANEKA Corp., is described in literature[1]. The manufacturing process uses carbonized polymer films and high-temperature heat treatment. By optimizing the conditions of the heat treatment, foils with high-thermal-conductivity values can be obtained along the in-plane direction. The maximum thickness of the sheets is only 40 µm. Since crystals of graphite consist of hexagonal mesh layers that are laminated by van der Waals forces, the thermal properties are different between the in-plane and the out-of-plane directions.

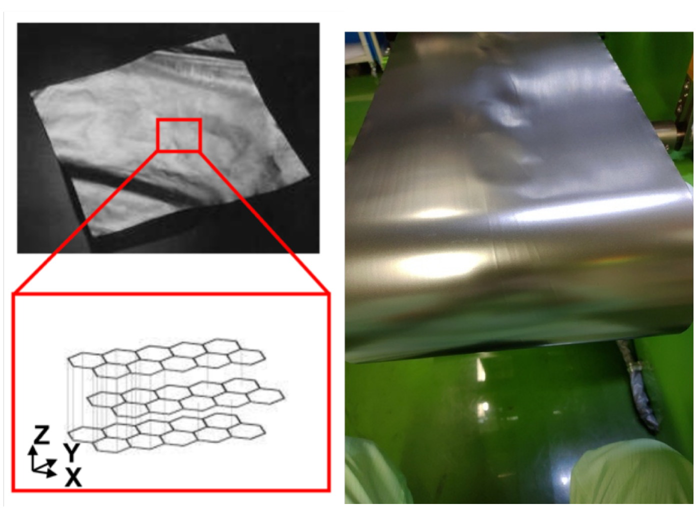


Figure 4: Graphite sheet structure

Typical properties are:

1. High thermal conductivity in the in-plane-direction
   - 1,500 W/(mK) (at -75°C)
   - about 4-times larger than Copper (398 W/(mK)), close to diamond (2000 W/mK)
   - about 6-times larger than pure Aluminum (237 W/(mK))
2. Large anisotropy of thermal conductivity
   - 5 W/(mK) in out-of-plane direction
   - Ratio: in-plane / thickness = 300
3. Low density
   - Graphite foil: 2.0 g/ cm^3,
   - Copper: 8.9 g/cm^3, Aluminum: 2.7 g/cm^3

The thermal conductivity is temperature dependent and the maximum values of near 1500 W/(mK) have been determined at about -75°C[2]. At a temperature of

80°C (maximum radiator design temperature) the conductivity is still about 1000 W/(mK), which is more than six times larger than the aluminum alloy used in spacecraft radiator structures.

The thin pyrolytic graphite foils are used in many terrestrial electronics applications. For example, such foils are incorporated in smart-phones to distribute heat from electronic hot spots. That is the reason that the material can be obtained at a relatively low price.

B. Foil stacking

The maximum available thickness of graphite foils is with 40 μm too thin for most practical applications in spacecraft thermal control systems. In order to obtain foil packages with a certain thickness, foils need to be packed on top of each other and bonded. Example: for a 2 mm package 50 foils of each 40 μm thickness need to be stacked.

The bonding should meet two important requirements:

- Bonding thickness very small in order to minimize the thermal resistance between the foils and thus not to lower the out-of-plane thermal conductivity of the stack.
- High bond strength, which should be larger than the mechanical strength of the graphite material (cohesive failure)

A suitable bonding technology must also consider the fact that the foil material is delivered in endless roles of 210 mm width, which require an overlapping technique to fabricate extended planar configurations.

In a trade-off we identified two promising bonding methods: 1) direct bonding, 2) adhesive bonding.

1. Direct bonding:

This bonding technology is carried out by applying plasma coatings on the graphite foil. In such a way, thin plasma polymer coatings will be covalently (=chemically stable) bond to the graphite during the deposition process. These plasma polymer coatings carry chemical functional groups, which can undergo chemical reactions, and are finally responsible for the bonding ("gluing") of the graphite foil layers against each other. The composition of the plasma polymers will be chosen in such a way that a first coated surface can be bonded against a second plasma-polymer coating on the next graphite foil by a subsequent reaction. Here, known binding mechanisms from polymer chemistry will be used.

Plasma coating can be conveniently applied by a roll-to-roll process and the technique has been used in the past for many foil materials in terrestrial applications and is regarded today as a reliable process. Such a coating is for us the preferred solution, since it provides a bonding with practical no intermediate layer between the foils, which would guarantee highest in-thickness thermal conductivity.

2. Adhesive bonding:

Graphite foils can be bonded by using adhesives, for example thin adhesive layers. This material is used frequently in spacecraft structures: known as Transfer Tapes in sandwich structures or as Pressure Sensitive Tapes (PSA). However, the disadvantage of using adhesive films is the relative high material thickness. The thinnest product, we found on the market, is 25 □m. In case of a stack with 50 graphite foils these adhesive films would add another 1,25 mm in compound thickness with the associated mass increase and with a considerable decrease in the out-of-plane conductivity of the foil stack.

Better results can be obtained with the so-called micro-dispensing techniques, which was developed in the course of ever-progressing miniaturization, where increasingly small and sensitive components need to be joined together. The technology is a spin-in from the ink-jet printing method, where tiny ink droplets are placed without contact on paper with significant speed and resolution. The same principles can be used for the dispensing of adhesives by "jetting" free-flying adhesive droplets from a small distance. Due to the functional principle of jetting, position tolerances of targets in z-direction are irrelevant since the free-flying adhesive droplet will reach the substrate surface anyway. This is a remarkable advantage compared to needle dispensing.

For conditioning graphite foils thermoplastic adhesive can be jetted at elevated temperature and in the liquid stage (hot-melt) onto the foil surface, in order to form a pattern of adhesive dots. Dot size and dot distance can be selected in a way that a very thin adhesive layer develops during foils bonding under temperature and pressure. Adhesive dot application can be performed roll-to-roll on both sides of the foil. The bonding of the foil stack is finally performed on a planar hot press.

C. Compound

Graphite foils, even if bonded and stacked together, have not sufficient strength for envisaged applications. In the proposed concept (Figure 2) the graphite foil package is therefore sandwiched between aluminum sheets, which have integrated hooks (Figure 5), machined out of the base material.

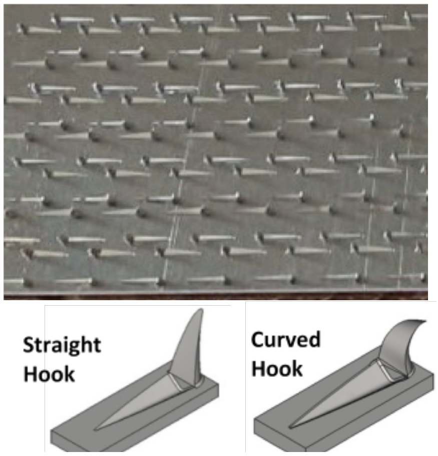


Figure 5: Hook configuration

Hook Configuration	Material Minimum Thickness (mm)	Density (hooks/ cm^2)	Hook Height (mm)	Max. Width (mm)
Heavy Duty	1,00	3,1	2,52	228,6
Standard	0,38	7	1,52	482,6
Mini	0,30	13	1,00	482,6
Micro	0,30	20	0,80	482,6
Nano	0,25	40	0,63	152,4

Table 2: Standard hook configurations

Property	5052-H32	2024-T81
Ultimate Tensile Strength (MPa)	228	483
Yield Tensile Strength (MPa)	193	400
Modulus of Elasticity (GPa)	70,3	72,4
Shear Modulus (GPa)	25,9	28
Shear strength (MPa)	138	295

Table 3. Comparison of mechanical properties for 5052-H32 and 2024-T81

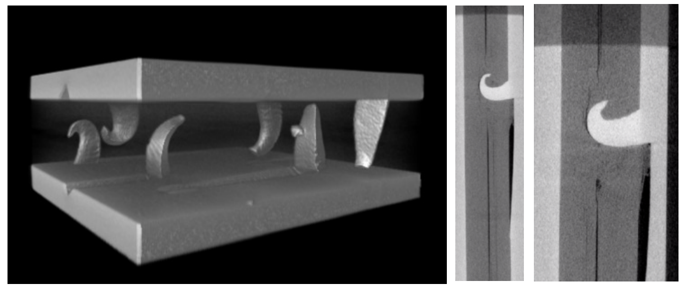


Figure 6: Behavior of hooks after penetration into graphite sheet package

Such material is commercially available from NUCAP Inc. with different hook configurations, as defined in Table 2. The increase in mechanical strength is due to the penetration of the hooks into the graphite sheets.

The hooks are expected to improve the compound in two directions:

(1) Increase the out-of-plane thermal conductivity and to overcome the disadvantage of the very low in-thickness conductivity of the graphite layers

(2) Increase the mechanical strength of the compound.

In case the hooks provide an anchorage in the graphite material, the interface strength between aluminum sheet and graphite will be improved and an adhesive can be avoided in this interface.

We observed that the tips of the hooks tend to bend, which increases the anchorage of the aluminum sheet onto the graphite foil package. This is shown in computer tomography pictures as presented in Figure 6. A possible reason, that hooks do not enter completely into the foil stack and bend prematurely, is probably the relatively low strength of the used standard aluminum alloy 5052-H32, which was for this project the only one available material. The alloy is not used in spacecraft applications and it will be in future substituted with the target material 2024-T81, which is applied for example in spacecraft applications for radiator face sheets.

The alloy 2014-T81 has much higher mechanical properties as seen in the comparison of Table 3. Strength testing is underway at the time of paper preparation, but we have information from test campaigns, performed by the supplier, that strength of the compound would be sufficient as to avoid any additional bonding between metal sheet and graphite package.

V. Sample Testing

A. Objective

The purpose of the test program is the following:

- Verification of the in-plane and out-of-plane thermal conductivity of the foil stack at different temperatures. Relevant values communicated by the manufacturer or found in literature are for the single foil only.
- Determination of the out-of-plane thermal conductivity of the compound sandwich and any improvements due to the hooks after entering into the graphite material.
- Measurement of the thermal expansion of the foil stack and of the compound, which includes the two aluminum sheets.

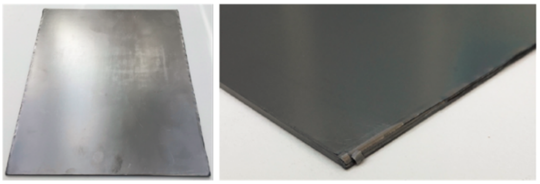


Figure 8. Graphite stack samples as delivered

The used foil stack was delivered by the material manufacturer (Figure 8). 50 foils of each 40 µm are bonded on top of each other to arrive at a stack thickness of about 2 mm. Bonding was performed by a thermoplastic adhesive sheet of nominal 5 µm. Theoretically, the overall thickness should then be 2,24 mm (50 graphite foils x 40 µm + 48 adhesive sheets x 5 µm). However, pressing at elevated temperature during the manufacturing process reduces the package thickness to a measured average of 2,03 mm.

Samples of different sizes were cut out of the delivered material to measure the thermal conductivity in the two orthogonal directions:

- 30 x 30 mm for measurement the out-of-plane conductivity
- 40 x 150 mm for measurement the in-plane conductivity

Several of these samples were sandwiched between the previously mentioned aluminum alloy sheets with straight integrated hooks. The sandwich process is performed under a planar press at 63 Bar. Figure 7 shows the two sample variants of the 30 x 30 mm sample. Geometries of the used hooks are specified in Table 4.

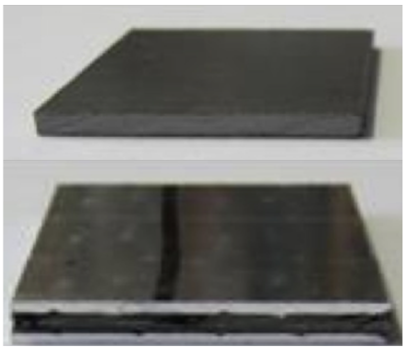


Figure 7. Two variants of the 30x30-mm samples

Sample Set	Type	Hook Height	Thickness of base material	Hook Density	Material
1	Thinner Hooks, Curved	1,52 mm	0,5 mm (0,02”)	7 hooks/cm^2	5052-H38
2	Thicker Hooks, Straight	2,2 mm	0,762 mm (0,03”)	6,6 hooks/cm^2	

Table 4. Hook geometry of used sample material

B. Thermal conductivity tests

1. Test method

Several methods are known for determining the thermal conductivity of high conductive solid and layered material.

We applied the most commonly used method based on Fourier’s Law, which states that the rate of heat transfer (Q) is proportional to the negative gradient in the temperature (dT/dx) and to the area (A), at right angles to that gradient, through which the heat flows.

$$Q = -kA(dT/dx)$$

Where,

‘k’ the thermal conductivity of the body material (W/(mK)).

For the Fourier Method different measurements (and samples) are necessary to measure out-of-plane and in-plane conductivity of a material.

2. Test equipment

In-plane thermal conductivity according to Fourier’s Law was measured by clamping a sample of 40 x 150 mm between a heating block and a block with liquid cooling (Figure 9). Heater power to the heating block was increased to a constant value (in most cases about 10 Watt) and the cooling block was regulated to a constant temperature (about 15°C for ambient measurements and -80°C for measurements at lower specified operating temperatures). Several temperature sensors are placed along the

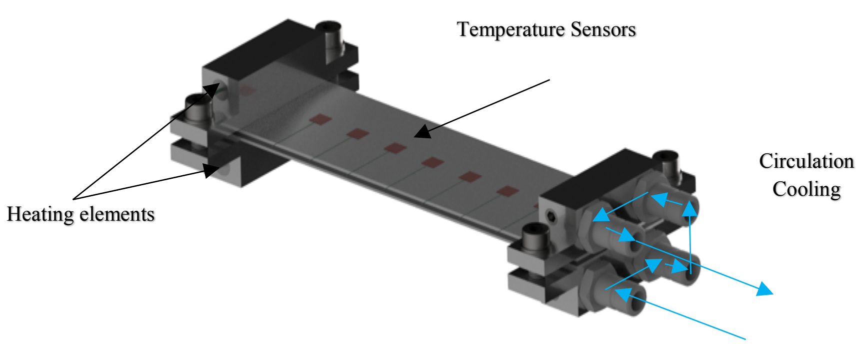
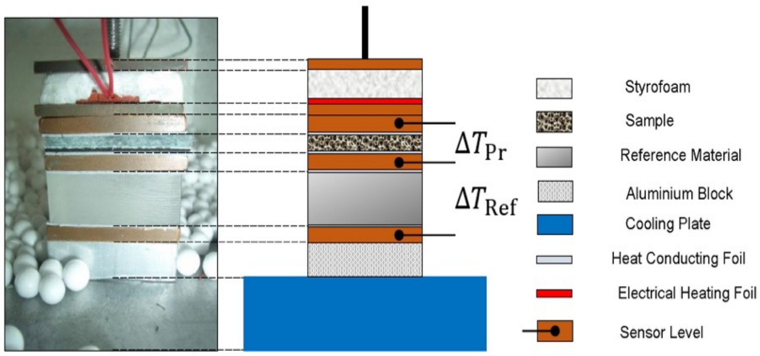


Figure 9.Schematic of set-up for in-plane conductivity measurement

sample, in order to determine the conductivity from the temperature slope in combination with the cross section of the sample.



ΔT_{Pr} = temperature difference across the sample, ΔT_{Ref} = temperature difference across the reference material (pure aluminum)

Figure 10. Principle build-up of guarded-hot-plate test equipment for out-of-plane conductivity measurement

Out-of-plane thermal conductivity according to Fourier's Law was measured by a guarded hot plate apparatus. The principle build-up of the measurement station is seen in Figure 10. The accuracy of the measurement is increased by comparison with the known thermal conductivity of a reference material (pure aluminum). Sample sizes for these tests were 30 x 30 mm.

3. Test Results

The results are summarized in Table 5. The in-plane conductivity measured according to Fourier Law is with 1150 W/(mK) close to the manufacturer value of 1190 W/(mK). The measured 600 W/(mK) is the expected average in-plane conductivity of the compound, consisting of the foil stack sandwiched between aluminum sheets. The out-of-plane conductivity is with 3,5 W/(mK) lower than the reported value (5 W/(mK)) for a single foil. This is due to the additional heat resistance of the adhesive layers, placed between the foils. However, the hooks, once entered into the foil stack, increases the out- of-plane conductivity to 8,5 W/(mK), an almost 60% increase in conductivity.

	Manufacturer data for single foil (W/(mK))	**Sample temperature (°C)**	**Test method: Fourier Law (Figure 9) (W/(mK))**	**Manufacturer data for single foil (W/(mK))**	**Sample temperature °C**	**Test method: Fourier Law (Figure 10) (W/(mK))**
Direction	**In-plane**			**Out-of-plane**		
Graphite foil stack sandwiched between hooked aluminum sheets (3 mm thick)		15	600		15	8,5
Pure graphite foil stack (2 mm thick)	Ca.1190 (at 20°C)	15	1150	5 (at 20°C)	15	3,5
	Ca. 1500 (at -75°C)	-68,5	1583			
		-73,4	1594			
		-72.5	1604			
		-61,0	1535			

Table 5. Summary of test results for thermal conductivity

The results for the pure graphite foil stack have been plotted over temperature in Figure 11 and compared with values for a single foil, as found in literature. The solid red curve in Figure 11 has been extracted from Figure 5 of Ref. 2 and represents values of in-plane thermal conductivity for a single graphite foil. The blue dots are own measured data of the graphite foil stack. While values correspond quite well near ambient temperatures, own measured data are higher (>1500 W/(mK)) at about -75 to -80°C. In general, the data confirm that the in-plane conductivity of the foil stack has its maximum at about -75°C and is about 1150 W/(mK) at ambient temperatures. The thermal conductivity is still about 1000 W/(mK) at specified maximum radiator design temperatures of 70 to 80°C.

C. Thermal expansion tests

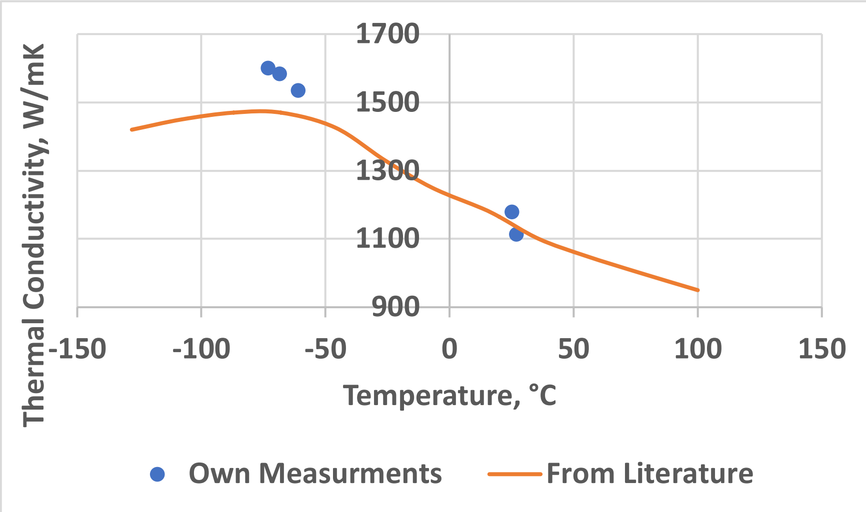


Figure 11. Comparison of thermal conductivity results for graphite foil stack with values for a single foil found in literature[2]

The coefficient of thermal expansion (CTE) was determined using a dilatometer (TMA Q400, TA Instruments). Measurements were made on pure graphite foil stack samples and on stack samples sandwiched between aluminum sheets with integrated hooks. The dilatometer determines the dimensional change of the sample material (µm/m) in the three orthogonal directions (Figure 12) and at various temperatures. The dimensional changes are then transformed into CTE values (10^{-6}/K).

The sample geometry is 10 x 10 x 2 mm (direction 1 x 2 x 3) for pure graphite foil stack material and 10 x 10 x 4 mm (direction 1 x 2 x 3) for foil stack samples sandwiched between aluminum sheets. The results are summarized in Table 6.

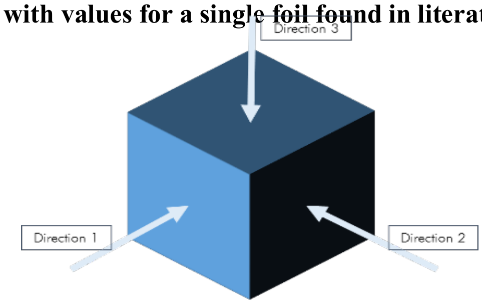


Figure 12. Definition of sample directions: direction 1 and 2 in-plane; direction 3 out-of-plane

Discussion of CTE results:

The CTE for the compound is in all direction about 13 ±1 x10^{-6}/K. When we compare this value with the relevant properties of the involved materials:

- Al-alloy of the two sheets: 5052-H38 CTE = 23,8 x10^{-6}/K between 20 and 100°C,
- Graphite foil stack: CTE = around 1,0 x10^{-6}/K (our measurements)

We can conclude that the measured CTE of the compound represents with 13 ±1 x10^{-6}/K an intermediate value for the involved materials. An explanation could be the metallic hooks, which enter the foil stack and provide a strong anchorage between metallic sheets and foil stack. Such anchorage is possibly the reason that the CTE of the compound is dominated by the CTE of the aluminum and is therefore much higher than the low CTE of the graphite foil stack.

	Sample No.	Direction (see Figure 12)	CTE (x10^{-6}/K) between -40°C and +80°C	CTE (x10^{-6}/K) between -40°C and +60°C
Graphite Foil Stack	1	1	1,63	1,74
		2	0,68	0,64
		3	-	
	2	1	0,96	1,52
		2	0,58	0,82
		3	1,57	1,88
Graphite Foil Stack with Al-Alloy Sheets	1	1	13,05	
		2	14,47	
		3	12,53	
	2	1	12,42	
		2	14,3	
		3	-	

Table 6. Summary of results for CTE measurement

VI. Verification by Thermal Analysis

In order to demonstrate the feasibility of the HiDuct concept and to determine minimum properties for an application example, thermal analysis is conducted based on a typical payload radiator of a communications satellite (Figure 3).

For this analysis verification the original thermal model of the radiator is used, but without introducing the influence of the solar array. For simplicity the inner face of the radiator is assumed to have MLI coverage. The following parameters of the original radiator are taken into account:

- Radiator panel: thickness 26 mm, total area 6.5 m²

- Face sheet material Al2024-T81, in plane conductivity λ = 151 W/(mK), thickness 0.5 mm,
- Honey Comb Core: 3/16"-Al5056-0.001“, α = 63.06 W/(m²K), ρ = 50 kg/m³
- Lightweight dual bore embedded heat pipes, 0,791 kg/meter, total heat pipe length 87.0 meter
- Total dissipation of equipment installed on the radiator panel: 2229 Watt
- Total radiator mass with heat pipes, without equipment: 96,4 kg.

For the model with the HiDuct material the heat pipes are deleted and the inner face sheet of the sandwich is replaced by the HiDuct compound, i.e. graphite foil stack sandwiched between two aluminum foils with integrated hooks. For simplicity the hooks are not modelled separately. Instead the measured values for heat conductivity are used. Figure 13 shows the different characteristics of the two models.

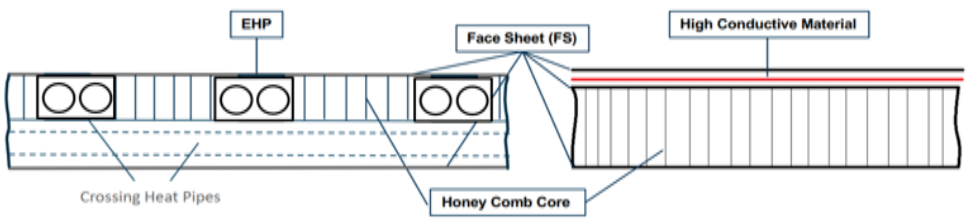


Figure 13. Left: Original radiator model with crossing (redundant) heat pipes; right: HiDuct model with inner face sheet as high-conductance hybrid material

For the HiDuct material the following properties are used and varied in the analysis campaign:

- Out-of-plane conductivity: 5, 10,20, 30, 40 and 50 W/(mK)
- In-plane conductivity: 500, 1000 and 1500 W/(mK)
- Thickness of graphite foil stack material: 0.5, 1.0,2.0 and 3.0 mm, density: 1800 kg/m^3

Several cases are analyzed and compared with each other. Most important results are summarized in Table 7. The results show that the margin against the maximum allowable temperature starts to achieve positive values with a 3-mm thick graphite stack (+1,7°C for Case 5 in Table 7). The associated mass saving against the conventional solution with a heat pipe network is for this case 19 kg.

The analysis result for Case 5 is compared in Figure 14 with the baseline heat pipe solution of Case 1.

Case		**HiDuct Material**		**Calculated max. temperature (°C)**	**Margin to max. design temperature of 75°C**	**Total radiator mass (kg)**	**Mass saving: Δ Mass to Case 1 (kg)**	**Comment**
		Thickness (mm)	**Mass (kg)**					
1	**Original radiator panel with heat pipe working**	N/A	N/A	58,2	+16,8	96,4		Presently used heat pipe radiator in telecoms
2	**Original panel, but all heat pipes deleted**	N/A	N/A	123,6	- 48,6	26,2	70,2	Theoretical, not working case for comparison
3	**Cases with HiDuct material as inner face sheet, no heat pipes**	1,9	26,6	78,2	-3,2	61,9	34,5	1,9 mm thick graphite foil stack, 3,2 °C negative margin
4		2,5	35,1	75,1	-0,1	70,3	26,1	2,5 mm thick graphite foil stack, 0,1 °C negative margin
5		3,0	42,1	73,3	**+1,7**	77,3	19,1	3,0 mm thick graphite foil stack, 1,7 °C positive margin, 19 kg mass saving.

Table 7. Summary of analysis results

Compared with the HiDuct configuration, the heat pipe network provides a more uniform temperature distribution and consequently, a higher margin against the maximum allowable temperature. Figure 14 right side shows clearly that the maximum temperatures for the HiDuct version appear under the TWT on both edges of the radiator. An optimization can be performed, where a redundant heat pipe is installed under these hotspots. Such a combination would considerably increase the margin against the maximum design temperature, allow to use thinner graphite foil stacks and could achieve a larger overall mass saving.

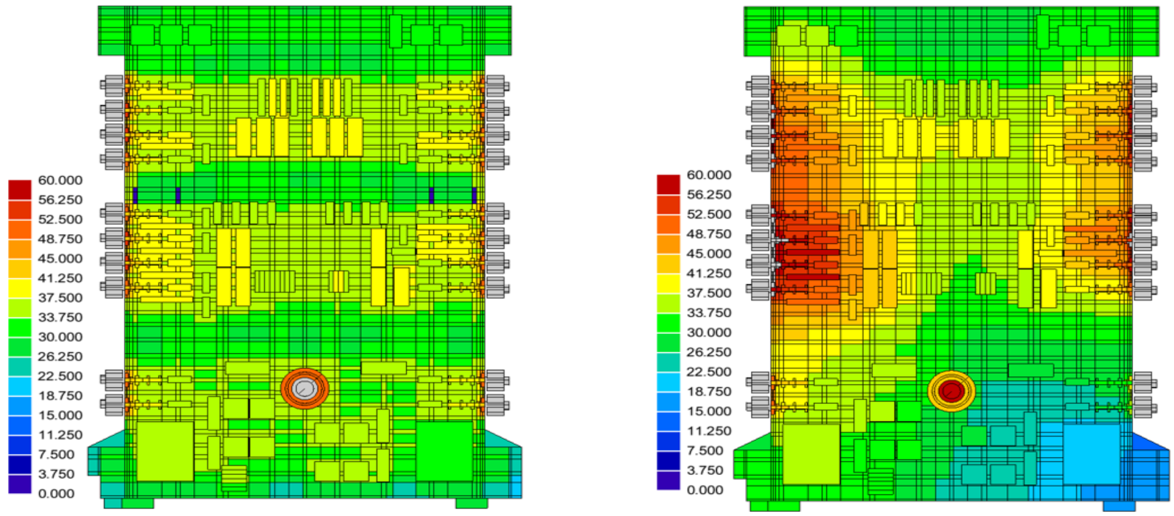


Figure 14. Comparison of calculated temperature distribution on the radiator panel. Left: Case 1 with all heat pipes working; Right: Case 5 with all heat pipes deleted and inner face sheet replaced by HiDuct material with 3-mm thick graphite foil stack. Cases are defined in Table 7. For radiator cross section see Figure 13.

The analysis for other cases shows also that the effect of out-of-plane conductivity is less important than initially thought. Increasing the out-of-plane conductivity from 5 to 10 W/mK would increase the margin to the highest allowable temperature by only 1°C.

The results show in general that it is possible to replace the entire heat pipe network with the HiDuct material. In such a case a mass saving of 20 kg is possible. Other advantages of deleting the heat pipe network would be lower recurring cost for the radiator panel, higher flexibility in electronic unit mounting and less constraints in system testing.

VII. Conclusion

We have shown that stacks of high-conductive graphite foils, which are sandwiched between aluminum sheets with integrated hooks, can replace in payload radiator applications the commonly used, expensive and heavy heat pipe network. The integrated hooks increase both the out-of-plane thermal conductivity and the compound strength. Other expected applications are passive deployable radiators, housings of high-power electronics and thermal doubler in spacecraft thermal management systems. In a next development step, we will validate the manufacturing process and perform thorough testing to determine the complete range of thermal and mechanical properties of the compound. A first prototype of a passive deployable radiator will be developed and verified by analysis and test in an ESA ARTES activity, which has started in March 2020.

Acknowledgments

The presented work has been performed under ESA contract within the program "ARTES Future Preparation Element – Innovative Technologies or Missions". The authors acknowledge the excellent and well received support of the ESA Technical Officer Daniel Bast.

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