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x Thermal Straps

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Overview

Thermal straps, also known as heat straps or flexible conductive links, offer design solutions for enhancing the thermal bond of two items that may need to be mechanically decoupled. The need for mechanical decoupling can be driven by requirements for things like vibration or load isolation, or simply by packaging constraints. A few examples include thermal straps used to mechanically isolate delicate spaceborne detectors from cryocooler vibrations, or thermal straps coupling a high-dissipation electronic component to a heat sink on an adjacent surface in a volume optimized electronics unit.

Although commonly made from metal, thermal straps achieve their high degree of flexibility from their configuration and construction, typically utilizing fine wire rope (Fig. x.1) or many layers of thin conductive foil (Fig. x.2), as discussed in Ref. x.1. Because foil layers can assemble tightly together with little space between them, foil based thermal straps usually require less volume to achieve an equivalent conductor cross-section when compared to a wire rope based thermal strap. One benefit of wire rope style thermal straps is the axisymmetric stiffness uniformity of the individual cables in multiple translational and rotational directions as shown in Fig. x.3[x.1]. Due to the planar shape of their individual foil layers, foil style thermal straps can be more flexible than wire rope straps in the perpendicular plane of their foils, as shown in Fig. x.4.[x.1]. Foil strap flexibility can also be made more directionally uniform by using a strap with a twist manufactured into its geometry as show in Fig. x.5[x.2]. Metallic foil layers can be formed into almost any shape using a high temperature inert gas oven Fig. x.6[x.2] and are commonly configured into an "S" or "C" shape to achieve increased mechanical compliance in a specific direction Ref. x.3.

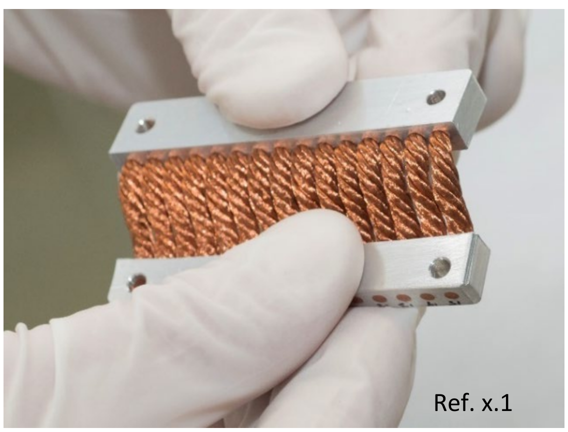

Fig. x.1. Wire Rope Based Thermal Strap

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Fig. x.2. Foil Based Thermal Straps

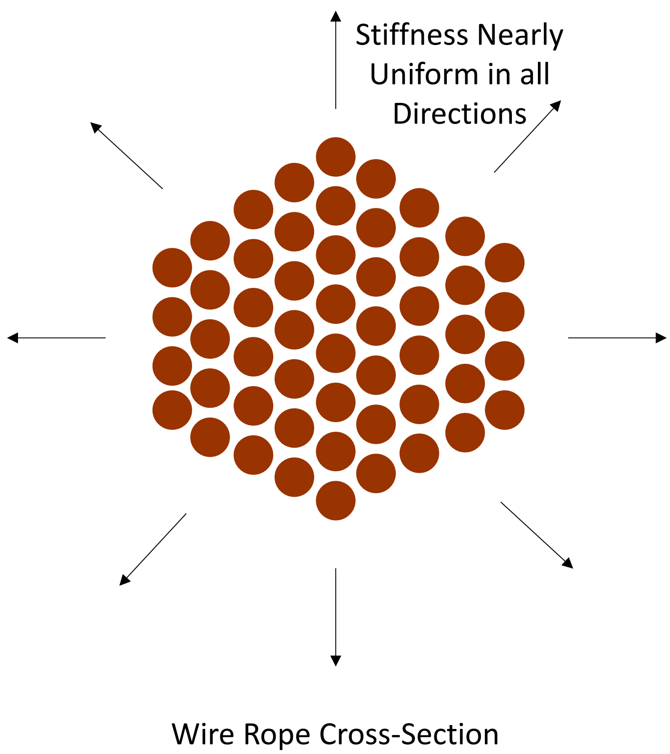

Fig. x.3. Flexibility of a Wire Rope Type Thermal Strap

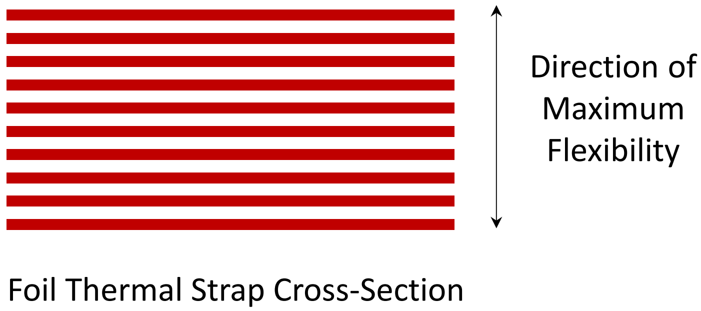

Fig. x.4. Flexibility of a Foil Type Thermal Strap

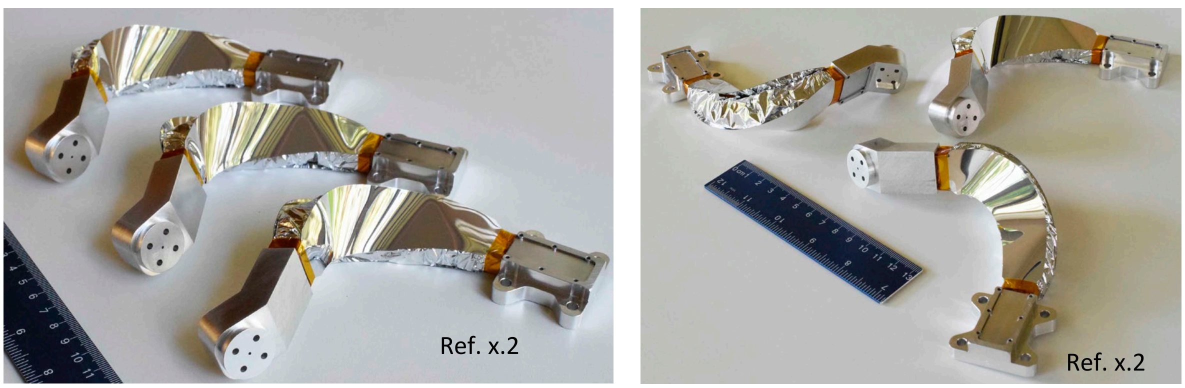

Fig. x.5. MAIA Focal Plane Pyrolytic Graphite Thermal Straps with Twisted Geometry

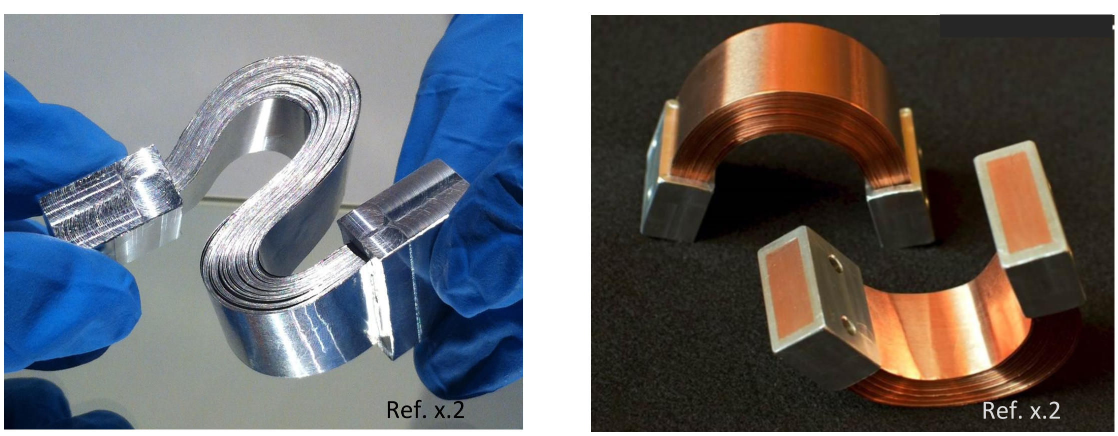

Fig. x.6. Typical S and C Thermal Strap Configurations

Thermal straps come in a range of configurations. For example, Figure x.7 shows simple two ended straps with block end fittings. In contrast, Figure x.8 gives examples of multi-branch configurations with complex interfaces. Typically, thermal straps are constructed of high thermal conductivity materials, with aluminum and copper being the most common. Graphite based materials are also widely used in thermal straps and have seen an increase in popularity in recent years. The forms of graphite commonly used in thrermal straps are anisotrocpic with a very high in-plane conductance compared to that of copper or aluminum at temperatures above 70K, as will be discussed in the Conductivity/Conductance section of this chapter. As a result, thermal straps made from graphite materials usually have significantly less mass and volume when compared to aluminum or copper thermal straps of equivalent thermal conductance.

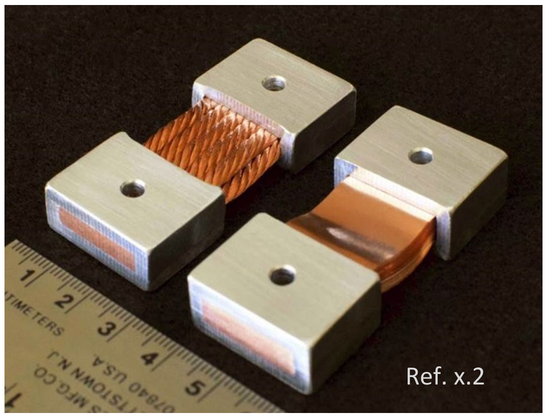

Fig. x.7. Basic Two Ended Thermal Straps

Fig. x.8. Multi-Termination Thermal Straps

Minimizing supported thermal strap mass is often a primary design objective for highly thermally isolated items like imaging detectors. To the first order, the more thermal strap mass a detector mount must support, the more cross-sectional area the mount will need in order to support that mass. This additional cross-sectional area usually drives an increase in parasitic heat load through the detector mount. This is one factor that has been contributing to the increase in popularity of graphite based thermal straps in recent years. Table X.1 provides a comparison of some key material properties of aluminum, copper and annealed pyrolytic graphite materials commonly used in thermal straps.

Table x.1. Comparison of Common Thermal Strap Material Properties at Room Temperature

Property	Pure Copper	Pure Aluminum	Pyrolytic Graphite
Thermal Conductivity (W/m-K)	401 [x.4]	237 [x.5]	1,700 [x.7]
Density (kg/m^3)	8930 [x.4]	2700 [x.5]	2260 [x.7]
Elastic Modulus (GPa)	117 [x.6]	69 [x.6]	552 [x.8]

End Fittings

Rigid fittings are typically used at thermal strap connecting interfaces to facilitate efficient heat transfer across the mating surfaces. In almost all cases end fittings are made from a high thermal conductivity metal (e.g. aluminum or copper) to provide structural load spreading and to maximize interface pressure across the mating interface. End fittings are attached to a thermal strap's flexible wires or foils using several processes including swaging, brazing, soldering, welding, bonding, clamping, and diffusion bonding. Aluminum end blocks can be used with copper, aluminum, or graphite-based foils, however use of copper end blocks with aluminum foils or wires is not recommended for cold applications. The coefficient of thermal expansion (CTE) mismatch between copper and aluminum will cause the interface pressure between the copper block and aluminum foils or wires to decrease, resulting in an increase in the strap's thermal resistance[x.1].

An interesting recent application of diffusion bonding at end fitting locations is showcased in the L'Ralph instrument thermal strap used on NASA's Lucy mission. The L'Ralph strap coupled a passively cooled infrared spectrometer to its radiator, which cooled the spectrometer to approximately 100K. The strap was 82.55 mm in length and used 25 high purity (99.99+%) copper foils that are each 0.127 mm thick and 35 mm wide. Fig. x.9 shows the strap at various stages of the manufacturing process[x.9].

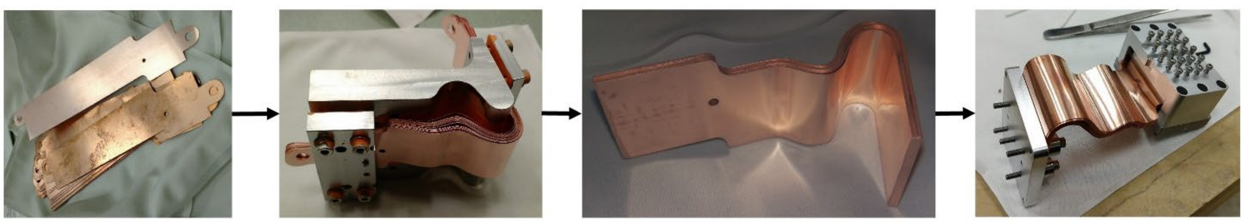

Fig. x.9. L'Ralph Thermal Strap at Various Stages of the end Fitting Diffusion Process

For very high-performance thermal straps, minimizing resistance between foils at end and interface locations can be a key factor in meeting performance requirements. The interface resistance between each foil can be reduced substantially by utilizing a diffusion bonding process. In the diffusion bonding process, the copper foils are stacked into a bonding fixture which clamps them in the desired configuration. The clamped foils are then annealed for several hours at 800°C in order to fuse them together at the clamped locations[x.9,x.10,x.11].

Conductivity / Conductance

Thermal straps are widely used in the cooling of delicate detector modules, and they are especially suited to transferring heat in cryogenic applications. This is primarily due to a large increase in the thermal conductivity of the metals commonly used in thermal straps at cryogenic temperatures. Fig. x.10 shows a comparison of the thermal conductivity of candidate thermal strap materials from room temperature to cryogenic temperatures[x.1]. Volume II of the Spacecraft Thermal Control Handbook[x.3] provides a well written overview of cryogenic applications of thermal straps.

It should also be mentioned that thermal conductivity of copper and aluminum is a strong function of purity at cryogenic temperatures. This relationship is shown in Fig. x.11 which compares the thermal conductivity of copper as a function of residual resistivity ratio (RRR, a measure of purity) at temperatures less than 100K[x.1].

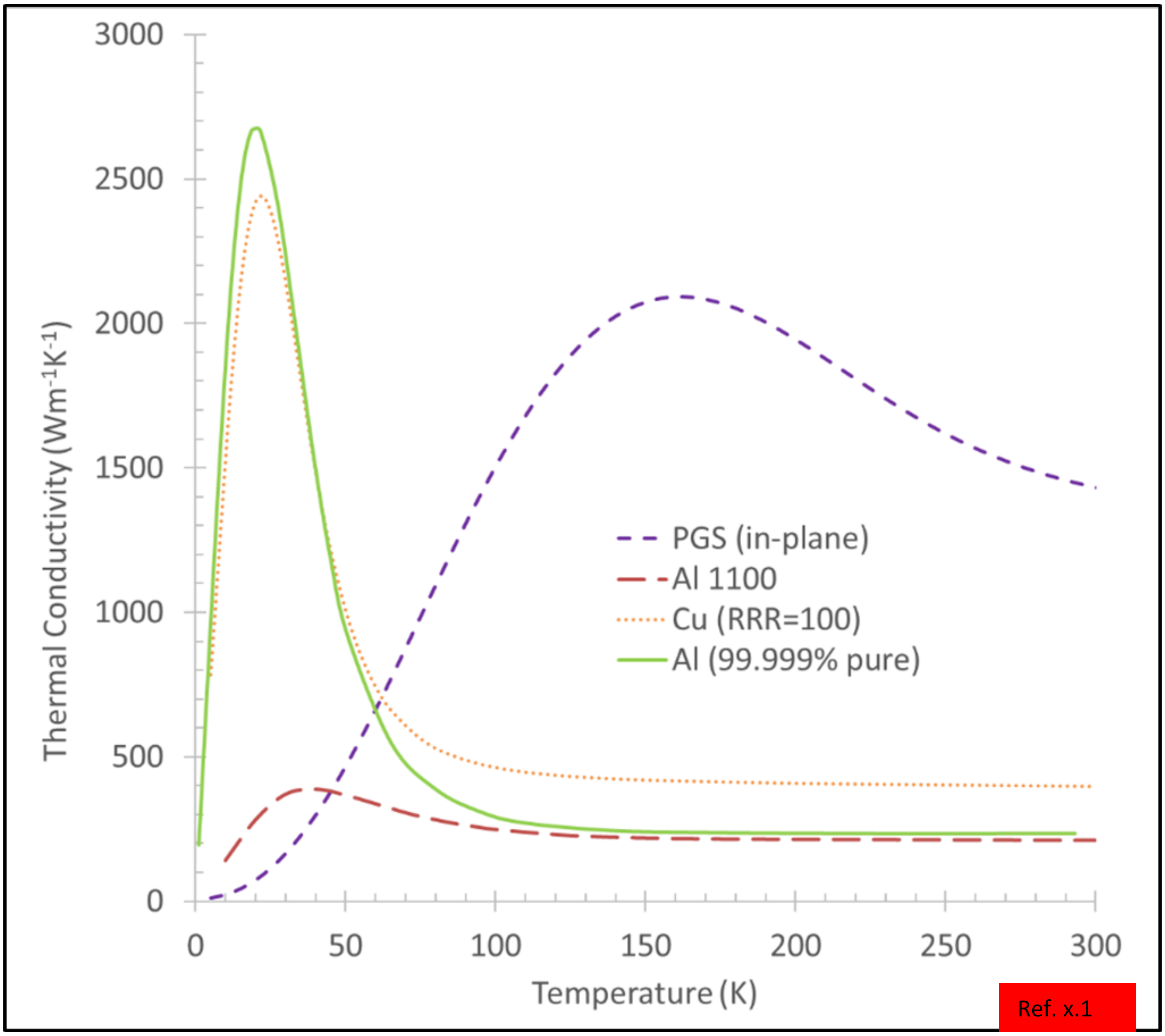

Fig. x.10. Metallic and Pyrolytic Graphite Sheet (PGS) Thermal Conductivity as a Function of Temperature

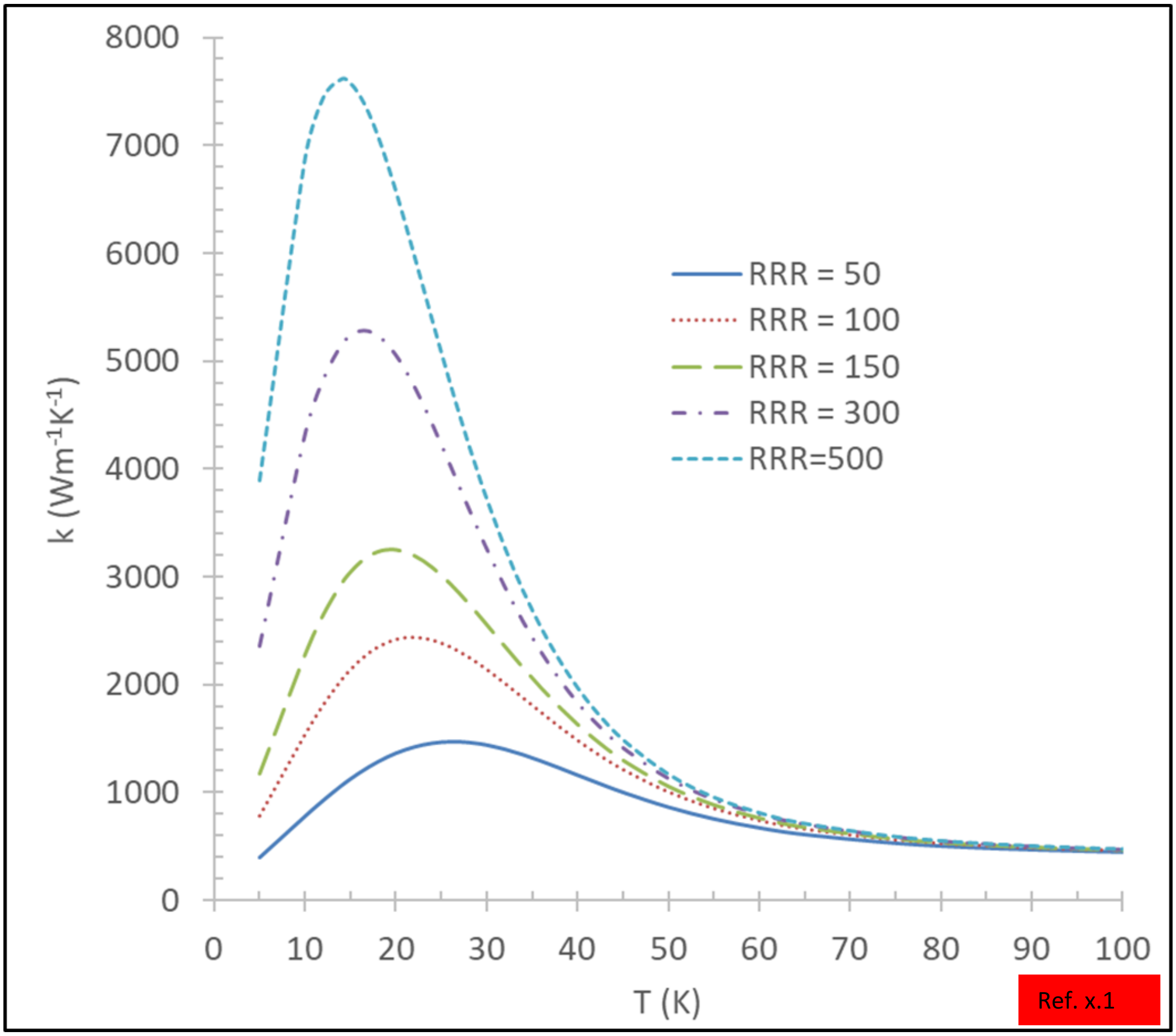

Fig. x.11. Thermal Conductivity of Copper as a Function of RRR and Temperature

Because thermal straps rely on conduction, they are best suited for transferring heat across short distances, such as 30cm or less. For heat transfer across greater distances requiring mechanical isolation, the use of a thermal strap in combination with a more efficient heat transfer device (e.g. a heat pipe) should be considered.

For non-cryogenic applications, the focus of this volume, radiation exchange between a thermal strap and its surroundings is usually negligible when compared to the heat flowing through the thermal strap. The analysis of a thermal strap's internal conductance (between its mating interfaces) is primarily a conduction problem. With current manufacturing technologies, the thermal resistance between conductive foil ribbons or wires and swaged end fittings can be assumed to be second order (Fig. x.2). As a result, thermal conductance for a thermal strap with a common material used for both its end fittings and flexible section can be determined to the first order by considering only the cross-sectional area and length of its conducting foil ribbons or wires and end fittings. An expression for evaluating such a thermal strap is provided in Equ. x.1[X.12]. In Equ. x.1, k represents the thermal strap material's thermal conductivity, A represents the cross-sectional area of the thermal strap perpendicular to the heat flow path and L represents the length along the heat flow path.

$$G_{TS} = (kA/L) \quad (x.1)$$

Equ. x.2 extends Equ. x.1 to account for a simple two-ended strap with swaged end fittings, where the end fitting material is different than the flexible section material.

$$G_{TS} = 1/\left((1/(k_{EF1}A_{EF1}/L_{EF1})) + (1/(k_F A_F/L_F)) + (1/(k_{EF2}A_{EF2}/L_{EF2}))\right) \quad (x.2)$$

In Equ X.2, k_{EF1}, k_F and k_{EF2} represent the thermal conductivities of end fitting 1, flexible section, and end fitting 2 materials, respectively. A_{EF1}, A_F and A_{EF2} are the cross-sectional areas perpendicular to the heat flow paths of end fitting 1, the flexible section and end fitting 2, respectively. L_{EF1}, L_F and L_{EF2} are the lengths of the conduction paths of end fitting 1, the flexible section, and end fitting 2, respectively. G_{TS} is the overall internal thermal conductance of the thermal strap between its mating interfaces. Once first order thermal strap requirements are determined, thermal strap vendors should be consulted for information about the thermal resistance between end fittings and foils or wires in order to verify the end fitting to foil (or wire) thermal resistance. Note that resistance at thermal strap mating interfaces is discussed in the Interface Resistance section later in this chapter.

Ref. x.3 extends Equ. x.1 to include an "end piece efficiency" η_e, that can be used to account for non-negligible flexible section to end fitting thermal resistance. Ref. x.3 also includes a "packing efficiency" η_p, that can be used if the dimensions and quantity of individual flexible section conductors is unknown. In addition, Ref. x.3 includes a "shape efficiency" η_s, that can be used if there is an interest in comparing the performance of a thermal strap to a non-compliant conductor spanning the minimum distance between mating interfaces. The extended equation from Ref. x.3 that utilizes these efficiency factors is repeated as Equ. x.3, below:

$$G_{TS} = (kA/L)\,\eta_p\eta_s\eta_e \quad (x.3)$$

Ranges of the three efficiency factors are given in Ref. x.3 as follows:

η_e: 0.3 to 1.0
η_p: 0.5 to 1.0
η_s: 0.5 to 0.75

Note that a simple foil type thermal strap with swaged ends (Fig. x.2) would have packing and end piece efficiencies (η_p and η_e) very close to 1.0.

For cryogenic applications, or applications where there is a large temperature difference between a thermal strap and its surroundings, radiation exchange should be considered. It is common knowledge that metal surfaces provide a fairly low thermal emissivity, and one may be tempted to assume that radiation is not a concern for a metallic thermal strap. Unfortunately, the cavities formed between the wires or foil layers within a thermal strap's flexible section have a high effective emissivity. As a result, wire thermal straps typically have a fairly high thermal emissivity in any direction, and foil thermal straps have a high emissivity at the open edges where gaps form between the foil layers. Because of this, thermal strap foils or wires are commonly enclosed in radiation shields constructed of a very thin low emissivity material to limit thermal radiation exchange (e.g., a polyimide film coated with vapor deposited aluminum). Representative radiation shield designs are pictured in Fig. x.5, and the top and bottom images in the right-hand column of Fig. x.8. The increased thermal strap stiffness (reduced flexibility) resulting from radiation shields of this type is usually acceptable in most applications. However, the effect of shield stiffness should be considered when shields are used on very flexible straps.

Mechanical Behavior

In addition to thermal performance, the mechanical behavior of a thermal strap is of primary concern. Thermal strap flexibility is usually quantified in terms of spring constants at the strap terminations in the six primary translational and rotational degrees of freedom, as shown in Fig. x.12.

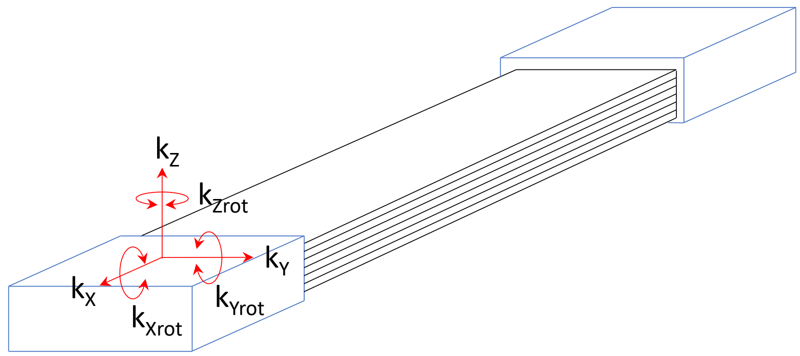

Fig. x.12 Thermal Strap Spring Constant Directions

A detailed analytical discussion of the mechanical behavior of thermal straps is beyond the scope of this chapter. However, in general, holding the total cross-sectional area of conductor constant, a thermal strap constructed of a larger number of finer gauge wires (or thinner foils) will be more flexible than a thermal strap constructed from a lesser number of larger gauge wires (or thicker foils). Unfortunately, due to the non-linear nature of the interactions between the thermal strap wires or foils, the mechanical performance of thermal straps is very difficult to predict accurately. As a result, the spring constants of new thermal strap designs are usually estimated using empirical data from thermal straps of similar construction. Spring constant data for existing thermal strap designs is often available from vendors.

In situations where the flexibility of a thermal strap is a driving design requirement, the responsible engineer should consider having a prototype thermal strap built and its spring constants measured before committing to a final design. Fig. x.13 shows a simple apparatus used to measure the spring constants of thermal straps along with their radiation shields. In the apparatus shown in Fig. x.13, force is applied through a thin wire and a precision force gauge is used to measure deflection force.

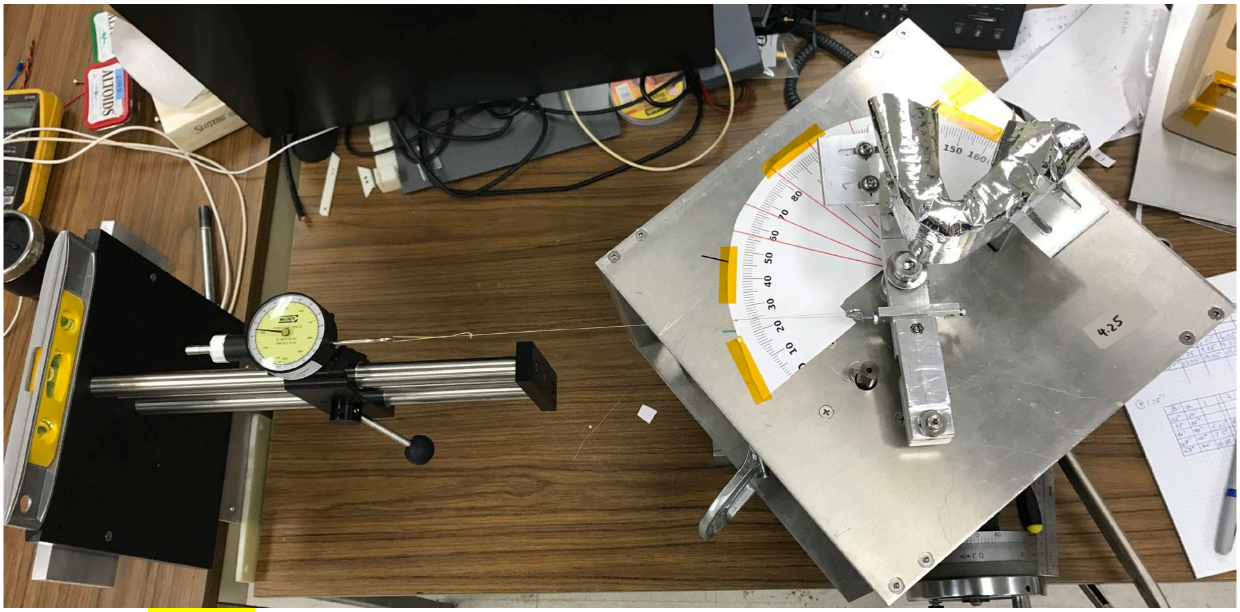

Fig. x.13 Simple Thermal Strap Spring Constant Measurement Apparatus

Interface Resistance

Clearly, the mating interfaces at a thermal strap's terminations and end fittings can induce significant thermal resistance and should be considered as part of the overall performance of the thermal strap system. Thermal interface fillers (see Chapter X) utilized at thermal strap end fitting interfaces can improve overall thermal strap system conductance. Unfortunately, some common thermal interface materials tend to creep with time, which can affect long-term interface thermal performance.

Because thermal strap end fitting interfaces are often small and of simple geometry, controlling end fitting surface roughness and flatness should be considered as a means of enhancing thermal strap interface performance. Often thermal strap end fitting interface resistance can be dramatically reduced by simply specifying very flat, polished interface surfaces[X.13]. This is especially useful in applications where the thermal performance of a system employing a thermal strap needs to be consistent for many years.

A key concern for cryogenic thermal straps is maintaining interface pressure at interfaces as temperatures drop from room temperature down to the cold operating range. The different coefficients of thermal expansion (CTE) of end fitting and fastener materials can cause a loss of interface preload. This is commonly addressed by the use of Belleville washers under thermal strap fastener heads.

An example of higher-performance thermal strap interfaces is showcased in the L'Ralph instrument's thermal strap which utilized unique approaches at both its radiator and detector interfaces[X.9]. At the radiator end of the L'Ralph strap the aluminum end fitting is sandwiched between the radiator and a titanium block. The total shrinkage of the longer stainless-steel fasteners needed to pass through the thickness of the thermal strap end fitting and the titanium block was matched to the total shrinkage of the titanium block and the strap end fitting. The CTE of the Titanium is less than that of stainless steel, and the CTE of aluminum is more than that of stainless steel. By tailoring the thickness of the titanium block and the aluminum thermal strap end fitting the total shrinkage of the two was matched to the shrinkage of the stainless steel fasteners[X.9].

The detector interface end of the L'Ralph strap used a clamp design stack-up to ensure interface pressure is maintained while meeting detector electrical isolation requirements (see Figs. x.14, x.15, and Ref. x.9). The detector interface combined the varying CTEs of aluminum, G-10, and sapphire to minimize interface resistance and maximize electrical isolation at 100K. An even distribution of pressure is needed to reduce the risk of the sapphire plate cracking. The L'Ralph thermal strap was able to achieve an end-to-end conductance of 0.41 W/K and an operational temperature delta of less than 1K[X.9].

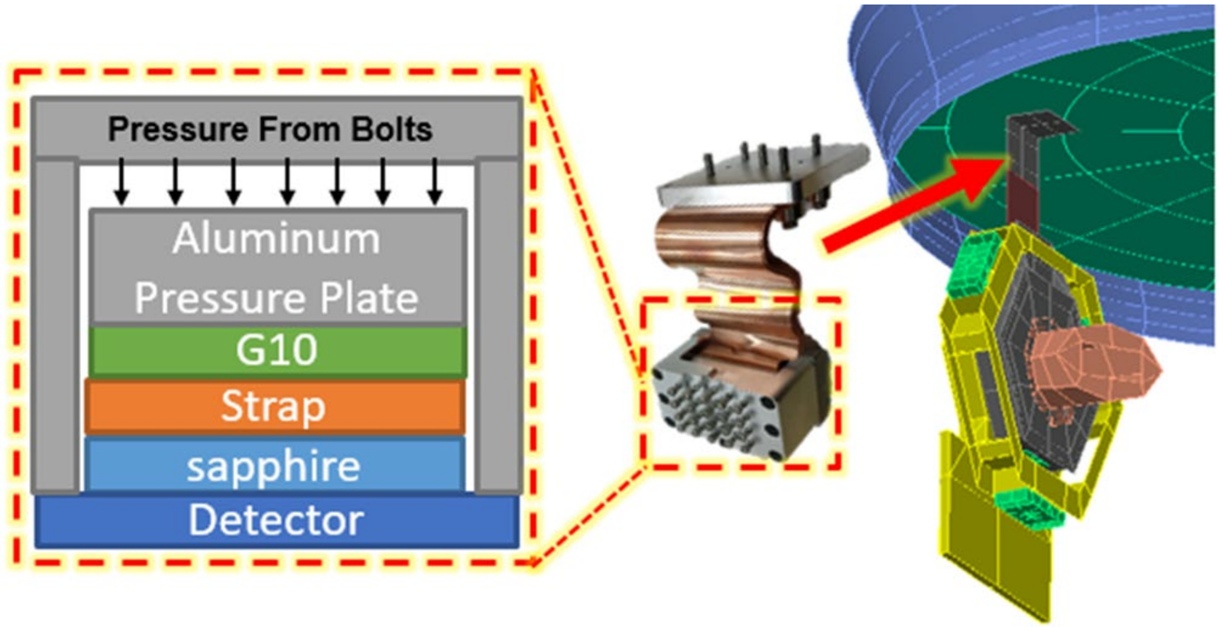

Fig. x.14 **L'Ralph Thermal Strap Detector Clamping Interface Stack-up**

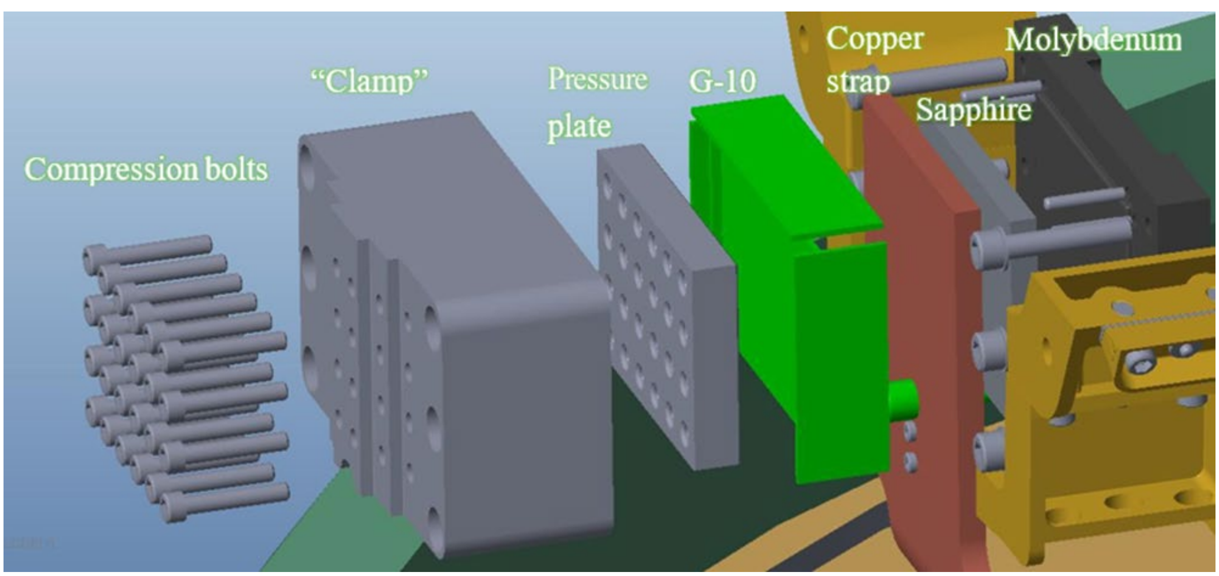

Fig. x.15 **Exploded View of L'Ralph Thermal Strap Detector Clamping Interface Stack-up**

Contamination

Thermal straps are often used near contamination-sensitive devices. Both copper and aluminum can oxidize in air, creating a risk of oxide particles shedding when disturbed, such as during launch vibration[X.1]. Graphite straps can also shed particles which could be a concern for nearby optics or detectors.

In addition, the many cavities formed between the wires or foils in a thermal strap make them difficult to clean. It is important to work with thermal strap vendors to specify appropriate cleanliness measures to be incorporated during the fabrication of thermal straps intended for contamination-sensitive applications. Fortunately, a single layer radiation shield can also act as a particle containment sleeve (PCS) if properly configured around a thermal strap's foils or wires[X.1]. Particle containment sleeves usually include a filter to contain particles as gas escapes during differential pressure changes, such as during launch ascent depressurization.

Radiation Sensitivity

Copper and aluminum are generally insensitive to the types of radiation seen in spaced based applications. Pyrolytic graphite materials have also been shown to withstand radiation levels of 40 Mrads at a dose of 215.2 rad/sec with no observable impact to performance[X.14].

Dynamic Movement

Thermal straps are often used where they will experience dynamic movements over their mission life and can be very robust when properly designed. If the number of dynamic movement cycles is expected to be high, the thermal strap vendor should be consulted for input on how best to configure the strap for the expected movement. In addition, qualification testing is recommended for these high cycle applications[X.1].

Due to their excellent flexibility, thermal straps are being used as a reliable, low-cost alternative to coiled loop heat pipes or flexible pumped fluid loops for transferring heat across rotating joints.

The fatigue behavior of aluminum is well documented, and as long as plastic deformation is avoided; it can withstand many thousands of flexure cycles. Pyrolytic graphite materials also exhibit excellent fatigue properties, with thermal strap foil material having been tested to hundreds of thousands of displacement cycles[X.1]. Copper is known to work harden, so copper straps used in highly cyclical applications should be assessed accordingly.

One specific example of a thermal strap being used to transfer heat across a rotating joint is the articulating thermal strap utilized on JPL's Multi-Angle Imager for Aerosols (MAIA) instrument[X.15]. The MAIA articulating thermal strap provides approximately 0.5 W/°C of thermal conductance while accommodating rotations of greater than 70 degrees. The images in Fig. x.16 show the qualification MAIA articulating thermal strap with and without its radiation shield after completing 115,000 articulation cycles over a temperature range of -98 to +70°C and a rotation range of greater than 70 degrees. As noted in Ref. x.15, there was no degradation in the thermal strap's performance after completing the cycles.

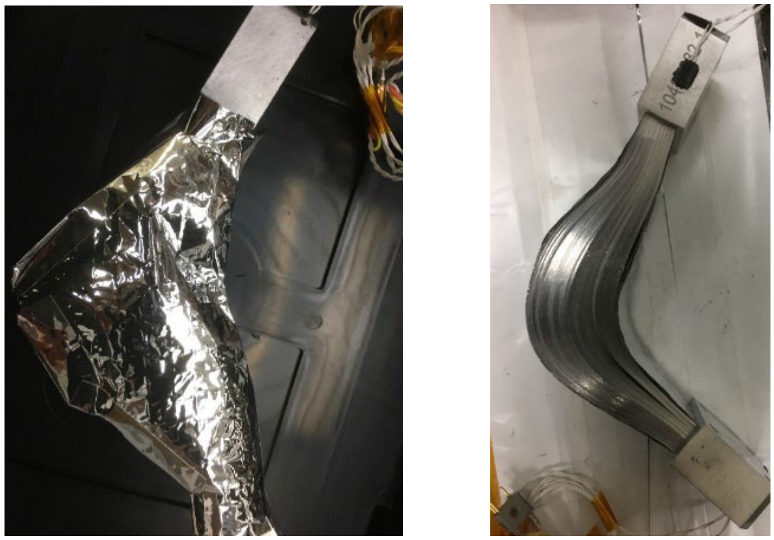

Fig. x.16 MAIA Articulating Thermal Strap and Radiation Shield

Other Considerations

Thermal straps are flexible. Applying geometric dimensioning and tolerancing (GD&T) that relates one end of a strap to the other end of the strap is not typically required. Doing so will add unnecessary cost to a strap procurement. Instead, consider the use of rigid fixtures as inspection aids for interfaces and geometry[X.1].

The foils or wires in a thermal strap typically pass through the rigid end or interface blocks, as shown in Fig. x.7. Although a strap's foils or wires can support compressive structural loads from through holes, they cannot support threaded interface loads. When designing a thermal strap be sure to specify that threaded holes in end or interface blocks are included only in regions that do not penetrate the straps foils or wires[X.1].

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