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CARBON VELVET THERMAL INTERFACE GASKETS

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ABSTRACT

Carbon velvet thermal gaskets are presented that have high interface conductance at low contact pressure. The velvet consists of aligned, high-κ carbon fibers that span the gap between mating surfaces. Gels may be used for low debris applications. High aspect ratio fibers bend easily and conform to surface roughness with low interface pressure. Different configurations are recommended for irregular gaps (bowed surfaces), sliding interfaces, high temperature applications, low pressure interfaces, and bonded interfaces that can be parted using simple tools. Experience with selected aerospace applications are reviewed.

INTRODUCTION

Although often under appreciated, effective interfacing of thermal components is very important in optimizing the performance of thermal management systems. Present commercial thermal gaskets are limited by either low bulk conductivity (κ < 10 W/mK), or by low contact (interface) conductance where the gasket contacts a surface, leading to typical overall conductance values of h < 5,000 W/m^{2}K. ESLI has developed high-conductivity (κ = 200 W/mK) gaskets with good interface conductance. The best ESLI gaskets have h values exceeding 10,000 W/m^{2}K. These gaskets consist of aligned, high-κ carbon fibers which span the gap between mating surfaces (see **Figure 1**). The velvety gasket is very compliant, conforming to nonflat surfaces and requiring only modest applied pressure (0 – 20 psi).

Conventional Thermal Interface Methods

Existing methods of thermal attach include bonding (brazing, soldering, adhesives, tapes) or bolting/clamping, often with a filler such as a thermal gasket or grease. The ideal interface will fill the gaps between the two elements with high thermal conductivity material. It will be compliant so that only a minimal amount of pressure is required for intimate contact, precluding the need for heavy bolts or clamping mechanism, and eliminating the necessity of flat, smooth mating surfaces. Furthermore, it will not fail under stresses induced by thermal expansion mismatch.

Conventional thermal gaskets consist of small, roughly spherical particles (e.g. alumina, BN, Ag) suspended in a compliant polymer media such as

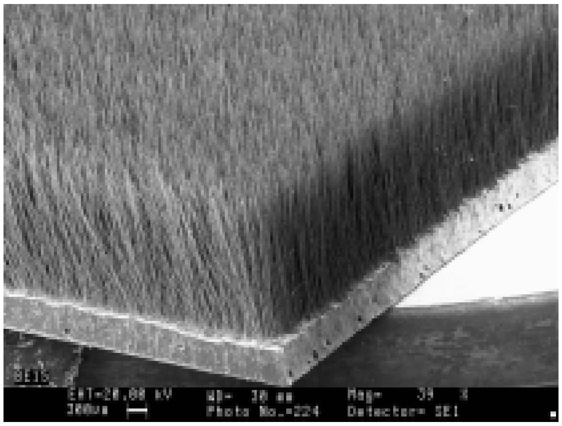

Figure 1. SEM of ESLI carbon fiber velvet in vinyl substrate. Fibers are ~1 mm in length.

Table 1. Properties of selected carbon fiber velvets, where L is fiber length, D is fiber diameter, ϕ is packing fraction of fibers, κ_f is the fiber thermal conductivity, E is fiber modulus, σ_{cr} is critical stress for buckling the velvet, κ_{vel} is the bulk conductivity of the velvet, and $R_\theta = h_{total}^{-1}$ is the total thermal resistance of the velvet, including interfaces.

Fiber	***L (mm)***	***D (μm)***	***φ (%)***	κ_f ***(W/mK)***	***E (Msi)***	σ_{cr} ***(psi)***	κ_{vel} ***(W/mK)***	R_θ ***(°C-in²/W)***
A20	0.5	10	10	1000	130	800	100	0.1
J60	1.5	7	3	100-200	63	5	3 – 6	1
F100	2.5	6	2	20	34	0.6	0.4	10

silicone. Although each particle has high thermal conductivity, the interface between the particles has low conductance. The effective κ of the composite is limited by these numerous interfaces and the highest κ achieved is of the order of only a few W/mK.

ESLI *Vel-Therm*™ Gaskets

Under a NASA JSC SBIR Contract, ESLI has developed a high-conductivity, ultra-compliant thermal interface material, which we presently market as *Vel-Therm*™. This material is a soft, carbon fiber velvet consisting of numerous high-κ (as high as 1000 W/mK) carbon fibers aligned perpendicularly to the substrate, anchored in a thin layer of adhesive. The velvets are fabricated by precision cutting continuous tows of carbon fiber and electrostatically "flocking" the fibers into uncured adhesive using proprietary techniques. Fiber diameters D vary typically from 5 to 12 μm. Fiber lengths L vary from 0.25 – 3 mm. Fiber packing fractions ϕ vary from 0.1 – 24%. Various substrates are used including metal foils, polymers, and carbon sheets. Various adhesives are used including silicones, epoxies, ceramic adhesives, and carbonizable adhesives for high-temperature use. **Figure 1** shows such a brush embedded in a vinyl substrate. Free-standing gaskets can also be fabricated.

These gaskets are particularly useful in applications with large or uneven gaps, CTE mismatch, or sliding interfaces. Each fiber provides a thermal path from one surface to the other. For uneven gaps due to bowed or rough surfaces, each fiber bends independently in order to span the local gap. In this way, high contact areas can be achieved. Low pressures are necessary to allow each fiber to touch both surfaces. Contact is maintained by either clamping, or pressing the fiber tips into adhesive and bonding in place. By using high-κ fibers oriented in the direction of heat flow, ESLI gaskets have much higher κ (as high as 200 W/mK) while at the same time being even more compliant than conventional, particle-filled gaskets. Thus, they exhibit high total thermal conductance in actual applications.

Many configurations are possible depending on the application requirements. Thus, the velvet can be bonded to one or both surfaces, with various adhesives or PSA "tapes" including metal foils. Fibers can be biased at an angle for improved compliance. Two velvets can be meshed together (like Velcro®) for an ultra-compliant configuration. These brushes can also be engineered for high temperature capability, low outgassing, relief of CTE mismatch, sliding applications, and vibration isolation. The highest measured total thermal conductance (h_{total} ~ 10,000 W/m^{2}K with 10 psi applied pressure) has been achieved by a high-κ carbon fiber interleaf "gasket" in which the fibers are encapsulated in a silicone gel encapsulant.

Thermal velvets can be tailored for specific applications by varying the fiber type, length, and packing fraction. The properties of carbon fibers are such that the higher the thermal conductivity, the higher the modulus. Thus, there is a trade-off between thermal and mechanical performance. Furthermore, the achievable packing fraction using present techniques varies inversely with the length of the fiber. Thus, the highest thermally conducting velvets are thinnest and stiffest while the softest (most compliant) velvets are thick and have lower thermal conductance.

We focus in this paper on three types of velvets with properties shown in **Table 1**. These span from the most conductive/least compliant to the most compliant/least conductive.

COMPLIANCE

These velvets are highly compliant in the sense that the fibers can bend independently by different amounts until all fibers come in contact with the mating surface. The theoretical minimum pressure needed to accomplish this is the critical stress for buckling, σ_{cr}. The measured stress-strain curves of these velvets are hysteretic as demonstrated in **Figure 2**. The stress-strain curve scales with the fiber Young's modulus E, the fiber packing fraction ϕ, and the inverse square of the fiber aspect ratio L/D as:

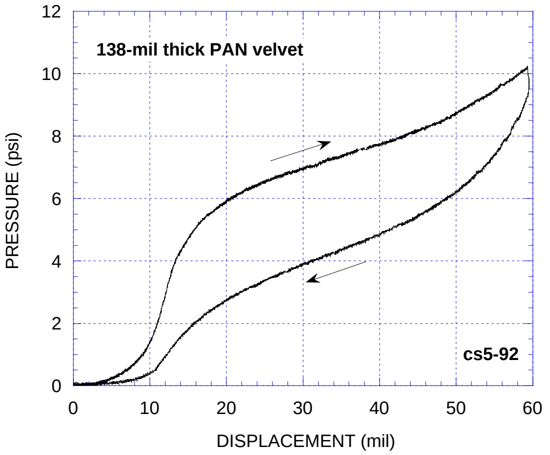

Figure 2. Stress-strain curve of PAN velvet obtained by vertically compressing (upper branch) and decompressing (lower branch) the velvet.

$$\sigma(\varepsilon) \propto E\phi \frac{D^2}{L^2} \qquad \text{(Eq. 2)}$$

In addition, a proportionality coefficient depends sensitively on the loading conditions of the fibers of the velvet. This coefficient is minimal when the velvet slides into position (fixed/free end conditions); it is maximal when both ends of the velvet are anchored (e.g. with adhesive) and forced to compress without any lateral movement (fixed/fixed). Most applications lie somewhere in between these two extremes which differ by a factor of 16.[1]

We believe that the hysteresis is caused largely by changes in the loading conditions upon compression and decompression. For example, upon decompression, the fibers ends are free to slide back into position with minimal buckling resistance. The fibers themselves exhibit elastic behavior up to the point of breaking [Dresselhauss].

The curve further deviates from theoretical expectations due to uneven fiber lengths, fibers that are not strictly perpendicular to the substrate, and fibers pushing into surrounding fibers.

THERMAL CONDUCTANCE

The total thermal resistance of a thermal gasket interface is the sum of three contributions: the resistance of the bulk velvet material itself, and the resistances of each interface where the material comes in contact with the interfacing surface. We prefer to use conductance (inverse of resistance) and therefore write this as:

$$h_{total}^{-1} = h_{vel}^{-1} + h_{\text{int}erface1}^{-1} + h_{\text{int}erface2}^{-1} \qquad \text{(Eq. 1)}$$

where $h_{vel} = \kappa_{vel}/L$ and $h_{interface}$ is a function of surface roughness, thermal conductivity, hardness, and applied pressure. For our best gaskets, $h_{vel} = 200{,}000$ W/m^{2}K, which is 20 times higher than h_{total}. Thus, the total joint resistance is dominated by the contact resistance between the fiber tips and the contacting surfaces. Each interface has $h_{interface} \sim 20{,}000$ W/m^{2}K. Current development efforts at ESLI are dedicated to increasing the contact conductance to values comparable to the bulk conductance, which could improve the total conductance by an order of magnitude, exceeding 100,000 W/m^{2}K.

Thermal Conductance Measurement

Thermal conductance h is measured at ESLI using a standard cut-bar steady-state method in which the test specimen is sandwiched between the flat, parallel faces of two 6061 alloy Al cylinders. the upper cylinder (bar) is heated from above and the lower bar sits on a cold plate. Platinum resistance temperature sensors (RTD's) in the Al bars measure the heat flux (q/A) flowing through them and the temperature drop (ΔT) across the test specimen. The thermal conductance (h) is calculated from their ratio. For measurement in air, our test rig is set up in a materials testing machine which gives simultaneous measurement of contact pressure and gap. Generally h increases with applied (uniaxial) pressure. Although the pressure and gap dependence of h depends on the loading history, data is usually taken for direct compression/decompression of the test specimen. The test rig can be placed in a vacuum chamber for thermal vacuum measurements ($P < 10^{-5}$ torr).

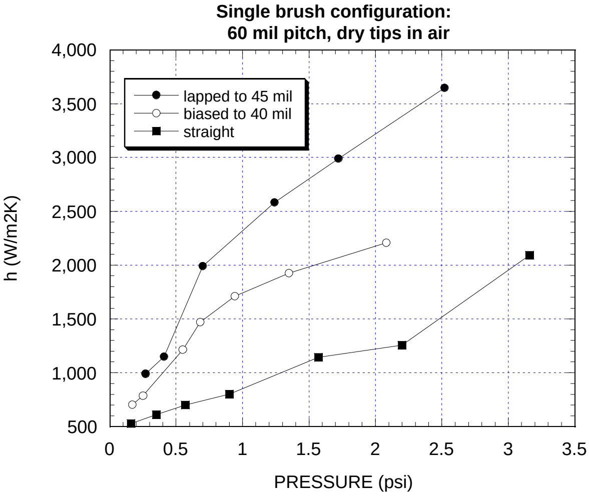

Figure 3. Thermal conductance h vs applied uniaxial pressure for 3 pitch carbon fiber velvets.

Thermal Conductance Results

Shown in **Figure 3** is the total measured thermal conductance *h* as a function of applied pressure *P* of 3 pitch fiber velvets. The fibers were applied directly into thermally-loaded adhesive spread onto the lower Al bar of the thermal rig. The upper fiber tips were pressed against the upper Al bar and the conductance recorded as a function of applied pressure.

The thermal resistance is dominated by the upper interface where the tips contact the Al. Much of the heat is conducted from fiber to Al through the air, which has low thermal conductivity (0.025 W/mK). The conductance improves for given pressure by biasing the fibers at an angle or by lapping the fiber tips so that they are all the same height.

The thermal conductance can be improved further by reducing the resistance at the dry tip interface. Shown in Fig. x is h vs P for 20-mil thick pitch fiber velvet which is encapsulated by a silicone gel. The thermal conductivity of the gel (0.1 W/mK) is higher than air, thereby decreasing the thermal resistance at the tips. Furthermore, the fibers are able to bend within the gel, which behaves much like a liquid.

Shown in **Figure** 55 is the total measured thermal conductance as a function of compression of the second specimen represented in **Table 1**. The base of the velvet is supported on an Al tape substrate, attached with flexible epoxy. The Al tape is attached to the bottom Al bar. The thermal conductance was measured in air after the velvet was slid between the Al bars. The approximate contributions to the conductance in W/m^{2}K are: 4000 for the tape/epoxy interface, 2500 for the fibers, and 1000 – 2000 for the dry fiber tips against Al in air interface. Wetting the tips with thermal grease, epoxy, or some other higher conducting medium than air ($\kappa \sim 0.025$ W/mK) significantly improves the conductance. The thermal conductance in vacuum is less than 300 W/m^{2}K. This dry, sliding configuration has been used for the Mars rover battery pack. Note that the velvet exerts only a few psi up to about 50% compression and fills a fairly large gap (30 – 50 mil). A 100-mil long fiber version of this configuration has been developed at ESLI to improve the thermal performance of the radiant fin interface planned for use on the International Space Station.[3] In this case, heat conduction through the fibers, even in vacuum, is more efficient than radiant heat exchange.

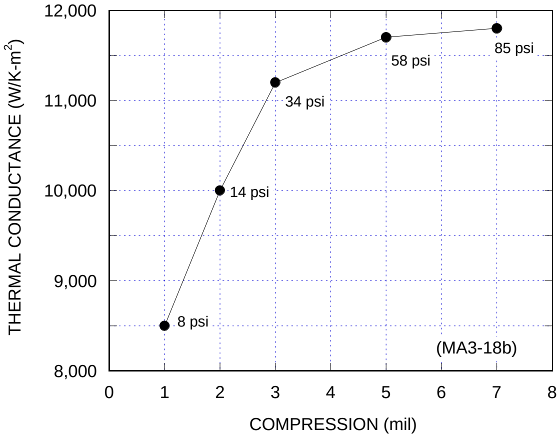

Figure 4. Thermal conductance of silicone gel-filled pitch fiber gasket (20 mil thick) as a function of compression.

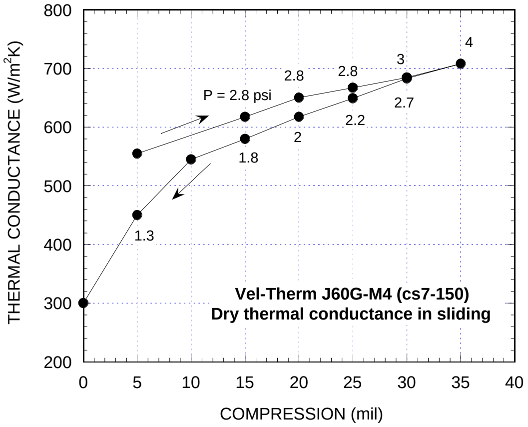

Figure 5. Thermal conductance of second test specimen of Table 1, as a function of compression and decompression.

REFERENCES

[1] See for example, W. C. Young, “Roark’s Formulas for Stress and Strain” (McGraw Hill, New York, 1989).

[2] M. S. Dresselhaus et al., “Graphite Fibers and Filaments.” (Springer-Verlag, New York, 1988).

[3] C. L. Seaman, B. M. Ellman, and T. R. Knowles, “Enhanced Thermal Conductance of ORU Radiant Fin Thermal Interface using Carbon Fiber Brush Materials.” Proceedings of STAIF-99.