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Material Selection for Cryogenic Support Structures

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Abstract Design specifications for the support structures of low temperature instrumentation often call for low thermal conductivity between temperature stages, high stiffness, and specific load bearing capabilities. While overall geometric design plays an important role in both overall stiffness and heat conduction between stages, material selection can affect a structure's properties significantly. In this contribution, we suggest and compare several alternative materials to the current standard materials for building cryogenic support structures.

Keywords Cryogenic, Low Temperature, Cryogenic Materials, Thermal Conductivity, Material Strength, Young's Modulus, Cryogenic Support, Support Structures, Truss, Structural Materials

1 Introduction

Cryogenic support structures are typically engineered to meet three design specifications: low thermal conductance, high strength, and high stiffness. Creating support structures that obtain the lowest thermal conductance between temperature stages while still remaining structurally adequate to support forces imposed during operation at base temperature and during handling at room temperature is a design optimization problem. The thermal consideration usually results in structures suspended by elements possessing minimized cross-sectional area – thin plates, webs of yarn, slender rods or tubes. The application will dictate which of, strength or stiffness, imposes the next most limiting design constraint. Focusing on the case of stiffness, we draw attention to the fact that both stiffness and power conducted are proportional to the cross-sectional area, A, divided by the length, l, of the structure support members.[1] As we shall explain, this provides a helpful parameterization for the selection of cryogenic support structural materials.

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2 Material Selection

The property that describes the stiffness or elasticity of a material is its Young's modulus[1]. It is slope of the stress versus strain curve and is sometimes different for tensile stress (the 'tensile modulus') and the compressive stress (the 'compressive modulus'). It should also be pointed out that different samples of the same material may have different moduli as a result of their defect characteristics, heat treatments, etc. When loading a cryogenic support structure, the forces experienced generally tend to be of the same magnitude in both compressive and tensile directions. Because of this, the smaller of the two moduli, the tensile modulus or the compressive modulus, must be focused on in order to keep a sufficient factor of safety and prevent premature failure.

Material	ρ ($\frac{g}{cm^3}$)	ν	σ_t (MPa)	σ_c (MPa)	TM (GPa)	CM (CPa)
POCO AXM-5Q	1.73	0.27	48	124	10.5	-
TIMET Ti 15-3-3-3	4.78	0.36	766	810*	82.0	90.0*
Stainless 316LN	7.99	0.29	690	-	200.0	-
Vespel SP-1	1.43	0.41	86	133	2.5†	2.4
Vespel SCP-5000	1.46	-	163	640	4.0	9.1
Vespel SP-22	1.65	-	52	112	2.5	3.3
Vespel SCP-5050	1.76	0.22	72	219	8.9	3.0
Torlon 4301	1.46	-	113	166	6.8	5.3
G-10CR	1.90	0.18	429	374	27.9	15.0
Graphlite CF Rod	1.55	-	2340	1900	134.0	131.0
Kevlar 49 Fibers	1.44	0.36	3000	-	112.4	-
Macor	2.52	0.29	90	345	66.9	64.0

Table 1 Some physical and mechanical properties of candidate materials. ν is the Poisson's ratio for the material, while σ_t and σ_c are the tensile and compressive strengths ¡-yield, elastic limit, or UTS? for the material, respectively. TM and CM are the tensile and compressive elastic moduli. A blank indicates that the specified property could not be found in the literature for a given material. Data comes largely from manufacturer's literature; where values were missing from manufacturer literature, outside references were used; references as well as relevant notes about the material properties are as follows: POCO AXM-5Q – ν[2]; Ti 15-3-3-3 – ν, σ_t, σ_c, CM from [3][4][5]. Properties were for solution-treated material. * - Properties estimated from graphs in manufacturer's literature; SS316LN – ν from [6]. Other data are from SS316LN data sheet for cold worked material (www.finetubes.com); Vespel – TM for SP-1 from [7]. All data were for isostatically formed parts. † - estimated from manufacturer's stress-strain plot; G-10CR – all data from [8][9]. Properties taken in the warp direction; Graphlite CFRP – properties along the fiber axis; Kevlar 49 – all data are for unfilled fibers; Macor – σ_t and CM from [9][10].

It is also important to note the other properties of the material being used. Ductile materials, such as most metals, tend to fail from shear forces first, while brittle materials like carbon fibers fail from normal forces first. Another aspect of ma-

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[1] Young's modulus is formally defined for tensile stresses, but one can easily extend the notion to compressive forces on a material. When tensile and compressive moduli are not equal this due to an asymmetry (e.g. maybe the specimen is a string) or a rapid variation of the modulus through zero strain, but not a discontinuity. Materials exhibiting this rapid change in modulus around zero stress are called *bimodulus or* bilinear materials. Young's Modulus is sometimes called *elastic modulus or* modulus of elasticity.

terial selection is that of metallic versus non-metallic support. Metallic supports can be quite stiff, however they are not ideal for structures with electrically isolated stages. The shape of the thermal conductivity curve plays an important role as steep thermal conductivity curves create susceptibility to thermal run-aways in the cryostat.

Overall, when deciding on materials, they must be stiff enough to not fail under expected loads ranges while keeping their cross section is low as possible to minimize the amount of heat transfer between temperature stages. Because stiffness and power conducted are both proportional to the cross-sectional area divided by the length, A/l, we can normalize the Young's modulus of a material by its thermal conductivity in order to compare multiple materials for use in these structures. Runyan[11] et al. presented a very similar plot comparing different materials not featured in this contribution. In general, because a high stiffness and low thermal conductance is typically desired, when choosing materials we want the smallest thermal conductivity to Young's Modulus ratio[1]. In the plot below we present a few newer useful materials along with familiar standbys that have the desired low thermal conductivity to Young's Modulus ratio.
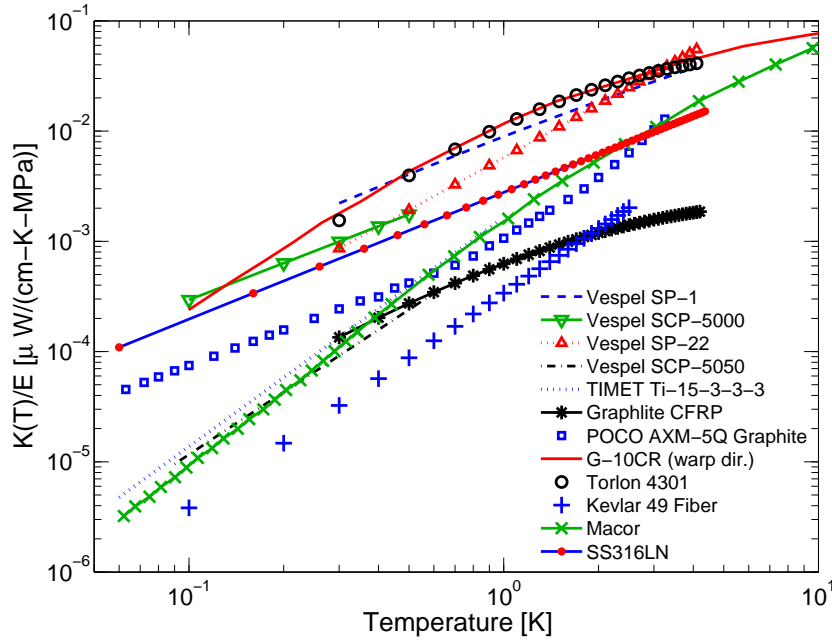

Fig. 1 A selection of useful materials with their room temperature Young's modulus normalized by their thermal conductivity. Lower values are desirable as support materials. Thermal conductivity references: Vespel SP-1, Vespel SP-22, Graphlite CFRP, and Torlon 4301 from Runyan[11]; Vespel SCP-5000, Vespel SCP-5050, and Ti 15-3-3-3 from Kellaris[12]; AXM-5Q, G-10CR, and Macor from Woodcraft[13][14]; Kevlar 49 from Ventura[15]; Stainless Steel 316LN from Barucci[16]. Youngs moduli from table above.

3 Conclusions

While many different geometric design solutions exist, once the geometric design of a cryogenic support has been selected, the materials used to build it determine its strength, stiffness, and thermal conductance. A parameter useful in material selection is the material's thermal conductivity normalized to its Young's Modulus. Unlike design geometry alterations, a change of material used to build a structure tends to be a much easier and predictable way to improve upon a design in terms of its performance under a force or heat load. Also, changes in material of a structure have the advantage of avoiding the necessity to make changes in the governing equations or model for theoretical evaluation due to the fact that material properties tend to be well defined dependent variables in both. For geometric designs that already exist and cannot be altered, a judicious change of support material using the data presented here could improve performance without necessarily entailing further detailed modeling.

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