OPEN-CELL FOAMS FOR ULTRALIGHTWEIGHT OPTICS

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ABSTRACT

Open-cell foams comprise an attractive class of materials for ultralightweight optics. They are easy to manufacture in bulk quantities and can be fabricated from a variety of lightweight materials. Open-cell foams offer excellent stiffness-to-weight ratios, and because they are composed of ≈90% open porosity, no machining is required for lightweighting. Furthermore, because the length scale of a foam ligament is much smaller than that of a typical web structure, print-through of the foam is much less of a concern. Taken together, the beneficial properties of open-cell foams not only improve performance and simplify optic manufacture, but they also allow optical components to be fabricated at reduced cost.

OPEN-CELL FOAMS

Open-cell foams are a class of materials that offer many advantages in the area of ultralightweight optics. As seen in Figure 1, a micrograph showing a typical open-cell foam microstructure, the material is ≈90% open pore space. By using chemical vapor deposition/ infiltration (CVD/CVI), the ligaments of the foam can be coated with any of a wide variety of materials, and the amount of material deposited can be varied to meet the needs of a particular application.

ADVANTAGES OF OPEN-CELL FOAM

Because open-cell foams are typically 80-95% porous, they are extremely lightweight materials. But because of their structure, they are remarkably stiff. When combined with a solid optical faceplate, the composite system acts like a three-dimensional truss. The result is a material with a very high stiffness-to-weight ratio.

Because a variety of materials can be used to coat the foam ligaments, additional flexibility is built into the system. Any material amenable to the CVD/CVI process can be used; however,

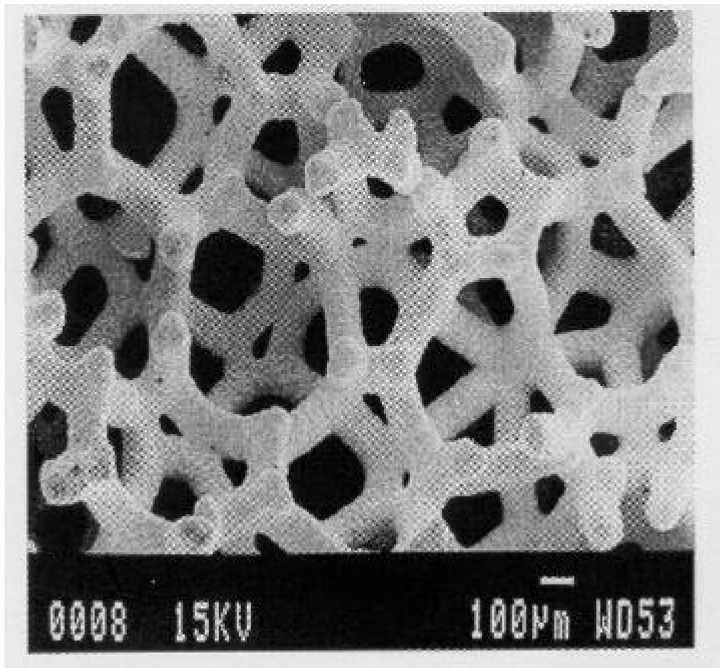

Figure 1.
Scanning electron micrograph of typical open-cell foam microstructure

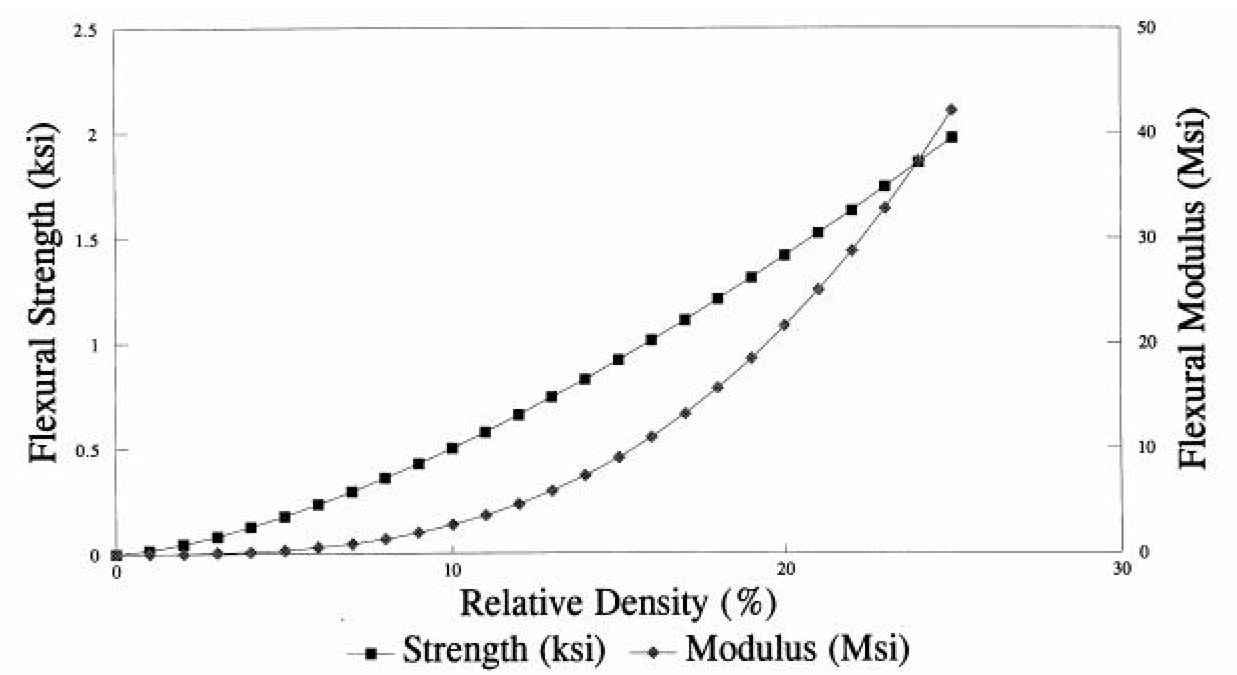

Figure 2.
Flexural strength and modulus vs. relative density for open-cell silicon foam

for ultralightweight mirror applications, the list becomes fairly short. Materials used to date by Ultramet for foam-based mirrors include silicon carbide, pyrolytic graphite, and silicon.

As seen in Figure 1, the length scale for the ligament spacing in an open-cell foam is on the order of a few hundred microns. Because the foam ligaments will contact the back of the optical faceplate at approximately 1000 points per square centimeter, print-through is not a problem. This has been demonstrated in subscale parts both at room temperature and under cryogenic conditions. Typical web structures, on the other hand, often suffer from print-through because the contact points are separated by large distances.

Because the ligamental structure is an inherent property of the foam, no micro-machining is required to achieve low density. Typical web structures, on the other hand, require extensive machining to reduce the weight. This machining not only impacts the cost and schedule, but it also affects the degree of print-through. A tradeoff between low areal density and good support of the optical surface must be made, and the precision and level of detail to which the supporting web can be machined plays a critical role. With an open-cell foam structure, all of this is free.

MECHANICAL PROPERTIES OF OPEN-CELL FOAM

Open-cell foams have been fabricated at Ultramet since the mid-1980s, and their mechanical properties are well understood. Gibson and Ashby [1] modeled the mechanical properties of cellular solids based on a cubic unit cell. Their equations have been modified to account for the geometric deviation from cubic in an open-cell foam, the cells of which have a pentagonal dodecahedral geometry, with the results given by the following equations:

$$s = s^{*}\left(\frac{r_b}{r}\right)^{3/2}$$

$$E = E^{*}\left(\frac{r_b}{r}\right)^{2}$$

where S is the crush strength, E is the modulus, ?$_b$ is the bulk density of the foam, ? is the density of the coating, and S^* and E^* are empirical constants.

Ultramet has used these equations with great success in predicting the properties of a wide variety of open-cell foams. Materials that have been successfully modeled are quite numerous and include silicon carbide, carbon, silicon, tantalum, niobium, and rhenium among others.

For the case of silicon, several specimens were fabricated with various relative densities, and their mechanical properties were measured. The data were then fitted to the above equations, with the results shown in Figure 2.

ADVANTAGES OF SILICON

For ultralightweight optics, especially those being operated at cryogenic temperatures, silicon offers a wide variety of advantages. Not only does silicon have a very low density (2.3 g/cm^3), but it also has a very high thermal conductivity and a very low coefficient of thermal expansion (CTE) (150 W/m·K and 2.6 ppm/K, respectively, at room temperature). Figure 3A illustrates how the CTE and thermal conductivity of silicon change with temperature. For comparison, the corresponding data for beryllium are also shown. As can be seen, the CTE of silicon starts at a low value at room temperature, crosses zero near 120 K, goes negative, and goes to zero again at absolute zero. The result is that a silicon optic cooled from room temperature to 30 K will undergo a shrinkage of only 0.07%. For a beryllium optic, the length change would be 0.3%, greater by more than a factor of four.

The thermal conductivity data are particularly interesting. As seen in Figure 3B, the thermal conductivity of silicon reaches a maximum near 25 K, which is very close to the desired operating temperature of the Next Generation Space Telescope (NGST). The maximum thermal conductivity of silicon, 5130 W/m·K [2], is even greater than that of diamond and more than an order of magnitude greater than that of beryllium [3,4]. Table I lists the thermal conductivities of several materials over the temperature range from 35 to 100 K [2-4]. As can be seen, silicon has the greatest thermal conductivity at 35 K.

Silicon also offers advantages with regard to finishing of the optical surface. The technology for single-point diamond turning of silicon exists and has been demonstrated. This enables thin faceplates of silicon to be turned to near net shape very quickly and cost-effectively. Silicon is superpolishable as well, which enables the surface to be polished to arbitrarily tight tolerances. A surface roughness of <10 A rms is easily achievable with silicon, and a roughness of 5 A rms has been demonstrated.

In addition to having attractive physical properties, silicon is also a low-cost material. Due to its use in the semiconductor industry, many ancillary technologies have already been developed. The physical properties of silicon are well characterized, and processes for its forming, bonding, and such have been developed extensively. With this data readily available, the time and cost associated with bringing the technology to market is greatly reduced.

SILICON FOAM-BASED OPTICS

By combining the advantages of open-cell foam with the advantages of silicon, the benefits of both technologies are obtained. The result is a mirror that has not only light weight and low areal density, but also excellent stiffness. This results in the ability to fabricate a large optic without the need for adaptive actuators.

The basic concept for a silicon foam-based optic is illustrated in Figure 4. The basic elements of this concept are two silicon faceplates bonded to an open-cell silicon foam core. The key element of this architecture is the silicon foam.

Because of the excellent thermal properties of silicon, the design is essentially athermal. The high thermal conductivity results in rapid thermal equilibration, so thermal gradients will be minimal, even during transients. And because of the low CTE, even if a thermal gradient is present, its effects will be minimal. This behavior is in direct contrast to that of other proposed mirror materials, which have lower thermal conductivities and higher CTEs.

MODELING

The foam-based silicon mirror concept was modeled to determine the optimal architecture. Two analyses were performed. In both, it was assumed that the composite structure consisted of

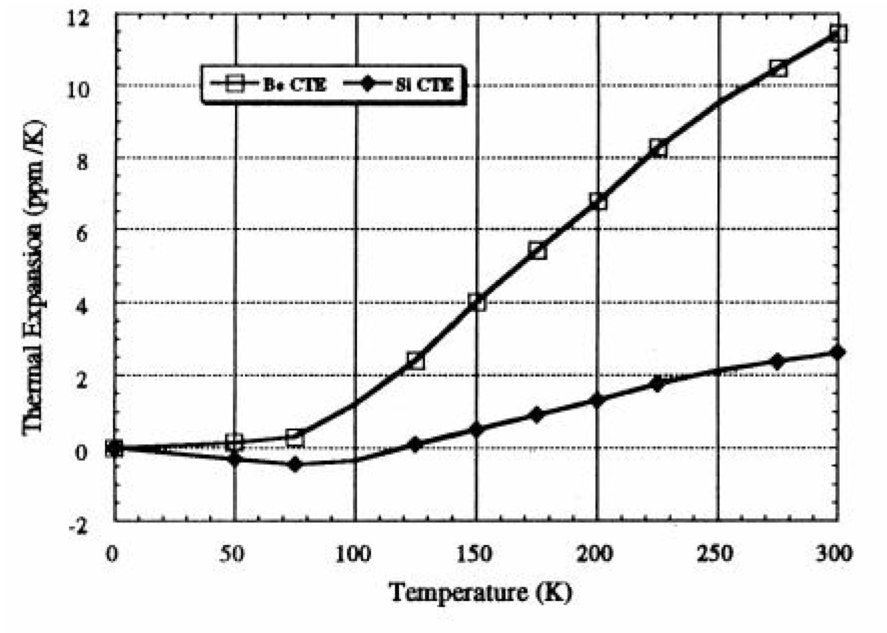

Figure 3A.
Linear coefficient of thermal expansion for silicon and beryllium

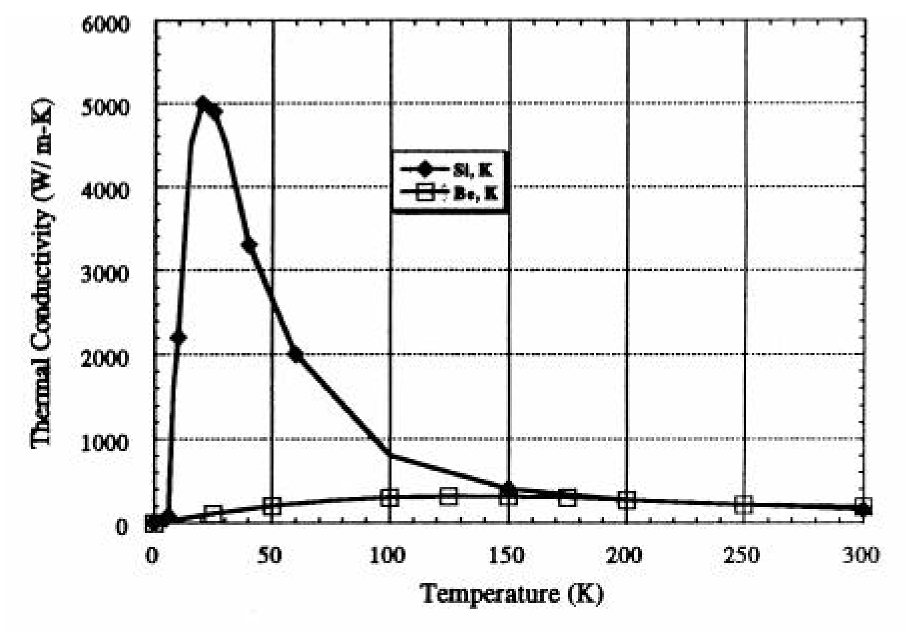

Figure 3B.
Thermal conductivity of silicon and beryllium

Table I.
Thermal Conductivities of Various Materials

Material	Thermal Conductivity (W/m·K)			
	@ 35 K	@ 50 K	@ 75 K	@ 100 K
Silicon	4130	2680	1510	884
Beryllium	160	200	275	300
Aluminum	3380	1350	509	302
Copper	3040	1250	602	482
Diamond (Type I)	2450	3530	3600	3000

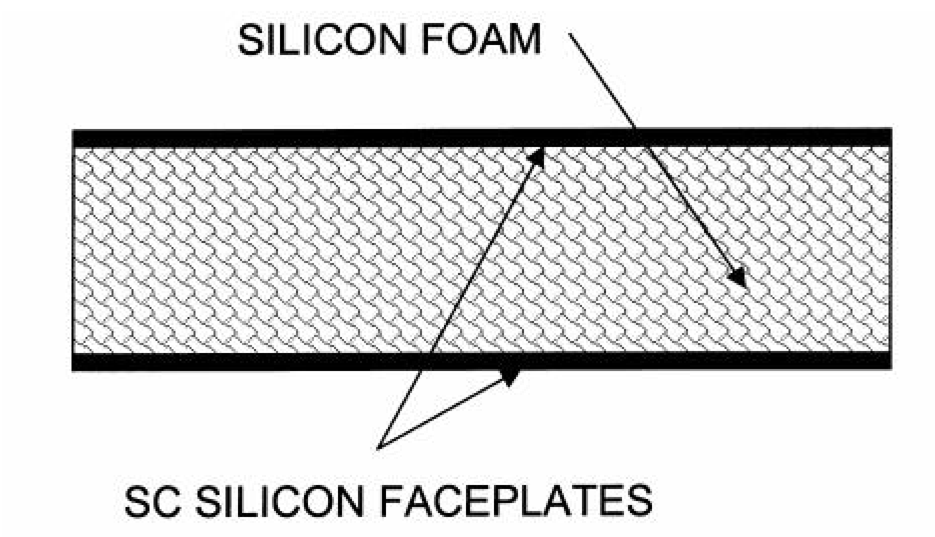

Figure 4.
Schematic of silicon foam-based optic concept

front and rear silicon faceplates on a silicon foam core, and that the areal density was fixed at 15 kg/m^2. The mechanical properties of the faceplates were taken from the literature, and those of the foam were measured empirically at Ultramet.

In the first analysis, it was further assumed that the relative density of the foam was 10%. Based on these assumptions, the analysis identified the optimal thickness of the faceplates to be 1.1 mm (0.043") and the optimal thickness of the foam to be 44.2 mm (1.74"). This resulted in a composite with the same stiffness as a 23.6-mm (0.93") thick monolith of silicon, which would have an areal density of 55 kg/m^2. It should be noted that monolithic silicon is an excellent material for lightweight optics. But by employing the foam core, the areal density can be reduced by more than a factor of three.

In the second analysis, the relative density of the foam was treated as a variable, but the overall areal density of the composite was still fixed at 15 kg/m^2. Foam relative densities of 5, 10, and 15% were investigated. The 5% foam gave better results than the higher-density foams. Generally, it was found that as the foam relative density decreases, the foam thickness increases significantly, while the faceplate thickness decreases as well but only by a small, insignificant amount.

Using 5% silicon foam for the core, the model predicted maximum stiffness when the faceplates were 0.9 mm (0.035") thick and the foam was 94.5 mm (3.72") thick. This configuration yielded the same stiffness as a 38.1-mm (1.50") thick silicon monolith. The monolith, however, would have almost six times the areal density as the foam-based composite.

DEMONSTRATED TECHNOLOGIES

While Ultramet has fabricated lightweight foam-based mirrors from silicon carbide and pyrolytic graphite, the focus here was on silicon foam-based optics.

In the development of this material system, several subscale parts have been fabricated. The first proof-of-concept part was fabricated in 1997, with the goal being simply to demonstrate the feasibility of combining an open-cell silicon foam core with silicon faceplates. The part consisted of a 1" thick disk of silicon foam and two single-crystal silicon faceplates. After bonding of the faceplates to the foam, one of the faceplates was polished to complete the optic.

The foam had a relative density of 8%, and the faceplates were ≈1.3 mm thick, which resulted in a composite optic with an areal density of 11 kg/m^2. Given that no effort was made to optimize the structure to make it lightweight, this was a significant achievement. Subsequent modeling work has shown that greater stiffness can be achieved at lower areal densities.

After demonstrating the foam composite concept, the focus shifted to bonding. To build up a large optic from smaller segments, it will be necessary to join them. For space-based telescope applications, it will be necessary for the segmented optic, and the joint in particular, to perform at cryogenic temperatures.

To that end, a segmented optic was fabricated from a 3" diameter disk of single-crystal silicon. The disk was polished and cut into two semicircles. The two halves were then bonded back together using a proprietary technique, repolished as a monolith, and tested. The testing was performed at both room temperature and cryogenic temperature. At 20°C, the surface figure measured 0.034 waves rms, while at -183°C it measured 0.037 waves rms. To establish a baseline, a similarly sized one-piece silicon monolith was also tested. Its results were 0.065 and 0.064 waves rms at 20 and -176°C respectively. Both mirrors were subsequently cycled between room and cryogenic temperature several times, with no change in surface figure.

This testing demonstrated that the bond joint across the optical surface did not compromise the optical figure. It also demonstrated the robustness of the bond joint under thermal cycling. These are both significant results because, together, they enable large optics to be fabricated from smaller segments without degrading the optical figure, even during thermal cycling.

The most recent demonstrator part to be fabricated was a 3" diameter composite optic comprising a silicon foam core and two silicon faceplates. This optic differed from the first one in that it utilized a closeout layer on the foam prior to faceplate bonding. Specifically, after the foam was fabricated, the surface was closed out with silicon via plasma spraying, and the plasma-sprayed layer was polished to near net shape. Faceplates were then bonded to the front and back closeout layers, and the front faceplate was polished to a surface figure of 1 wave. Polishing time was limited due to scheduling constraints at the test facility. Consequently, the ambient surface figure contained some residual astigmatism and coma. This composite optic was tested both at room temperature and under cryogenic conditions. At 20°C, the surface figure measured 0.093 waves rms, while at -175°C it measured 0.094 waves rms. It should be noted that power was removed from the analyzed data, to account for the test fixture inducing power as the composite optic was being cooled. The fixture had previously been optimized for testing of solid optics; it is now being modified for optimal performance with composite optics.

CONCLUSIONS

Open-cell foams in general, and silicon foam in particular, offer many advantages for lightweight mirror structures. They provide an extremely low-density, high-stiffness core to which an optical surface can be attached. Modeling work, based on empirical data for the foams, predicts that silicon foam mirrors can be made as stiff as silicon monoliths, but at almost one-sixth the areal density.

Subscale mirrors have been fabricated to demonstrate various fabrication technologies, including closing out the foam core, polishing the closeout layer, bonding faceplates to the closeout layer, and polishing the resulting composite optic. This bonding technology, when applied across the optical surface, has been shown to not degrade the optical figure during cryogenic cycling.

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