MOUNTING OF LARGE OPTICS FOR SPACE INSTRUMENTS

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ABSTRACT

The light collection capability of an interferometer is dependent on the aperture size of the instrument. Increasing the aperture size can reduce the noise level of the instrument. Instruments that collect light at wavelengths longer than about 15µm often use Potassium Bromide (KBr) beamsplitters. KBr has a high coefficient of thermal expansion (CTE) and low strength, which make it difficult to mount in a robust manner. As a result, many engineers have been hesitant to design their instruments using the full aperture size required for optimal performance. The overall objective of this effort was to examine novel methods of mounting KBr beamsplitters to improve their vibrational, optical, and thermal characteristics. A new thermally engineered composite material (TECMat) was developed that appears to match the CTE of KBr over a wide temperature range. TECMat's material properties and possible methods of implementing it in beamsplitter mounts are described.

Key Words: optics, mounting, composite material, beamsplitter, potassium bromide

BACKGROUND

Beamsplitters have three primary challenges that make mounting them difficult. First, a KBr beamsplitter is quite fragile, with a yield strength of approximately 160 psi which is about 0.4% of the strength of a 6061 T6 aluminum alloy. Second, deformation of the surface must be kept small to allow the light to pass though the beamsplitter without unacceptable distortion. This is a challenge because to survive a harsh launch environment, a tightly clamped mounting system is often needed. However, these clamping loads can easily cause excessive surface distortion. The third design challenge is the mismatch in the thermal expansion between the KBr and the telescope material which is typically aluminum. This third challenge usually has the largest influence on the beamsplitter design.

Beamsplitter mounting has been typically accomplished using some kind of spring loaded (or flexure) mounts. This low stiffness spring system allows different contraction rates with a small change in stress levels as the system is cooled. The magnitude of this initial load needs to be sufficiently small that the resulting distortion of the beamsplitter surface is acceptable. The initial load applied to the springs during the assembly process keeps the beamsplitter seated against fixed mounting points.

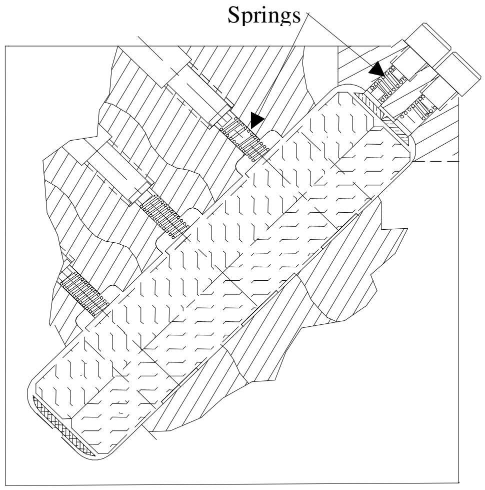

Fig.1 Proven beamsplitter mounting design

However, to survive high vibration induced g loads from rocket launches, the initial loads need to be sufficiently large to prevent unseating of the beamsplitter from its fixed support points. Typical beamsplitter designs are passive spring support systems with carefully selected initial loads applied to the springs to prevent unseating during the launch of the instrument. This proven approach has worked in the past for smaller beamsplitter designs.

There appears to be a limit to the size of beamsplitters that can be mounted using this approach. For large beamsplitters in higher vibration environments the spring force required to hold KBr distorts the surface excessively and can produce local plastic deformation. With larger beamsplitters come lower natural frequencies of the vibration modes involving the beamsplitter. As resonant frequencies drop, the vibration amplitudes generally increase.

One good design approach is to find a material that has a thermal coefficient of expansion that is very closely matched to KBr. Hopefully, this material would have reasonably good strength. Since the coefficients of expansion of the two materials are similar and the mounting area could be large, the differential mounting stresses and surface distortions could be small. This design would produce high natural frequencies and low stresses during g loads. Flexures would be incorporated into the mounting to allow for a mismatch in the thermal expansion between the beamsplitter and the telescope materials. The major challenge with this approach is to find a material with a matching thermal expansion. The coefficient of expansion match would need to be very close over the temperature range of interest. Otherwise, thermally induced stresses would be large. This material could be a metal alloy or a composite material. Developing this material is anticipated to be an expensive procedure with no guarantee of success. This approach has been successfully used at the Space Dynamics Laboratory at Utah State University for supporting other optical components, but the alloy development was a trial and error process.

DEVELOPMENT OF A THERMALLY MATCHED COMPOSITE FOR KBR

The design temperature for the beamsplitter was chosen as 77 K, which can be economically reached using liquid nitrogen. The coefficient of thermal expansion of KBr was carefully measured over the desired temperatures and compared data reported in literature. From ambient temperature to 77K, the change in length per unit length (dL/L) was found to be approximately 0.77 percent.

Early in the research process, it was assumed that a commercial isotropic material could be found that closely matched the thermal expansion of KBr from room temperature to the design temperature. A survey of available materials was made, and several samples were purchased based on the only available information, the room temperature coefficient of thermal expansion. The change in length that resulted from a temperature change from 300K to 77K was then measured and compared to KBr. If it was deemed close enough, the material was bonded to a sample of KBr and thermally cycled from ambient to the design temperature. This trial and error approach was time consuming and largely unproductive.

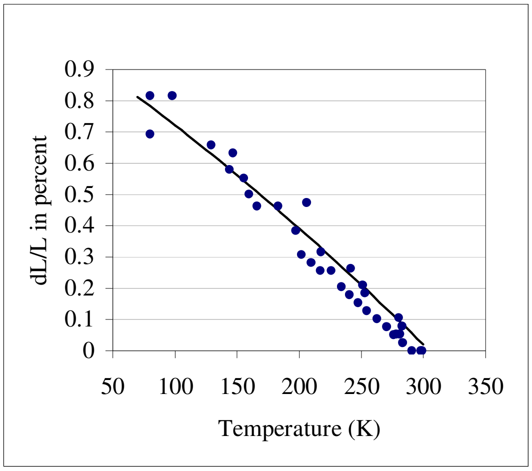

Fig.2 Coefficient of thermal expansion for Potassium Bromide as a function of temperature. The solid line is a curve fit from literature[8] and the points are measurements taken by the authors.

A second approach involved designing an isotropic composite to match the thermal expansion of KBr by finding a space qualified matrix and altering its properties by the addition of a fill material. The fiber and matrix each have different properties. When combined, the properties of the composite material are some combination of the properties of the two constituent materials. For certain properties (including density, modulus, coefficient of thermal expansion, dielectric constant and cost), the resulting composite property can be predicted by the "rule-of-mixtures". The composite property depends on how much of each of the original materials was mixed together -- hence rule-of-mixtures. This property may be calculated by multiplying amount of the fiber property by the volume percentage of fiber plus the amount of matrix property multiplied by the volume percentage of matrix.

A space qualified adhesive epoxy was selected as a possible matrix material. It has minimal outgassing, is chemically stable in high radiation environments, and is widely used in cryogenic applications.[3] Powdered silica was chosen as the fiber material.

A measurement of the percent change in length of the matrix material showed it contracted about .944 percent over the 300K to 77K temperature range. The matrix has a density of 1.3 grams/cc.[5] A value for the percent change in length of silica was obtained from literature as .05 percent, and a density of 2.2 grams/cc.[2] Applying the rule of mixtures to the matrix and the fiber predicted that the volume percent of silica required to match the CTE of KBr was about 12 to 13 percent. The resulting composite was named Thermally Engineered Composite Material (TECMat).

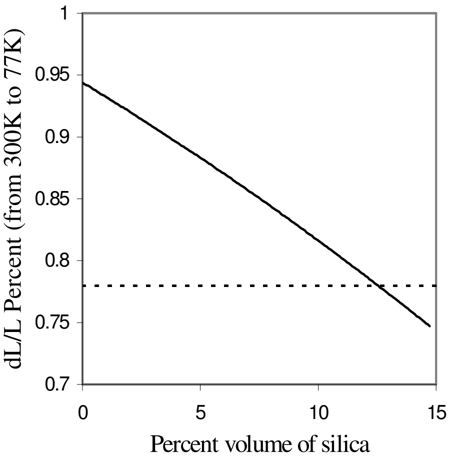

Fig. 3 The rule-of-mixtures applied to the selected matrix and fiber materials. The solid line is the rule-of-mixtures calculation and the dotted line is desired dL/L. The intersection is the desired percentage of silica in the composite.

MANUFACTURING AND MACHINING

Producing a composite material with a relatively high fiber ratio requires special mixing equipment to ensure that all of the fibers are wetted and uniformly distributed though the matrix. The resulting uncured composite is an extremely viscous semi-solid. It was shaped using a pressurized mold to minimize voids and improve consolidation during the cure cycle. The oven cure process for the TECMat filled pressure mold was 80 C for 16 hours.

Ongoing tests may indicate that the percentage of silica may need to be increased to match the KBr expansion more exactly, which is beyond the reach of the current mixing apparatus. Further improvement in the repeatability of the process would also be desirable. Several techniques used in the composite industry could improve the manufacturing process, such as Resin Transfer Molding (RTM), or Bulk Compound Molding.[7]

Cured TECMat can be machined by modifying conventional processes. The silica dulls cutting and abrasive tools quickly. These tools should be replaced often to avoid applying excessive force to the material. Because TECMat is loses strength at high temperatures, the shaping process should be modified to minimize heat generation. Distilled water may be used as a coolant, but alcohol, acetone, and oils degrade the matrix and bonding properties. The TECMat should be thoroughly dry before it is bonded. TECMat is weaker than most machined materials and its own strength should not be relied on to support it during machining. Because of its high CTE, the temperature of the TECMat should be monitored during machining if close tolerances are required.

PHYSICAL PROPERTIES OF TECMAT

There are three physical properties of TECMat that are of primary interest: coefficient of thermal expansion, strength, and thermal conductivity.

Of fundamental importance is the coefficient of thermal expansion. The testing of this property is a precise and expensive science. Traditional methods include eddy current sensors, capacitive measurements, interferometery and dilatometer measurements. Each of these requires a carefully controlled environment and significant investment in hardware. These were beyond the reach of the research effort.

Our primary concern was not to measure the exact CTE of TECMat, but to ensure that it closely matches that of KBr. In order to qualitatively confirm the rule of mixtures calculations, a number of cured TECMat specimens were bonded to a KBr sample and cycled to 77 K. The TECMat specimens with silica ratios below 7% fractured the surface of the KBr immediately beneath them in during a single cycle. Mixture ratios between 7% and 9% showed some peripheral cracking but did not fracture over the entire bond area. Mixtures between 9% and 13% had no evidence of failure through multiple cycles. It was felt that these results qualitatively confirmed the rule of mixtures approach.

Testing was then done to measure cryogenic bond strength of the TECMat/KBr interface. The room temperature bond strength was measured for a reference, and was found to be about 250 psi. The failure was typically in the KBr crystal immediately below the bond area. The cryogenic tensile tests were performed using the apparatus shown below. In all cases the KBr failed, not the bond or TECMat. The 9% silica filled specimens failed at approximately 160 psi, and the 12% filled specimens failed at about 200 psi. Crystal flaws played a major role in the uncertainty in these tests.

The cryogenic bond strength of the 12% filled specimens exceeded the 160 psi yield strength of the KBr. It was felt that 200 psi was an acceptable bond strength for a demonstration of a thermal match.

The average tensile strength of the unfilled matrix was reported by the manufacturer[6] to be 2060 psi, using a 120 hr cure at ambient temperature. Tests on 5% filled TECMat showed an increase in strength by almost a factor of three to 5700 psi. The increase in strength due to the addition of small silica particles (<10 micron diameter) could be due to the fact that the matrix has a higher adhesive strength than cohesive strength. Tensile tests on 12% specimens showed a reduction in tensile strength, which may indicate that the particles were not entirely wetted by the matrix.

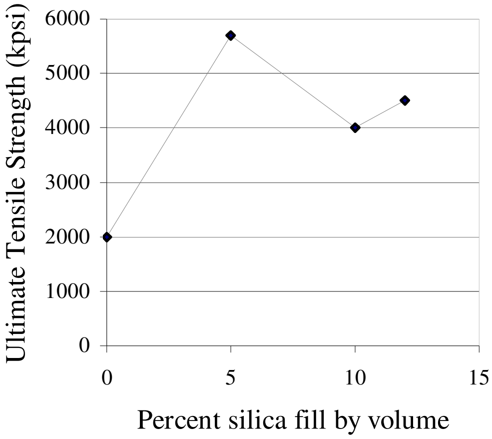

Fig. 4 Strength vs. fill for TECMat

The thermal conductivity of TECMat is important to the optical and thermal performance of the instrument. In most designs, TECMat would be the only conduction path to the beamsplitter plate. The matrix thermal conductivity is reported by the manufacturer as approximately .001cal cm/sec-cm²-°C (.42 W/m-K). At the time of this writing further testing of the thermal conductivity of filled TECMat has not been performed.

IMPLEMENTATION OF TECMAT IN A BONDED BEAMSPLITTER DESIGN

The figure below shows a design that was chosen to demonstrate a possible method of implementing TECMat in a beamsplitter mounting. The potassium bromide window is the disk in the center. The TECMat was bonded to the beamsplitter creating hard points that the flexures could be attached to. The hourglass shape of the TECMat was chosen to minimize the transmission of stress from the TECMat/Aluminum bond to the TECMat/KBr bond. The flexures are made from 6061 T6 aluminum and are bonded into the aluminum frame with potting compound.

Fig. 5 Finite element model of the beamsplitter design

The finite element model predicted a maximum stress of 50 psi at the TECMat/KBr interface as a result of cooling the beamsplitter mount to the design temperature. Based on this stress there is a safety factor of four for bond failure. The vibrational model predicts three fundamental mode shapes at 680 Hz, 690 Hz, and 1000 Hz.

The first beamsplitter was manufactured with thicker flexures than were used in the model and failed in cold tests. The KBr window failed in tension along crystal shear planes near the bonds. The bonded areas showed no failure due to CTE mismatch. Figure 7 compares the two fracture patterns.

Fig. 6 Photograph of the prototype

Fig. 7 a) Tensile failure of KBr along shear planes
b) Typical KBr failure due to CTE mismatch

Fig. 9 Beamsplitter response to a 1 g sine input from 10-2000 Hz. Only the 500-2000 Hz. portion of the frequency range is shown. The three traces correspond to the accelerations in the three principal directions.

The beamsplitter mount was tested to determine if the predicted modes match the actual modes. The lower two modes were at 825 Hz and 880 Hz. The upper mode was determined to be at about 1200 Hz. The results are slightly higher than predicted, which can be explained by the thicker arms.

Sine wave vibrational shakes from 10-200 Hz were conducted up to six times the force of gravity with no damage to the beamsplitter.

DISCUSSION

The TECMat development process produced a material that closely matches the CTE of KBr over the design temperature range. The rule of mixtures accurately predicted the composite mixture ratio required. TECMat performed consistently in all thermal tests and demonstrated a cryogenic bond strength that exceeded the yield strength of the KBr window. The rule of mixtures approach could be extended to a wide variety of materials. A typical approach might be to find a matrix with a CTE that is slightly higher than the material in question. The rule of mixtures could then be used to determine the approximate amount of lower CTE fill required to match the material.

Additional testing of TECMat could fine tune its properties, and improvement could be made in the manufacturing process.

The implementation of TECMat in a beamsplitter design demonstrated the need to consider the KBr crystal strength, as well as TECMat/KBr bond interface. Possible reasons for the crystal failure include:

1. Crystal damage during assembly: Crystal structures are sensitive to nicks and scratches that act as stress risers when a load is applied.[1]
2. Thermal shock: KBr is susceptible to thermal shock due to its low thermal conductivity and its high coefficient of thermal expansion.[1]
3. Differential cooling: Differential cooling of the KBr window and the mount may have intensified the stresses in the KBr.
4. CTE mismatch: The TECMat may have created additional stress in the KBr due to an inexact CTE match.
5. Inaccurate thermal modeling: Although the CTE of all materials involved were carefully averaged the temperature range, the elastic modulus was not. The modulus of aluminum increases with decreasing temperature, making the arms stiffer at lower temperatures.

If the future implementation of the proposed design is proven to be mechanically and thermally sound, several optical challenges must be addressed. In the proven flight design the beamsplitter pressed against lapped surfaces, which allows its location to be precisely determined. In the TECMat beamsplitter design, the arms will warp slightly during the cool-down process. This adds an additional element of uncertainty in the optical performance of the instrument.

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