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Author(s):

WILLIAM O. MILLER, LANL, MECHANICAL AND ELECTRONIC ENGINEERING
TIMOTHY T. THOMPSON, LANL, MECHANICAL AND ELECTRONIC ENGINEERING
JOHN A. HANLON, LANL, MECHANICAL AND ELECTRONIC ENGINEERING
MICHAEL T. GAMBLE, LANL, MECHANICAL AND ELECTRONIC ENGINEERING

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SILICON-BASED ELEMENTARY PARTICLE TRACKING SYSTEM: MATERIALS SCIENCE AND MECHANICAL ENGINEERING DESIGN

W. O. Miller, M. T. Gamble, T. C. Thompson, and J. A. Hanlon
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Research and development of the mechanical, cooling, and structural design aspects of a silicon detector-based elementary particle tracking system has been performed. Achieving stringent system precision, stability, and mass requirements necessitated the use of graphite fiber-reinforced cyanate-ester (C-E) resins. Mechanical test results of the effects of butane, ionizing radiation, and a combination of both on the mechanical properties of these materials are presented, as well as progress on developing compression molding of an ultralightweight graphite composite ring structure and TV holography-based noninvasive evaluation.

Keywords: particle tracking system, mechanical design, composite materials, dimensional stability, thermal conductivity, compression molding, TV holography.

1. INTRODUCTION

Los Alamos National Laboratory is engaged in research and development of a silicon detector based elementary paricle tracking system for use in the world's largest high energy physics experiment to be located in the United States.[1] This silicon microstrip detector-based system, termed silicon tracking system (STS), is composed of detectors arranged both in a cylindrical array and in an array of flat panels about the interaction region. The overall length of the STS is 5.16 m, while the maximum diameter is 0.93 m. For the STS to achieve its physics goals, its mechanical structures and services must

- support 17 m^2 of silicon microstrip detectors and stabilize their positions to within 5 µm,
- uniformly cool the detector system to 0°C, while potentially removing up to 13 kW of waste heat generated by the detector electronics,
- provide up to 3400 A of current to supply 6.5 million electronics channels,
- supply all control and data transmission lines for those channels,
- minimize mechanical structure and use low Z materials, and
- remain dimensionally stable throughout exposure to 10 Mrad over a 10-year period.

The method for supporting the individual central region silicon layers combines adjacent layers into a silicon shell as shown in Figure 1. Central region silicon shells are supported pairwise by two composite support cylinders composed of graphite/cyanate-ester resin (G/C-E) to minimize structural materials while maximizing stiffness and dimensional stability. The maximum silicon detector module length in the central region is 24 cm. Each silicon module is stiffened by edge bonding two 0.125-mm-thick G/C-E strips along the length of the detector edges. These silicon modules are then bonded to the structural rings made from G/C-E to form the silicon shell assembly. Besides providing structural support, these rings, hereafter denoted cooling rings, contain an internal heat pipe wick artery structure. Because the detectors in the central region are canted at an

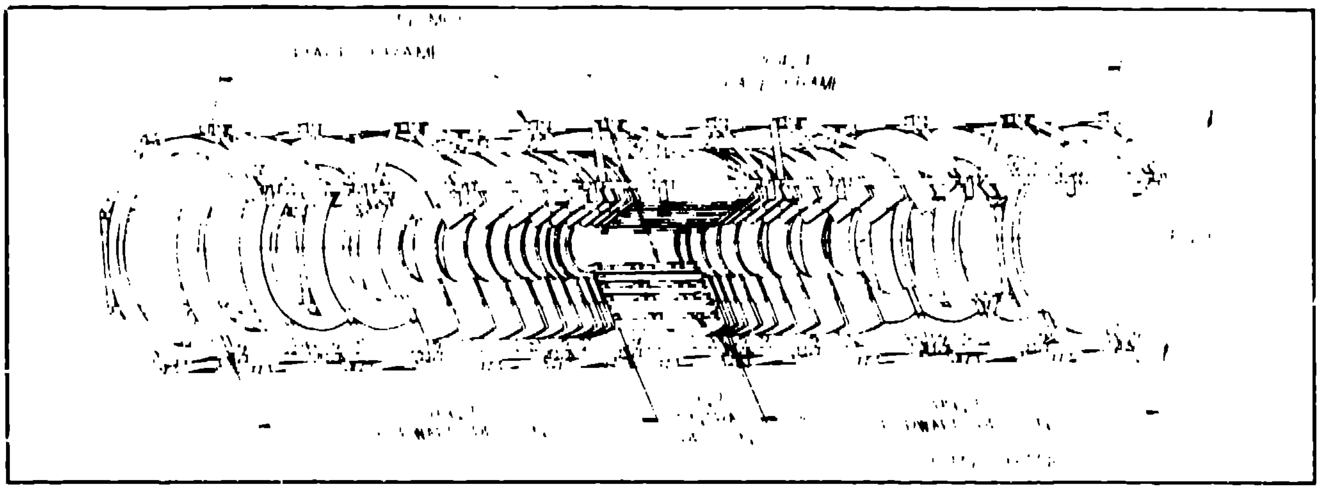

Figure 1. Internal view of Silicon Array with Space Frame (cutaway).

angle of 7.4°, the top and bottom surfaces of the cooling ring assume a serrate geometry. Electronics mounted at each end of the module assemblies generate heat which flows through the thin-walled composite cooling ring surface facets, onto which the module is mounted, and evaporates the cooling fluid.

A dimensionally stable metal matrix composite (MMC) space frame will provide structural support for the central and forward regions. Ultrahigh elastic modulus, immunity to moisture-induced distortions, and tailorability of coefficient of thermal expansion (CTE) motivated this selection. Aluminum and magnesium matrices, combined with P120 fibers @ 60 v/o are candidates. These yield axial moduli of 525 GPa and 515 GPa with CTEs of -0.25 ppm/°C and -0.6 ppm/°C, respectively.

An ultralightweight G/CE sandwich construction enclosure contains evaporated butane vapor and provides transfer of STS mechanical support loads. This shell and its end cover plates have an areal density of only 1.2 kg/m^2. Experimental quasi-isotropic (QI) panels of 250 μm material thicknesses have been constructed from P75 graphite and 1939-3 epoxy and irradiated using protons at a fluence of 10^{15} particles/cm^2, representing 10 operational years. Out of plane mechanical distortions were measured to be less than 5 μm, instilling confidence in the general material selections and construction approach. A 0.5 mm thin beryllium inner liner will complete this stiff, low mass structure.

2. MATERIALS CONSIDERATIONS AND TESTING

Stringent detector precision required use of materials capable of maintaining dimensional stability in the presence of thermal gradients, moisture, ionizing radiation, and volumetric deviations caused by butane vapor ingress. The requirement to minimize system structural mass while providing a stiff support for the silicon detection media further complicates the design. Beryllium is nearly transparent to particles and impervious to moisture and butane. Unforunately, it has a large CTE, is very costly, and requires complicated machining procedures. G/CE materials are a good compromise, having more favorable particle interaction characteristics than monolithic metals and more favorable CTE, cost, and fabrication characteristics than beryllium. The STS' environmental factors required special consideration because the performance of G/CE exposed to a combination of butane and ionizing radiation is not well known. For this reason, a mechanical testing program was undertaken. Mechanical tests were performed before and after environmentally conditioning the coupons in a butane filled container, and irradiating them with a cobalt gamma ray source. These results are shown in Table 1.

LANL and one independent testing organization used similar, conventional (CONV) load frame- and load cell based tests. A third organization used nondestructive evaluation (NDE) methods, scanning electron micros

Table 1. Mechanical Properties Test Results for P-75S/954-3 Laminates Normalized to 60% Fiber Volume Fraction

Mechanical Property	Test Institution	Specimen Description: Neat	0°	90°	QI
Elastic Tensile Modulus (GPa)	LANL	3.7	323	6.9	100
	LANL*	3.4	321	6.6	110
	CONV	3.8	324	6.4	96.5
	NDE	3.7	280	8.1	97.5
Elastic Comp. Modulus (GPa)	LANL	3.7	300	6.7	81.3
	LANL*	3.5	283	6.8	81.3
	CONV	3.4	270	6.2	77.2
Elastic Shear Modulus (GPa)	LANL	1.2	4.5	1.7	
	LANL*	1.1	4.8	1.7	
	CONV	1.2	4.0	1.6	
Poisson's Ratio	LANL	0.38	0.25	0.0043	0.28
	LANL*	0.37	0.25	0.0031	0.31
	CONV	0.40	0.32	0.0063	0.33
	NDE	0.40	0.32	0.0060	0.33
Ultimate Tensile Strength (MPa)	CONV	60	1000	23.4	294
Ultimate Comp. Strength (MPa)	CONV		337	41.7	131

*Denotes results for specimens environmentally conditioned by 10 Mrad and butane

copy and scanning acoustic microscopy to determine the elastic properties of specimens.[2] The data generated by all institutions and methods were comparable and closely matched published data including manufacturer's specifications. The overall conclusion of the mechanical properties test program is that the P-75/954-3 materials system is now mechanically fully qualified and is acceptable for achieving STS baseline performance objectives.

The coefficient of moisture expansion (CME) for hydrophobic resins, such as 954-3, has been well documented.[1] The STS application, however, will require dimensional stability in the presence of butane vapor at 0°C. Investigations of the strain, saturation level, and time constant for this phenomenon are promising. The quality of the laminate will have an effect on its uptake as well as its mechanical performance. Quality has been investigated using ultrasonic techniques, such as pulse-echo scanning and time-of-flight measurements. These techniques were used to quantify the NDE elastic mechanical properties of Table 1 and to evaluate the quality of thin, compression molded cooling rings.[1] Figure 2 demonstrates an example of pulse-echo scanning applied to a segment of a cooling ring.

3. COOLING RING DEVELOPMENT

The need for dense, high fiber volume, high quality, QI cooling rings motivated the use of compression molding for their fabrication. An incremental approach has been required, resulting from manufacturing challenges to fabricating a 360° cooling ring with a 400 μm thick wall of serrated geometry using P75/CE molding compound.[1] The frailty of these thin walled components, composed of very brittle P75 fiber based molding compound, necessitated using a 30° arc segment mold and commercially available molding compounds such as those available from ICI Fiberite, Inc. for initial attempts. Arc segments were fabricated from a mold

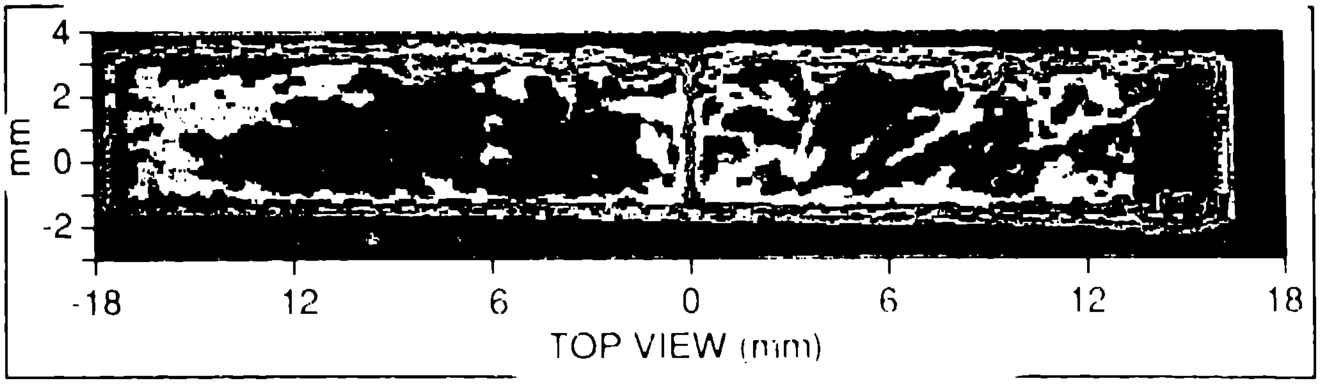

Figure 2. Image of pulse-echo amplitude variations indicating where compositional changes occur within the composite.

producing components with 450 μm thick walls using 6 mm long fibers in the phenolic base with 58 v/o fiber and 32 v/o resin. Fiber length was reduced from 12 mm because of flow problems encountered.

An improved 120° arc segment mold was fabricated and produced 400 μm wall thickness ring arcs. These were composed of intermediate modulus graphite fibers, approximately 90 μm long, in a toughened epoxy resin. High viscosity hindered success of all arc segments bearing more than 45 v/o fibers. High viscosity also hindered the fabrication of high P75 fiber volume 120° arc segments using TEM 9000 resin.

The CE resin chosen for use in the STS cooling rings is ICI Fiberite, Inc.'s 954-3. This resin's viscosity is nearly 100 times lower than that of TEM 9000 epoxy, hence a materials system using 954-3 flows well at 45 v/o of fiber. Problems releasing arc segments from the mold were overcome with mold coatings and proper selection of mold release agents while a post-curing mandrel mitigated ejection breakage.[3]

Satisfactory progress was made towards the intermediate objective of producing dense, high fiber volume, high quality 120° arc segments composed of P75/CE based molding compound. A photograph of a successful cooling ring arc segment produced with P75/CE prepreg molding compound of 45 v/o fiber is shown in Figure 3. The single remaining obstacle for this stage is successful use of P75 fibers longer than 90 μm for production of 400 μm wall thickness components with higher volume fraction.

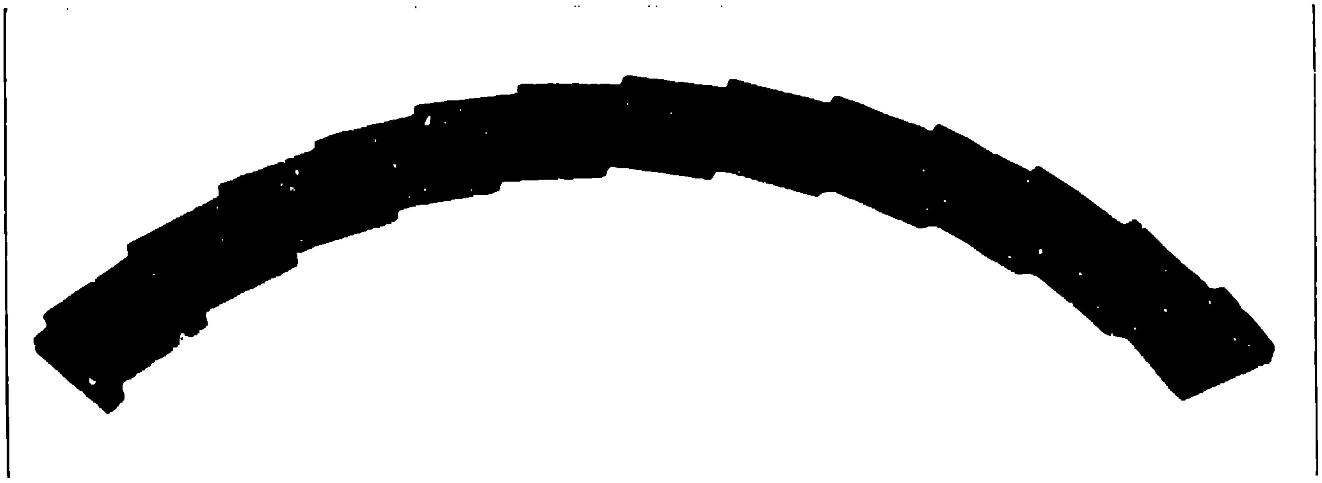

Figure 3. Photograph of a cooling ring arc segment bearing 45 v/o P75 fibers and 55 v/o epoxy re[illegible] sectional view).

4. MATERIALS BULK PROPERTIES ENHANCEMENT

Exacting precision tracking design goals required maximizing key composite materials bulk properties used for supporting the delicate silicon modules. Compression molded cooling rings provide mechanical support for the silicon detectors as well as providing a thermally conductive path for removing heat dissipated from the electronic modules. The latter requires minimizing the thermal gradient transverse to the cooling ring wall. Consequently, the elastic modulus and thermal conductivity properties achievable with compression molding were a primary concern . An experimental program was undertaken to enhance the transverse thermal conductivity (k_t) of the C-E resin-based compression moldings. Test samples were produced using aluminum nitride (AlN) particles, diamond particles, and discontinuous, randomly-oriented graphite fibers separately and in particle/fiber combinations. The thermal conductivities of these substances are 0.2 W/m°C, 180 W/m°C, 18 W/m°C, 280 W/m°C, and 2000 W/m°C for the C-E resin, P75 fiber longitudinal, P75 fiber transverse, AlN, and diamond particles, respectively. Specimens were cut from 3.2 mm compression molded disks and their thermal conductivities determined using laser flash diffusivity. A maximum additive volume fraction of 27% was tested and compared with published data for resin thermal conductivity enhancement.[4] These data suggested that a significant increase in conductivity would not be realized at such low additive volume fractions.

For comparison with the particulate additive samples, test samples were produced using P75 fibers compression molded with C-E resin. The fiber lengths varied from 90 µm to 600 µm with an average length of approximately 100 µm. Fiber volume fractions of 45% to 56% were tested. Enhancing the neat resins thermal conductivity while reinforcing it with the P75 fiber was ultimately sought. The objective was to use short fibers, approximately 100 µm long, possessing an aspect ratio (AR) of more than 10, to demonstrate "long-fiber" reinforcement characteristics per theoretical predictions. Specific processing steps were taken to effect random fiber orientation as a means to achieve a QI, low CTE composite with an enhanced thermal conductivity. It was anticipated that the cooling ring k_t would be considerably enhanced by this because the 400 µm wall-thickness could be spanned by a few fibers, effectively producing a psuedo percolatic effect nominally accomplished by agglomeration of 5 µm to 25 µm effective-diameter particles. Alternatively, enhancement by single fibers spanning the thickness would result in taking maximum advantage of the 180 W/m°C longitudinal thermal conductivity of P75 fibers. The ultimate goal of adding a high thermal conductivity metal to the P75/C-E system, to produce a high modulus, high k_t cooling ring continued to seem feasible until several cooling ring arc segments were produced with AlN, 11 v/o, and P75 fiber, 39 v/o. The k_t of these partial rings was enhanced as expected but those with solids content above 50 v/o were very brittle, hence indicating the infeasibility of this approach.

The design parameters of the STS could be achieved using a cooling ring with a k_t of 4 W/m°C. This was now to be accomplished using only the P75/C-E combination. Subsequent mechanical tests on the specimens bearing 100 µm long fibers revealed very low mechanical properties, in the range of those expected from short fiber reinforcement. This warranted additional investigation. In the interim, 400 µm long P75 fibers were used in cooling ring arc segment samples to promote improved moldability of extremely thin sections and to achieve more single fibers spanning the wall thickness for enhanced k_t. Figure 4 illustrates the measured k_t for cooling rings with a 60/40 volume fraction ratio for fiber/resin content. Thermal conductivities very near the design goal were obtained. It was observed that the k_t data for composite ring specimens produced with 100 µm long fibers were decidedly lower. As a further comparison, thermal conductivity data obtained from a carbon/phenolic molded ring with relatively long fibers is included. Chamis[5] and Springer[6] present theoretical models for k_t characteristic of continuous graphite fiber/polymeric resin systems. These models were used as a baseline for assessing k_t enhancement of the discontinuous fiber system.[1] Figure 4 demonstrates the enhancement factor approaches seven

Sheng's prediction[7] for a randomly oriented, acicular ("needle-like") particle with an AR of 10 is depicted in Figure 4. This AR is similar to that of the 100 µm long fibers. Similar predictions exist for the major axis of ellipsoidal particles oriented normal to the direction of heat flow.[5] For this case, the predicted thermal conductivity is similar in magnitude to Chamis model at fiber volume fractions less than 40%. For both higher fiber volume fractions and randomly orientea fibers, Shengs model predicts considerable thermal conductivity enhancement.

The Lewis-Nielsen model[8] can be used to characterize the elastic modulus as a function of fiber AR and volume fraction as was done for k_t enhancement because both are bulk material properties as previously indicated. Using that model, it is possible to predict the elastic tensile modulus to resin modulus ratio for the composite as a function of fiber AR and volume fraction for longitudinal fiber orientation. At a fiber AR of 1000, the modulus ratio for 60% fiber volume fraction is 82.11, which approaches a continuous unidirectional fiber matrix. For AR = 10000, the modulus ratio is 83.6. For the C-E resin, a tensile moduls of 3.7 GPa was established. Hence, the predicted composite modulus for the long fiber of 0.1 m would be 309.3 GPa per Nielsen. This agrees with the test value of 321.3 GPa to approximately 4%. This exercise demonstrated that fiber reinforcement AR must be greater than 100 to approach the stiffness of a continuous fiber composite. This represents a factor of 10 greater length for total shear stress transfer than yielded by theoretical predictions. Longer fiber reinforcement has a negative influence on cooling ring fabricability as previously stated, but is overridden by mechanical performance concerns.

Attainment of high cooling ring stiffness, indicating a large composite elastic modulus. Ec, mandates a high fiber volume fraction. For an AR of 100, a 60% fiber volume fraction produces a factor of 1.7 greater stiffness over 40%. The improvement in stiffness is also apparent at lower fiber ARs. Most cooling ring specimens were fabricated using fiber ARs on the order of 10 to 40, with random orientation. The bulk properties of such a complex matrix can be predicted, however. Figure 5 demonstrates 2-D and 3-D predictions and test data for published models.[4] These data are plotted at a nominal AR of 10, corresponding to a fiber length of 100 μm. Acid digestion tests indicated the fiber volume fraction to be approximately 45%, considerably below the goal of 60%. It is difficult to estimate the extent to which the composite approaches a highly three-dimensional matrix. A review of arc-segment photomicrographs suggests that for compression-molded components, the composite is three-dimensional, but not homogenous. At an AR of 1000, the elastic modulus has a definite positive slope. Extrapolating the modulus calculation to AR equal to 10000 results in a value of 118 GPa for the 2-D case. This value is close to the 98 GPa measured on QI continuous fiber coupons. These results indicate the Nielsen model for elastic modulus can provide a reasonable approximation for composite bulk properties over a range of discontinuous to continuous fiber reinforcement.

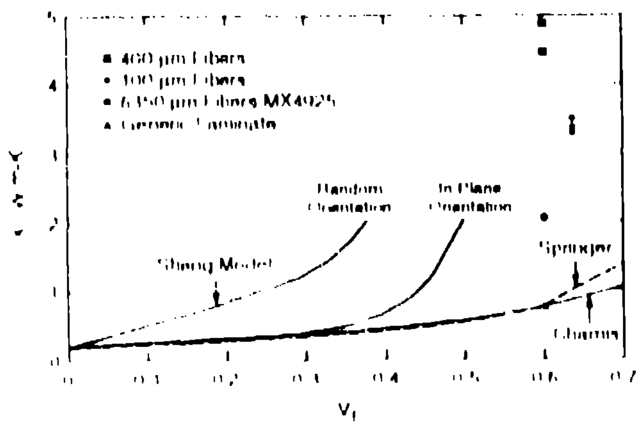

Figure 4. K_t of 450 μm thick cooling ring segments from compression molded P75/CE dis continuous fibers (100μm, 400μm).

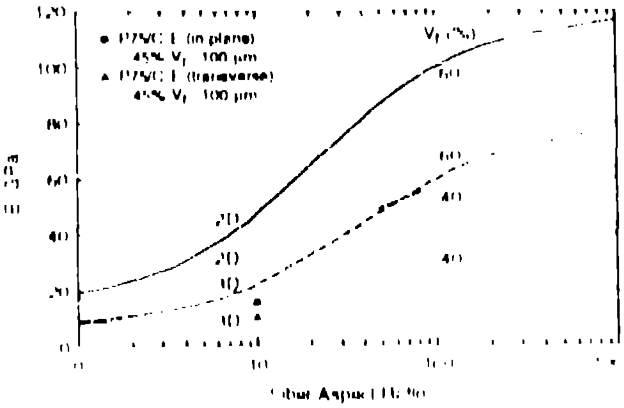

Figure 5. E_c versus fiber AR, for 2-D and 3-D randomly oriented fibers at 60% and 40% V_f

5. NONINVASIVE EVALUATION BY TV HOLOGRAPHY

Long term dimensional stability and dynamic behavior of the STS will be evaluated absolutely noninvasively with submicron accuracy using TV, or electro-optic, holography. Similar to classical interferometry, in which an object beam and refernce beam interact forming fringe patterns. TV holography will be used to produce holographic fringes containing information about STS shape changes. These will be gathered by a television camera, instead of film, input into a computer, and computationally interfered with a baseline state of the STS to determine the magnitude of environmentally-induced static or dynamic deformations. This extension of classical holography allows three dimensional, diffusely reflecting, nonplanar surface motions to be quantified in near real-time. Figure 7 demonstrates a static thermal stress gradient whose source was the heat from a human hand placed near a silicon detector module, deforming the 24-cm-long assembly by approximately 0.6 μm. The dynamic capability of TV holography is demonstrated by Figure 8 in which fringes describing the fundamental natural vibration frequencies of bending and torsion of a silicon module are shown. The fundamental bending mode of 94.16 Hz and torsional mode of 113 Hz were acoustically excited and recorded. The characteristic contours of the fringe patterns express the mode shape while the magnitudes of the vibratory displacements can be determined from the fringe density.

6. CONCLUSIONS

Several conclusions are clear from the STS' materials science and mechanical design information presented herein. The use of C-E-based composite materials for applications requiring dimensional stability in the presence of a combination of ionizing radiation and butane is feasible. Elastic and inelastic mechanical properties were found to be affected negligibly by 10 Mrads of dose in a butane-filled cannister. The C-E also demonstrated minimal absorption of liquid butane, approximately xx% by weight. Strain measurements are underway to quantify the coefficient of butane expansion, which is expected to be no more than that of moisture expansion, making it acceptable as an STS design material.

Success with compression molding 400-μm-wall-thickness cooling ring arc segments composed of 60 v/o, 90-μm-long, P75 fibers and 40 v/o, 954-3 C-E resin is encouraging. Maximum cooling ring mechanical and

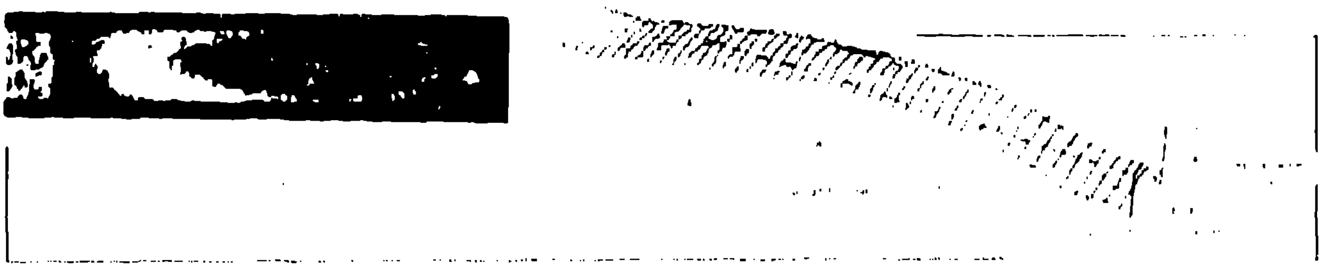

Figure 6. TV holography fringe pattern (left) and computer reconstruction (right) of a silicon module's thermally induced static deformation of 0.6 μm.

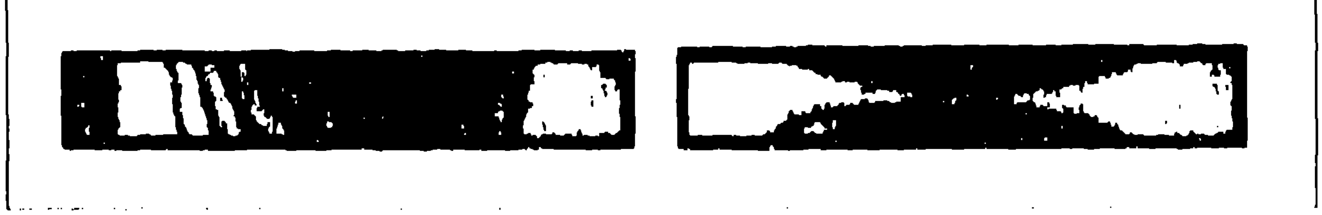

Figure 7. TV holography fringe patterns of a silicon module's fundamental dynamic bending mode of 94.16 Hz (left) and torquing mode of 113 Hz (right).

thermal properties will be attained, however, with high fiber volume fractions of long fibers, ARs near 100 and lengths of approximately 1000 μm, used in the molding compound. This fact was gleaned from published data and extensive resin k_t enhancement attempts using monolithic metal additives in conjunction with high modulus graphite fibers. Charge deposition and cure cycle optimization must be accomplished to enable production of dense, high quality components using long P75 fibers.

Static and dynamic TV holography tests of silicon modules experiencing bending and torsion were very successful. The capability to quantify STS shape changes to the submicron level will provide useful information regarding the system's long term dimensional stability.

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