Recent applications of metal matrix composites in precision instruments and optical systems

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Abstract. This paper describes three unique metal matrix composite (MMC) material systems that have been developed for use in dimensionally stable platforms, precision mechanical systems, and lightweight reflective optics. These engineered materials, consisting of aluminum alloys reinforced with fine particles of silicon carbide, offer distinctive performance advantages over conventional metals, including greater specific stiffness, higher strength, and better resistance to compressive microcreep. Weighing about the same as aluminum, certain grades of these MMC materials are isotropic and have excellent thermal conductivity, and they can be tailored to match the coefficients of thermal expansion of other materials, including beryllium, stainless steel, and electroless nickel. Such flexibilities in establishing material properties and characteristics present new opportunities to the designer in producing weight-critical, precision hardware. Practical applications of MMC materials in advanced guidance equipment and lightweight optical assemblies are presented and discussed.

Subject terms: optomechanical instrument design; metal matrix composites; dimensional stability; engineered coefficients of thermal expansion; guidance system components; optical mirrors; ultra-lightweight telescopes.

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1. INTRODUCTION

The development and implementation of new materials are almost always driven by the need to improve the capabilities of high performance systems. The broad class of craft and equipment required to function through the earth's atmosphere and space must be of minimum structural weight, must function with high precision, and must be produced at reasonable costs within established budgets. In formulating plans for the physical realization of such machines, the engineer must utilize a design methodology that integrates several technical disciplines to satisfy the complex array of system requirements. The proper selection of materials is a particularly important part of the design process and should include a consideration of recently developed composites as well as conventional metals, polymers, and ceramics.

Engineered metal matrix composites (MMCs) are a new class of synthesized materials that provide the design flexibility, dependability, and economy necessary for producing lightweight, dimensionally stable assemblies. In this paper we consider three distinct grades of MMC materials. We examine the relationships among the constituents that make up each grade and the associated properties, and finally we discuss some of the interesting applications of these MMCs in inertial guidance equipment and optomechanical systems.

2. BACKGROUND

When silicon carbide powders are uniformly dispersed within an aluminum alloy matrix, the resulting composite generally exhibits greater stiffness (Young's modulus), higher strength,

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and better resistance to creep than the unreinforced alloy. Three types of aluminum/silicon carbide composites have been developed for use in high performance applications. They are categorized as (1) structural-grade, (2) instrument-grade, and (3) optical-grade MMCs.

The distinguishing qualities of the constituents in the composite microstructure relate directly to the resultant properties of the composite material system. Although a number of standard aluminum alloys have been used successfully to produce composites, special matrix alloy compositions have been designed to optimize the composite material properties and characteristics. Best properties are obtained when the SiC reinforcement and the matrix alloy are as physically and chemically compatible as possible.[1]

Especially important are the specific features of the SiC reinforcement: particle morphology, particle size distribution, particle surface chemistry, fractional content, and dispersion uniformity. Depending on the intended application, the aluminum-base MMC will generally contain from 15 to 45 vol % SiC reinforcement. Special particle coatings have been devised to improve the chemical compatibility of the SiC reinforcement with the aluminum matrix alloy, thereby improving composite performance. The conditions that affect the matrix/particle interface and that control the transfer of stresses from the matrix alloy to the SiC reinforcement greatly determine the mechanical (and micromechanical) behavior of the composite.

The qualities of the metallic matrix must also be considered. Strengthening of the aluminum matrix alloy through heat treatment and by oxide dispersion is also a significant contributing factor. The mechanisms that operate within a composite microstructure are controlled by a complex interdependence of several variables that collectively enhance strength, elastic modulus, dimensional stability, and MMC component response to environmental effects.

To build a mechanism using SiC-reinforced aluminum composites, one must understand the differences among the various grades relative to microstructure, properties, and fabrication procedures. A thorough knowledge of these MMC materials will enable the designer to select the best grade of composite for a given application.

2.1. Structural-grade MMC materials

Structural-grade composites are produced using powder metallurgy processing techniques to combine and consolidate rapidly solidified aluminum alloy powders with high strength SiC whiskers.* The acicular single-crystal whiskers, Fig. 1, have an average diameter of 0.6 μm and lengths ranging from 10 to 80 μm.[2] Experimental data indicate that the tensile strength of these whiskers can approach 7000 MPa (about 10^6 lb/in.^{2}).[3]

One of the principal advantages of structural-grade MMCs is that a preferred orientation of the SiC whiskers can be textured in the microstructure, as shown in Fig. 2, using standard metal-forming equipment. Higher directional strengths can be established in finished whisker-reinforced components through extrusion, rolling, forging, or superplastic forming. The fabrication of high strength structural-grade MMC parts in one operation can appreciably reduce manufacturing costs and simplify secondary assembly requirements. Such components may be produced with section thicknesses less than those of unreinforced metal parts, resulting in significant weight savings. Selection and use of structural-grade MMCs provide opportunities for reducing both the initial costs and the life cycle operational costs in many weight-critical applications. Typical properties of structural-grade MMC extruded rod, tubing, and barstock are shown in Table I. These materials are characterized by high strength and stiffness with ductility and toughness sufficient for many advanced space platform and aerostructural assemblies.

The flight control surfaces shown in Fig. 3 were fabricated from structural-grade MMCs to operate under the severe conditions of supersonic flight. This application is an excel-

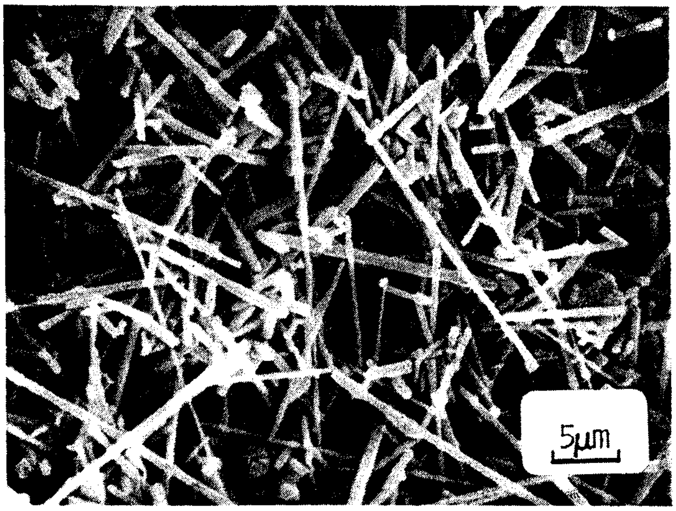


Fig. 1. Scanning electron micrograph of silicon carbide whiskers used in structural-grade MMC materials.

Fig. 2. Optical-light micrograph of structural-grade MMC material showing the alignment of silicon carbide whiskers in the extrusion direction.

*The reader should understand that single-crystal whiskers usually have a much greater tensile strength than other types of discontinuous reinforcements, such as polycrystalline flakes, particulates, or chopped fibers. Therefore, whisker reinforcement is generally used to produce the highest strength discontinuously reinforced MMCs.

TABLE I. Typical properties of structural-grade MMC extruded rod, tubing, and barstock.

Material; test specimen	Orientation	Ultimate tensile strength MPa (10^3 lb/in.^{2})	0.2% offset yield strength MPa (10^3 lb/in.^{2})	Elongation e %	Young's modulus E GPa (10^6 lb/in.^{2})	Density ρ g/cm^3 (lb/in.^{3})	Coefficient of thermal expansion ppm/K (ppm/°F)
6061-T6* 20 vol % SiC_w; rod 1.27 cm (½") diameter	longitudinal	586 (85)	441 (64)	3.6	121 (17.5)	2.803 (0.101)	15.1 (8.4)
6061-T6* 20 vol % SiC_w; tubing 2.54 cm (1") o.d. 1.25 mm (0.050") wall	longitudinal	600 (87)	469 (68)	2.8	124 (18)	2.803 (0.101)	14.6 (8.1)
2124-T6* 20 vol % SiC_w; bar 1.27 cm × 12.7 cm (½" × 5") cross section	longitudinal	862 (125)	496 (72)	2.4	127 (18.4)	2.860 (0.103)	14.8 (8.2)

*Aluminum alloy containing 20 vol % silicon carbide whisker reinforcement, heat treated to T6 condition.

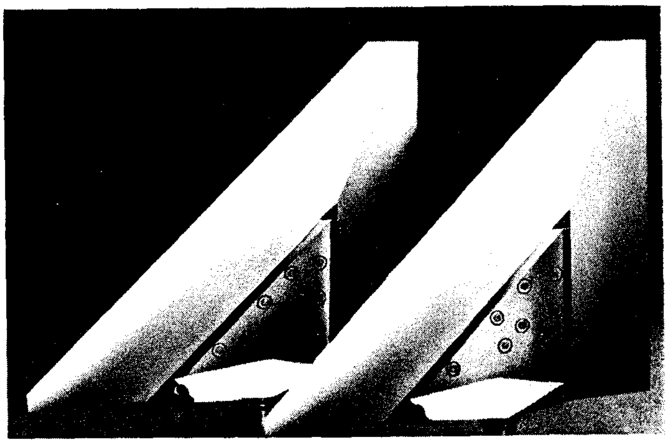


Fig. 3. Supersonic flight vehicle control surfaces fabricated from structural-grade MMC.

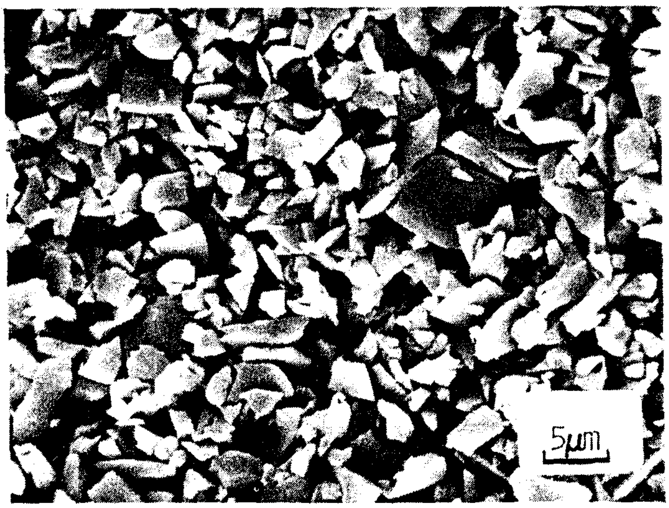


Fig. 4. Scanning electron micrograph of particulate silicon carbide used in instrument-grade MMC materials.

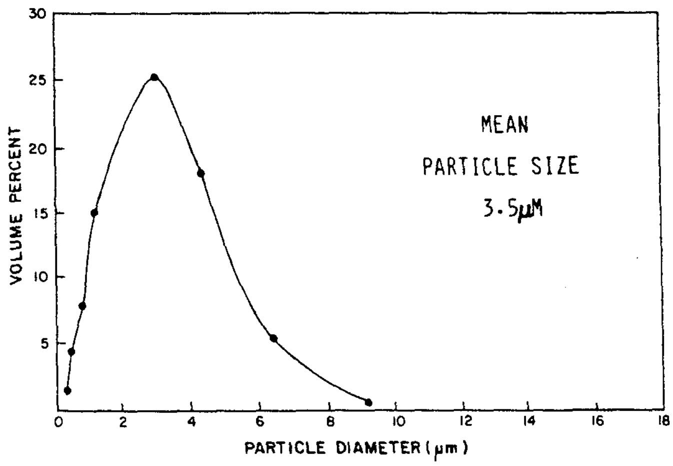


Fig. 5. Silicon carbide particle size distribution used in instrument-grade MMC materials.

lent example of the elevated temperature strength and ablation resistance of the metallic composite material being fully utilized to withstand heavy dynamic loading and aerothermal heating.

2.2. Instrument-grade MMC materials

Instrument-grade MMC materials, like structural-grade composites, are produced using adapted powder metallurgy processes. Instrument-grade composites, which are isotropic, consist of aluminum alloys reinforced with a uniform dispersion of fine particulate SiC, shown in Fig. 4. A plot of the SiC particle size distribution used in instrument-grade composites is displayed in Fig. 5. The mean SiC particle diameter is 3.5 μm.

The microstructure of instrument-grade MMC material, Fig. 6, shows the arrangement and close spacing of the 3.5 μm SiC reinforcement particles within the aluminum alloy matrix. The discrete light-shaded circular regions are remnants of rapidly solidified spherical metallic powder particles used in the synthesis of this composite. The aluminum matrix alloy is

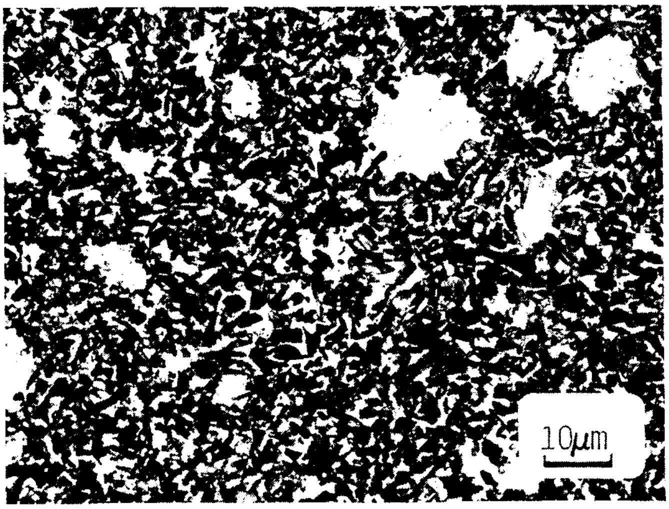


Fig. 6. Optical-light micrograph showing the microstructure of instrument-grade MMC material containing 40 vol % silicon carbide (mean particle size of 3.5 μm).

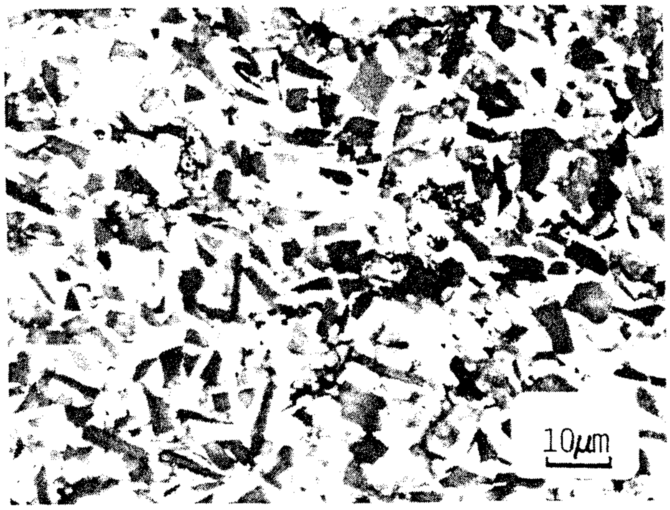


Fig. 7. Optical-light micrograph showing the microstructure of MMC material containing 40 vol % silicon carbide (mean particle size of 5.0 μm).

essentially homogeneous, having fine grains on the order of 1 μm in diameter. Since the crystallographic structure is face-centered cubic, the anisotropy limitations normally associated with hexagonally close-packed materials (such as magnesium, titanium, or beryllium) are not encountered.[4]

Contrasting microstructures of non-instrument-grade aluminum MMC materials containing larger SiC particulate reinforcements (mean particle sizes of 5.0 μm and 9.0 μm) are shown in Figs. 7 and 8. These composites were produced by the same process, with the same matrix alloy, and with the same volume fraction of SiC reinforcement used in producing the instrument-grade MMC material. Note that the average distance between SiC particles becomes greater with increasing mean particle size. Such differences in size and separation of the SiC particulate reinforcement have a significant effect on both the stress field and the dislocation mobility within the matrix alloy.

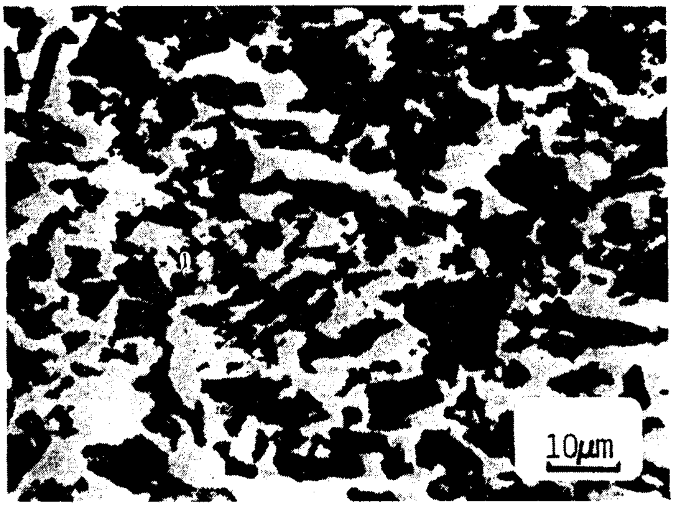


Fig. 8. Optical-light micrograph showing the microstructure of MMC material containing 40 vol % silicon carbide (mean particle size of 9.0 μm).

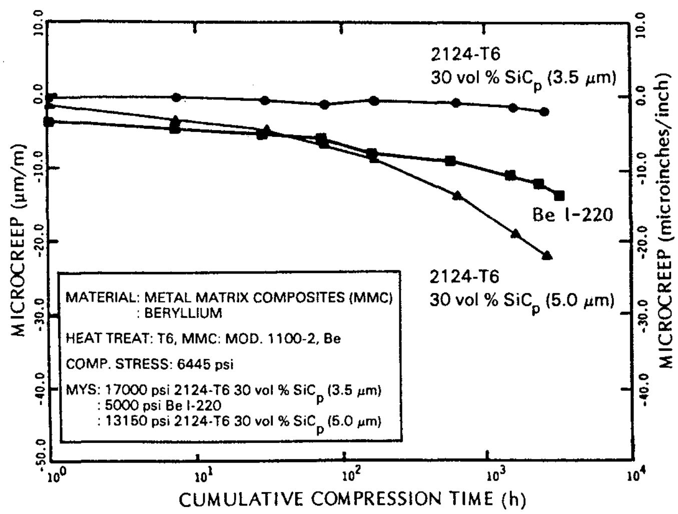


Fig. 9. Comparison of microcreep behavior for MMC materials and beryllium.

The importance of mean SiC particle size on compressive microcreep behavior is shown in Fig. 9, in which two MMC systems are compared to beryllium I-220. The instrument-grade composite containing a mean SiC particle size of 3.5 μm exhibits microcreep resistance superior not only to beryllium but also to the composite containing a coarser mean SiC particle size of 5 μm. The microyield strength* of the instrument-grade MMC (117 MPa, 17×10^3 lb/in.^{2}) is significantly greater than those of the other materials as well.[5]

The presence of the small, uniformly distributed SiC particles in the instrument-grade MMC microstructure inhibits grain growth by hindering grain boundary motion. Acting as insoluble second-phase dispersoids, the particles help to pre-

*Microyield strength (also called precision elastic limit), a major design parameter for dimensionally stable hardware, is the stress required to cause a permanent (plastic) strain of 1×10^{-6}.

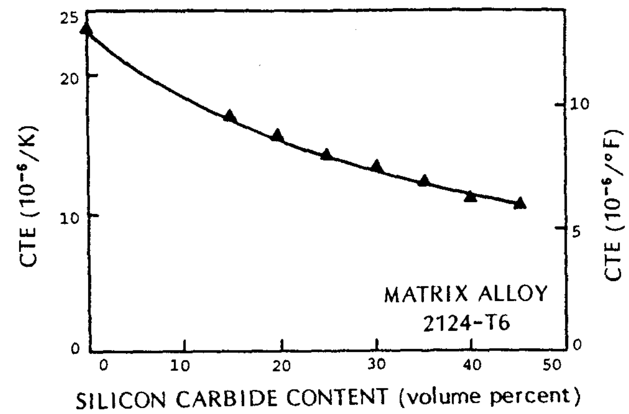


Fig. 10. Relationship of silicon carbide (particulate) content to the coefficient of thermal expansion of optical-grade MMC materials (temperature range: 222 to 366 K).

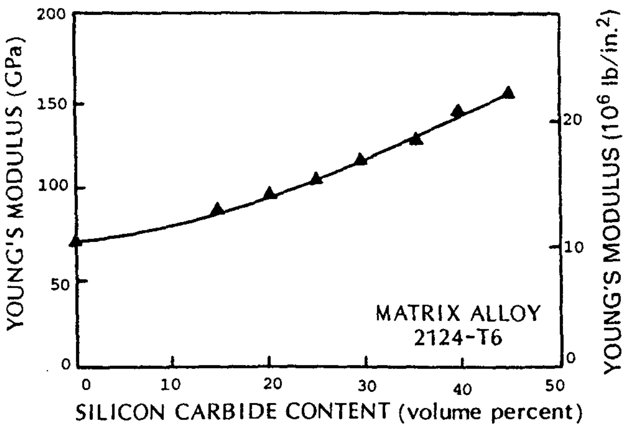


Fig. 11. Relationship of silicon carbide (particulate) content to Young's modulus of optical-grade MMC materials.

serve the fine grain structure of the matrix alloy, even at elevated temperatures. The particles also pin dislocations and cause dislocation pileups, effectively increasing the resistance of the MMC material to creep during service.[6]

Instrument-grade MMCs, because of their excellent physical and micromechanical properties, are typically used to make precision components for inertial guidance systems. These materials were first produced in 1981, and prototype MMC guidance system components were supplied for evaluation in 1984.

2.3. Optical-grade MMC materials

Optical-grade MMC materials, developed especially for use in metal mirror optics, are a result of several significant improvements in instrument-grade composites.[7] Although prototype mirrors were first fabricated from instrument-grade MMCs, better performance was obtained after a number of important refinements were made to the composite material system. The distinguishing characteristics of optical-grade MMCs include (1) modified matrix alloy chemistry, (2) modified SiC reinforcement particle size distribution, (3) higher content of dispersed oxide, (4) optimized homogenization and precipitation heat treatments, and (5) incorporation of special stress relief procedures and cryogenic (cyclic) stabilization treatments.

One of the unique features of optical-grade MMCs (similar to instrument-grade composites) is that the coefficient of thermal expansion (CTE) can be tailored to match that of another material. Figure 10 shows that the CTE of optical-grade MMC materials decreases almost linearly with increasing volume fraction of SiC particulate. If the designer wants an MMC part to have the same CTE as beryllium (11.5×10^{-6}/K, 6.4×10^{-6}/°F), he should select a SiC content of 40 vol % in an aluminum alloy; or to match 304 stainless steel (17.3×10^{-6}/K, 9.6×10^{-6}/°F), he should choose 22 vol % SiC. The thermal conductivity and specific heat of the composites, which are slightly less than those of the unreinforced aluminum matrix alloy, are excellent for most precision system applications.

Increasing the SiC content in MMC materials will also increase the Young's modulus, Fig. 11. The incorporation of 40 vol % SiC in matrix alloy 2124 will raise the Young's modulus to 145 GPa (21×10^6 lb/in.^{2}), twice that of the unreinforced aluminum alloy. Because the density of this composite is only slightly greater than unreinforced aluminum, the specific modulus (E/ρ) is nearly doubled. Components fabricated from these MMC materials may be strategically configured with section thicknesses less than those of unreinforced metal counterparts, allowing significant weight savings.

Table II presents a comparison of properties for both optical-grade and instrument-grade MMCs with conventional materials, again showing that with the appropriate volume fraction of SiC, the CTE of the composite can be established to match the CTE of other materials such as beryllium, stainless steel, and electroless nickel.

By carefully selecting the SiC reinforcement content for an MMC mirror substrate, one can optimize a combination of high stiffness and microcreep resistance, as well as match the CTE of an electroless nickel plating deposited on the reflective surface, thereby establishing exceptional component figure stability over a wide temperature range. A variety of substrates and finished mirrors that have been prepared from optical-grade MMC materials are shown in Fig. 12.

3. DESIGN APPLICATIONS

In recent years, many advancements have been made in the area of precision mechanical systems design.[8] The development of new materials and analytical methods have given engineers greater options in producing instrumentation to meet stringent military, space, and commercial requirements. Engineered metal matrix composites provide a combination of properties and characteristics that are desirable for a broad range of aerospace and optics applications. The following examples demonstrate the effective use of MMCs in producing high performance precision hardware.

3.1. Inertial guidance systems

The instrument covers shown in Fig. 13 were approved for use in the inertial measurement unit (IMU) of a missile guidance system in 1985.[9] These parts were precision forged to near-net shape from instrument-grade composite material and were the first MMC components ever to be qualified for a guidance system application. The MMC covers, which are assembled to a beryllium stable gimbal of an IMU, match the CTE of beryllium, and they have displaced beryllium instrument covers on the basis of lower cost and demonstrated perfor-

TABLE II. Comparison of properties of instrument-grade and optical-grade MMCs to conventional materials.

Property	Instrument-grade MMC 6061-T6 40 vol % SiC_p	Optical-grade MMC 2124-T6 30 vol % SiC_p	Be I-220	420 stainless steel	Electroless Ni coating
Coefficient of thermal expansion 10^{-6}/K (10^{-6}/°F)	10.7 (5.9)	12.4 (6.9)	11.5 (6.4)	10.3 (5.7)	12.1 (6.7)
Thermal conductivity W/mK ($BTU \cdot h^{-1} \cdot ft^{-1} \cdot °F^{-1}$)	127 (74)	123 (72)	178 (104)	24.9 (14.4)	8.0 (4.6)
Young's modulus GPa (10^6 lb/in.^{2})	145 (21)	117 (17)	303 (44)	200 (29)	200 (29)
Density g/cm^3 (lb/in.^{3})	2.91 (0.105)	2.91 (0.105)	1.85 (0.067)	7.8 (0.28)	7.75 (0.28)

mance advantages. Machining and assembly of the MMC parts also cost less since the composite materials can be handled without having to take the special precautions associated with beryllium, which is known to be toxic.[10] The certification and commercial supply of these composite instrument covers have established a significant milestone in the development and commercialization of MMC materials. The success of the MMC covers has prompted the fabrication of associated IMU parts for testing and qualification, including instrument-grade MMC stable gimbals and electronics shell packages.

Some other inertial guidance applications of instrument-grade MMCs that are nearing qualification are components for ring laser gyros, a newer type of navigation system. Ring laser gyros, like their gimballed predecessors, require dimensionally stable parts to minimize "drift," a deviation from established reference coordinates. Both beryllium and stainless steel components are being displaced in these gyro assemblies with instrument-grade composite parts engineered to the same CTE.

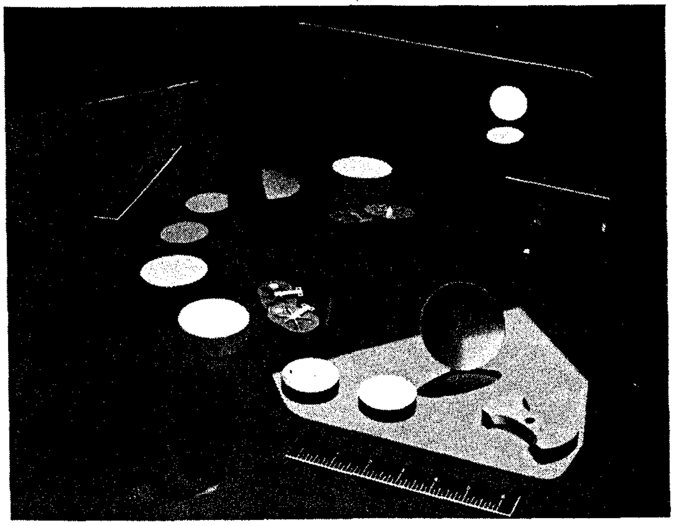


Fig. 12. Two MMC tank mirrors reflect the images of other MMC optical components, including, from left, ion vapor coated substrate, web and pocket FLIR mirrors, two laser mirrors, a satellite solar reflector (faceted), and an hourglass-shaped optical switch.

3.2. Imaging infrared guidance systems

Under a U.S. Army Missile Command Advanced Development Program, the Aeronutronic Division of Ford Aerospace was assigned to design and build imaging infrared seekers for evaluation.[11] These seekers were being developed under the Joint Service Seeker (JSS) program for application to advanced tactical missiles such as the Fiber Optic Guided Missile (FOG-M) and HELLFIRE. Analysis of the original seeker system design indicated a need to reduce the weight. In that effort, the Mechanical Engineering Design Group at Ford Aerospace identified a number of components that might be fabricated from alternative, lighter materials. These selected parts were originally made from 416 stainless steel to match the CTE of gimbal bearings made from 420 stainless steel.

The CTE of wrought 420 stainless steel at 300 K is 10.3×10^{-6}/K (5.7×10^{-6}/°F).[12] From the data curve of Fig. 10, Ford Aerospace engineers recognized that instrument-grade MMC material containing 40 vol % SiC had a CTE closely matching that of 420 stainless steel. They also knew that components machined from this composite would have excellent dimensional stability and would have about the same weight as aluminum. By replacing the 416 stainless steel parts with instrument-grade MMC components, a 62% weight savings could be obtained.

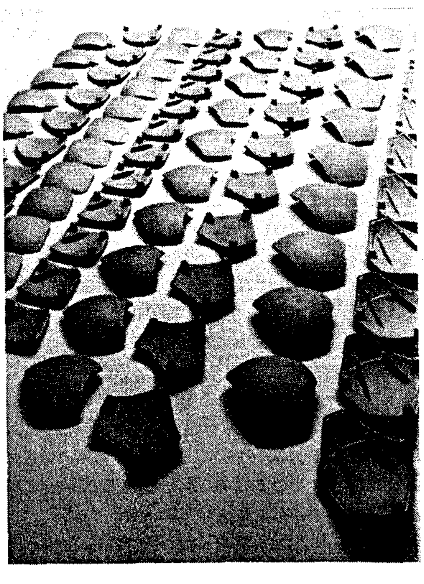


Fig. 13. Precision-forged MMC instrument covers used in a missile guidance system.

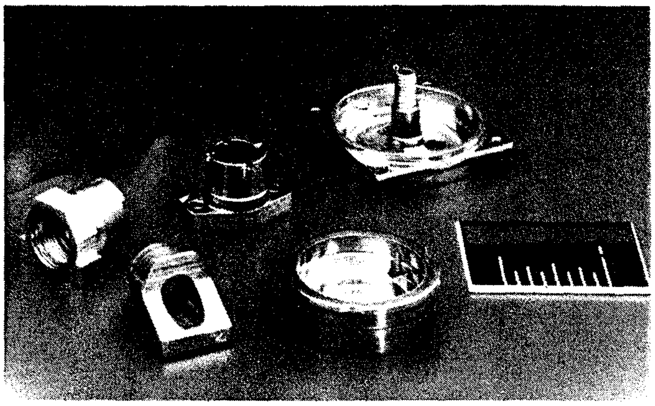


Fig. 14. Precision-machined instrument-grade MMC components for an imaging infrared guidance system.

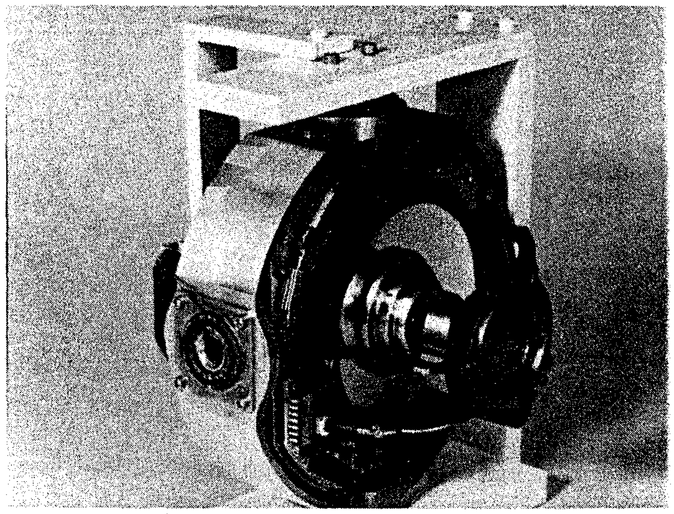


Fig. 15. JSS imaging infrared guidance system built with instrument-grade MMC components.

A decision was made to fabricate seeker gimbal components from instrument-grade MMC consisting of 6061 aluminum reinforced with 40 vol % SiC, heat treated to T6 condition. The 6061 matrix alloy was selected to provide a good substrate for hard coating some of the parts, as well as to maintain an excellent resistance to corrosion. Parts were machined from MMC billet stock to assure isotropic properties. Figure 14 shows some of the intricate part configurations produced from the instrument-grade composite material.

All of the parts were machined using polycrystalline diamond tooling since the machining characteristics of SiC-reinforced aluminum MMC materials are significantly different from those of the identical unreinforced aluminum alloys.[13] The presence of the extremely hard ceramic SiC reinforcement, within a comparatively soft matrix, is abrasive and leads to higher temperatures between tool and workpiece, resulting in faster tool wear. This abrasive action must be compensated by selecting appropriate tool materials (compacted diamond or carbide) and by modifying other machining parameters.

After final preparation, the MMC parts were installed in the imaging infrared guidance system, Fig. 15. This application establishes another example of MMC materials displacing conventional materials on the basis of significant performance/cost advantages.

3.3. MMC mirror optics

The successful development of infrared detection systems and space-based laser systems depends on high performance mirrors, which provide surfaces with the required specularity and geometrical precision. Dimensionally stable MMC mirrors are being qualified for use in several optics applications in which they must function under conditions of extreme thermal cycling and mechanical shock.[14]

A 5 cm (2 in.) diameter flat mirror was fabricated using optical-grade MMC material as a substrate, coated with a reflective layer of electroless nickel, aluminum, and silicon monoxide. The mirror was tested for thermal cycling stability to determine the potential of MMC materials for use in star sensor optics. Each cyclic exposure of the mirror involved cooling from room temperature (293 K) at 1.3 K/min to 230 K, holding for 20 min, then heating at 7 K/min to 340 K. After cycling, two tests were applied at room temperature: (1) interferograms (contour maps) of the surface as viewed in a laser-illuminated Fabry-Perot cavity and (2) resolution of bar patterns as seen in autocollimation with a 3 in. Davidson D656-102 autocollimator. Test results, based on fringe patterns, showed 1/10 wave flatness after 320 thermal cycles, with no evidence of change throughout the test sequence. The autocollimator showed better than 3.4 arcsec of resolution. Other tests of larger, 6 in. diameter MMC mirrors were conducted at cryogenic temperatures. The flatness of these mirrors, cooled and measured in vacuum at 77 K, was maintained to within 1½ fringes.

The tactical tank mirrors shown in Fig. 12 were produced from optical-grade MMC materials. By selecting a silicon carbide reinforcement content of 30 vol %, the designer was able to match the CTE of the electroless nickel plating used on the reflective surface. This kind of mirror has been specified for use in a tank infrared sighting system, in lieu of beryllium or glass substrate mirrors, because of substantial performance/cost advantages.

One should recognize that in addition to their technological advantages, optical-grade MMC mirrors and associated components can be economically hot pressed to near-net shape. More complex configurations may be precision machined and subsequently drilled and tapped to facilitate mounting and assembly.

3.4. Advanced MMC optical applications

A funded program is being conducted at the Optical Sciences Center, University of Arizona, to develop a system concept for a 0.3 m (12 in.) diameter ultra-lightweight (ULW) space telescope. The principal tasks in the program have been to design, build, and evaluate a telescope using new materials, including engineered MMCs. A fundamental goal is to establish the lightest functional configuration that can deliver the required optical precision and high performance at the lowest cost.

Two ULW telescopes have been constructed in this program. Some of the major design features are illustrated in Fig. 16., The truss assembly, which connects the primary and secondary mirrors, was fabricated from structural-grade MMC extruded tubing, 25 mm (1.0 in.) o.d. with a 1.25 mm

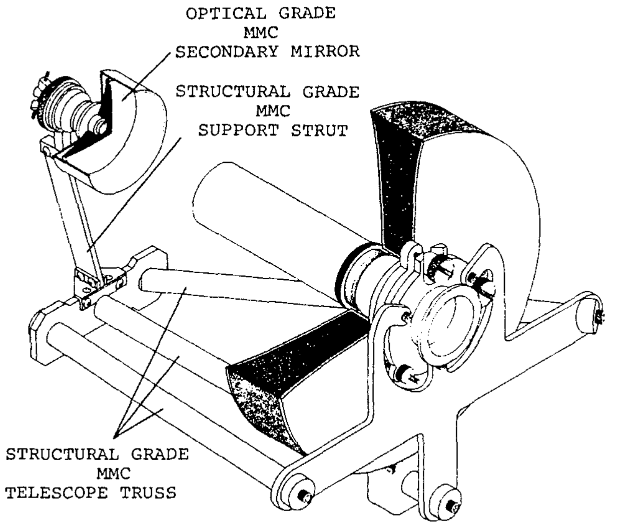
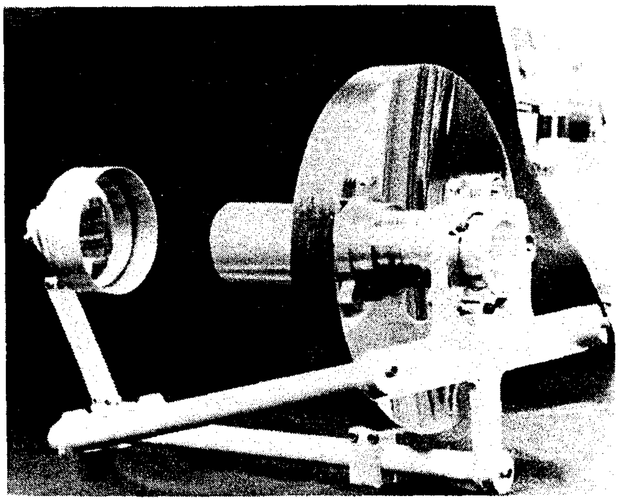
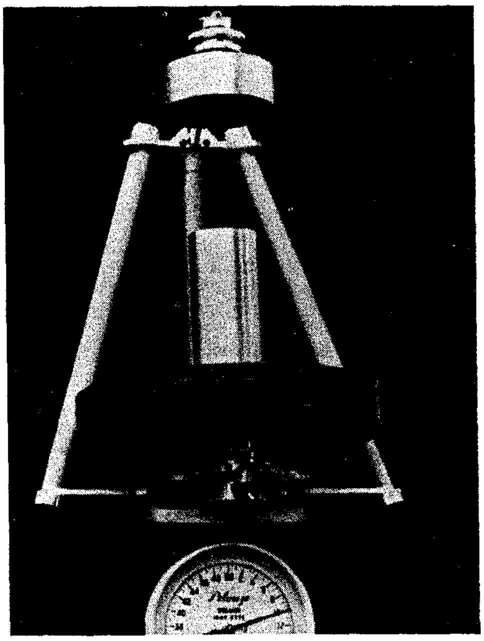


Fig. 16. Design concept for the ultra-lightweight telescope.



(a)



(b)

Fig. 17. Prototype ultra-lightweight telescope incorporating MMC materials: (a) side view and (b) telescope assembly on scale showing a weight of 10 lb.

(0.050 in.) thick wall. The secondary mirror support was made from structural-grade MMC extruded bar. The secondary mirror substrate was machined from optical-grade MMC material, plated with electroless nickel, and polished. Once fabricated, the total weight of each ULW telescope (Fig. 17) was 4.5 kg (10 lb).

The two secondary mirror substrates for the prototype telescope assemblies were machined from solid optical-grade MMC billet using polycrystalline diamond tooling. If production quantities of these substrates had been required, near-net-shape MMC blanks would have been produced (by direct hot pressing) to reduce machining costs. The unique back contour of the center-supported mirror design was generated to closely approximate self-weight-induced uniform stress.[15] Each substrate weighed about 156 g (5½ oz), less than half the 370 g (13 oz) weight of a conventional glass mirror of similar configuration. After machining, the optical surfaces of the MMC substrates were ground using diamond abrasives. Residual stresses were relieved by heating the substrates from room temperature (293 K) at 1.7 K/min to 450 K and holding at that temperature for 3 h, after which they were air cooled to room temperature, chilled to 233 K using dry ice, and finally warmed to room temperature. This cycle was repeated five times. After heat treatment, measurements of the front surface of the substrates indicated a dimensional change of less than 2.5 μm (0.0001 in.), an exceptionally small amount compared to the greater deformations typically seen in conventional metal mirrors.

To prepare the finished MMC mirrors, a 200 μm (0.008 in.) layer of electroless nickel was plated over all surfaces of the substrates. Slight nonuniformity in the plating thickness, caused by inexperience of the commercial plating shop with optical-grade MMC materials, resulted in some difficulty during polishing of the optical surface. When the mirrors were supported at their hubs during the first tests, interferograms (taken at 633 nm) showed about three fringes of astigmatism. This defect, which occurred in both parts, rotated with the mirrors. Additional polishing and use of a uniform back support, however, solved the problem, and later interferograms showed a maximum error of about one fringe. These results, which were quite encouraging, demonstrate that lightweight MMC secondary mirrors, with edge sections as thin as 3.2 mm (0.125 in.), would provide the image quality and cost advantages required for the precision optics of the ULW telescope. The prospects for expanded use of MMC materials in this and other optical systems appear quite good.

4. CONCLUSIONS

Three grades of silicon-carbide-reinforced aluminum metal matrix composites have been developed for use in aerospace structures and dimensionally stable assemblies. These composites can provide differential advantages in the design of many precision instruments and optical systems. A unique feature of instrument-grade and optical-grade MMCs is that the CTEs can be tailored to match those of other materials, allowing the engineer greater flexibility in material selection. Significant performance/cost advantages have already been demonstrated in the commercial production of MMC components for inertial guidance systems and for infrared optics. Accordingly, these engineered materials are being used in the development of advanced space optics, including an ultra-lightweight telescope.

5. ACKNOWLEDGMENTS

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Daniel Vukobratovich: Biography and photograph appear with the Guest Editorial in this issue.