Applications of Multifunctional Structures to Small Spacecraft

John DiPalma, Jeff Preble, Mike Schoenoff, Stephen Motoyama
SpaceWorks, Inc.
7301 E. Sundance Trail, Carefree, AZ 85377; (480) 575-1676
jdipalma@spaceworksinc.com, jpreble@spaceworksinc.com, mschoenoff@spaceworksinc.com, smotoyama@spaceworksinc.com

James Guerrero, Capt. Russell Burks
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Ave. SE
Kirtland AFB, NM 87117; (505) 846-5936, (505) 853-1502
jim.guerrero@kirtland.af.mil, russell.burks@kirtland.af.mil

ABSTRACT: A process for the design and fabrication of multifunctional structures has been developed to increase the utility and efficiency of spacecraft. The process addresses the unique requirements associated with small spacecraft and other highly integrated systems. By integrating items such as electrical conductors for signals and power, thermal control elements, and materials for radiation and EMI shielding, these multifunctional structures offer benefits in terms of mass savings, reduced parts count, reduced manufacturing costs for medium to high production quantities, simplified assembly, integration and test, and more highly integrated (smaller) spacecraft.

INTRODUCTION

The multifunctional structures fabrication process developed at SpaceWorks in collaboration with AFRL is based on compression-molded composite structures with multiple functional elements embedded into the structural substrate during the molding process. The multifunctional structure includes elements such as wiring harness, radiation shielding, heat spreaders and batteries. The result is an overall increase in efficiency. For example, an embedded flexible printed circuit may replace a traditional wiring harness bundle at a lower mass while making additional surface area available for component mounting and eliminating the additional mass of harness mounting brackets.

Small spacecraft typically have a unique set of requirements and challenges in comparison to larger systems. The close proximity of components required to meet overall size limitations tend to exacerbate thermal design problems. Dissipated heat must be managed in smaller volumes and components with significantly different operating temperatures must be located in close proximity. The management of the wiring harness becomes more difficult as spacecraft size decreases. Small spacecraft are often envisioned in large constellations which will require low-cost automated production methods as opposed to the labor intensive methods used for current fabrication, assembly and test. These unique requirements were considered in the development of the multifunctional structures concept described in this paper.

Demonstrated Technologies

A number of key technologies have been developed to enable the production of multifunctional structures, including, 1) a molding process that allows a variety of functional elements to be embedded in the composite substrate, 2) composite molding compounds that are compatible with the space environment, 3) low-cost tooling, 4) material coatings to enhance EMI shielding and component durability.

The compression molding process has been demonstrated to produce complex geometry, such as thin-walled structures and integral mounting brackets, with tolerance control to ±0.005 in. and surface finishes to 32 µinch. Matched-metal tooling is used to produce dimensionally-controlled surfaces over the entire part. Electronics enclosures have been molded which require
minimal post-cure operations, such as machining or bonding. Mounting surfaces for electronics boards, power converters and FETs are produced directly from the mold with no requirement for post-machining operations. Individual molded components may be drilled for conventional fasteners and attached without separate machined brackets, bonded doublers or special fasteners. The TechSat21 EPS chassis is assembled from eight separate molded parts with standard NAS socket-head screws and locknuts (Figure 1).

The TechSat21 Composite EPS Chassis

The process of co-molding embedded elements, such as flexible printed circuits (FPC), high thermal conductivity pyrolytic graphite inserts, structural threaded inserts and high density metallic foils for radiation spot shielding has been demonstrated. These elements are placed in the mold with woven fabrics prepegged and chopped fiber molding compounds prior to cure. The elements may be located by several methods, including locating pins in the mold. Flexible printed circuits fabricated from copper laminated polyimide film have proven to be very durable during molding operations. There have been no cases of damage to an FPC during molding. Multifunctional panels and structural parts have been qualified to Goddard Environmental Verification Specification (GEVS) levels for random vibration and thermal cycling.

Embedded high-conductivity thermal inserts are composed of pyrolytic graphite materials that can exceed 1500 W/m-K conductivity. The pyrolytic graphite material is supplied by GE Advanced Ceramics in the form of thin panels. These panels are machined into shapes as required by the thermal design and placed in the mold to be over-molded with a structural composite material. Multifunctional panels have been fabricated with both regions of high conductivity and thermally isolated (<1.0 W/m-K) regions.

The materials used for the structural substrate are in the form of chopped-fiber molding compounds (0.5-1.0 in. fiber lengths) (Figure 2), continuous fiber unidirectional tapes and woven fabrics. These are pre-pegged with a space-qualified, low outgassing resin system. Outgassing data for the YLA RS-35 epoxy system is 0.063% TML and 0.00% CVCM, tested per ASTM E595. The composite cure schedule of 280°F and 2000 psi consolidation pressure is compatible with the FPC and thermal insert materials.

Coatings have been evaluated to enhance the EMI shielding of the composite material and allow the structure to meet specific electrical grounding requirements. The bulk electrical resistivity of a thermally conductive version of the molding compound is 9.0x10⁻⁶ ohm-m, due to the conductivity of the Mitsubishi K13D fiber (1.9x10⁻⁶ ohm-m). While this is adequate for many electrical grounding and ESD charge bleed-off requirements, an additional coating may be added for more stringent grounding and EMI shielding requirements. An electroplated copper-nickel coating provides 80 dB (at >100 MHz) of EMI attenuation and meets grounding requirements of <0.002 Ω across any structural joint.

Composite Substrate Materials and Manufacturing

Several key requirements were established for the composite substrate material and molding process:

Requirement: The structural properties of the substrate should exceed the properties of the typical low-cost spacecraft structural material, 6061-T6 aluminum alloy.

Result: Tensile strength of the baseline carbon fiber/epoxy molding compound with 1.0 in. chopped fiber is 45 ksi. 6061-T6 aluminum alloy is 38 ksi.
**Requirement:** The density of the structural substrate should result in a significant mass savings (40%) when compared to aluminum alloys.

**Result:** The density of carbon fiber/epoxy composite materials is 1.50 – 1.65 g/cc, or approximately 40% less than 2.7 g/cc aluminum alloy.

**Requirement:** The manufacturing method should utilize low-cost tooling, and allow molded parts to be readily re-worked by conventional manufacturing methods.

**Result:** Flight parts have been molded with low-cost aluminum tooling. Modifications such as drilling and milling operations are performed with standard machining methods.

**HARDWARE FABRICATION EFFORTS**

The following are summaries of components with multifunctional features, or components that demonstrate the production techniques for multifunctional structures.

**Embedded wiring harness panel**

The wiring harness panel (Figure 3) is a molded composite panel with flexible printed circuits embedded in the composite substrate. The FPC includes a 150-conductor wiring harness with 12 surface-mount connectors for access to the conductors. The connectors are surface-mount type connectors assembled by standard practices for PWB fabrication.

An assembly with an aluminum panel, traditional wiring harness and D-subminiature connectors was constructed for comparison purposes (Figure 4). The traditional panel mass was 594 g, the multifunctional panel assembly was 257 g, representing a mass savings of 57%. The multifunctional panel allows much greater flexibility for component mounting, while the traditional panel has limited mounting area due to the size of the harness.

The multifunctional approach allows multiple, redundant conductors to be included in the circuit for a very small mass penalty. These conductors may be routed to a central switching hub where signals may be re-routed by ground commands while on-orbit. This concept for a re-configurable or “programmable” harness allows much greater flexibility to recover from on-orbit anomalies or to support on-orbit servicing missions.

Vibration and thermal cycle testing were performed to validate the construction of the embedded harness panel (Figure 5). Test levels were based on NASA GEVS qualification levels.

Thermal cycling was performed at -70°C to +100°C for 12 cycles. This temperature range should envelope most small spacecraft structural applications. The thermal cycle testing was performed to uncover any issues associated with the mismatch of CTE between the FPC (17 ppm/°C) and the composite substrate (0-7 ppm/°C). Circuit continuity was monitored continuously throughout the test for intermittent failures. No failures were reported. Vibration testing was conducted successfully at the 14.1 grms NASA GEVS qualification level.

**TechSat21 electrical power subsystem (EPS) chassis**

The TS21 EPS chassis is an all-composite,
compression-molded design consisting of eight separate molded components (Figure 1). The chassis is a modular design with multiple components that are bolted together with traditional fasteners. Materials were selected for each component to tailor the properties to their thermal and structural requirements. FET mounting rails and 6U board mounting rails are K13D2U high thermal conductivity fiber with an equivalent in-plane thermal conductivity of 170 W/m-K. The remaining parts are molded from a molding compound based on intermediate modulus Toray T700 fiber for high strength and reduced cost.

The design was tested in thermal vacuum with 60 W total dissipated power in the 6U cPCI boards and chassis-mounted FETs and power converters. All components were maintained within acceptable operating limits at 60 W dissipated power.

Random vibration testing was performed to the NASA GEVS qualification level, 14.1 grms, then to an additional +3dB (20 grms overall level) to demonstrate margin. Thermal cycle testing was performed for 12 cycles at -40°C to +80°C for a total test time of 45 hours.

**TechSat21 PIE chassis**

The TS21 PIE chassis (Figure 6) is a compression-molded design that demonstrates the capability to mold thin-wall, lightweight structures with complex geometry. The PIE chassis includes 0.050 in. thick walls, integral co-molded mounting feet, integral board mounting bosses, threaded metallic inserts, and high thermal conductivity material. The wall thickness of the PIE is equivalent to a 0.030 in. thick aluminum chassis on a mass-equivalent basis. This level of lightweighting in aluminum would be difficult to achieve due to machining limitations, machining costs, and thermal and structural performance. The mass of the PIE chassis assembly is 210 g.

A qualification test sequence was performed on the PIE, including random vibration testing at 16.6 grms, modal survey testing, thermal balance testing in vacuum with 14 W dissipated power and thermal cycle testing at -40°C to +90°C for 8 cycles.

**Embedded thermal insert panel**

A multifunctional panel with embedded thermal inserts was fabricated to demonstrate the capability to provide tailored thermal conduction paths and isothermal areas within a structural panel. The basic construction is a thermal pyrolytic graphite insert embedded in a low-conductivity composite molding compound. Thermal pyrolytic graphite (TPG) from GE Advanced Ceramics is an extreme thermal conductivity material with 1500 W/m-K in-plane conductivity and a density of 2.26 g/cc. In comparison to aluminum, the TPG material is 20% lower mass at 8.5X the thermal conductivity.

The thermal panel includes an L-shaped conduction path which serves to tie a component mounting location to the spacecraft primary structure or a radiator. The area adjacent to the insert is thermally isolated due to the low-conductivity material. Zones of the panel can be iso-thermalized with embedded TPG inserts, as demonstrated by the dogbone-shaped insert which serves to iso-thermalize two components despite differing power dissipations. Thermal model results of the thermal insert panel are shown in Figure 7.

**Sensor platform**

The sensor platform is a composite structural panel that is cantilevered from the spacecraft deck and serves to support 400 g of sensors for an electric propulsion diagnostic package. The sensor platform, as shown in Figure 8, is required to be low mass (<188 g), high

![Figure 6. Propulsion Integrated Electronics ( PIE) Enclosure](image6.png)

![Figure 7. Thermal Model Results of a Panel with Embedded Thermal Conduction Paths](image7.png)
thermal conductivity (>400 W/m-k) and meet structural strength (81 g load factor) and minimum first-mode frequency requirements (>80 Hz). The requirement for high thermal conductivity is driven by the need to maintain the sensors at isothermal conditions.

This set of requirements would not be attainable without the use of a composite material. Use of high modulus (135 Msi), high conductivity (800 W/m-K) fibers (Mitsubishi K13D unidirectional tape) allows the lightweight structural panel to meet an 80 Hz first-mode frequency requirement.

**Integrated power panel (IPP) for small spacecraft**

The IPP (Figure 9) is a 16 in. diameter deck for a small spacecraft bus that includes integrated thin form-factor batteries, an EPS electronics board and interconnect flex-print circuit harnessing. The IPP development is a joint effort of the University of Colorado, Ball Aerospace and SpaceWorks.

EPS control electronics are directly mounted to the structural panel, eliminating separate electronics chassis mass. The thermal design includes three separate thermal zones: a high conductivity battery panel which serves as a battery radiator, a thermal isolator layer to allow battery and EPS electronics to operate at different temperatures, and a moderate thermal conduction layer to tie the EPS electronics to the bus structure. Integrated threaded inserts are included for mounting of components such as a deployable boom.

Limitation on the temperature range of the batteries has prevented the co-molding of batteries into the structural substrate. The cure temperature of the composite material is 130°C, which is above the acceptable temperature limit for flight-qualified lithium polymer or lithium-ion batteries. For the current design, the batteries are potted into the panel in a separate operation.

The benefits of this multifunctional panel are: 1) Reduced structural mass by combining the battery chassis, bus structural close-out panel and EPS electronics enclosure into a single structural component. 2) Volume efficient packaging of battery cells does not intrude on primary structure component mounting area. 3) Minimized harness mass and cable length between battery and EPS electronics, typically one of the larger harnesses on a spacecraft. 4) Ability to create separate thermal zones in a single part, which otherwise would be accomplished with separate thermal isolators and heat spreaders.

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**SUMMARY**

Design, fabrication and test have been completed for several assemblies that demonstrate multifunctional characteristics. Composite structural panels with embedded wiring harness, thermal control inserts, foils for spot shielding, and structural inserts have been fabricated. These assemblies have successfully passed qualification test levels for thermal and dynamic environments. Multifunctional structures such as those described in this paper are a mature technology prepared to make a significant contribution to the utility and efficiency of future small spacecraft.