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LEVERAGING METAL MATRIX COMPOSITES TO REDUCE COSTS IN SPACE MECHANISMS

Ted Nye, Rex Claridge, and Jim Walker
TRW Space and Electronics Group
Redondo Beach, California

ABSTRACT

Advanced metal matrix composites may be one of the most promising technologies for reducing cost in structural components without compromise to strength or stiffness. A microlight 12.50 N (2.81 lb), two-axis, solar array drive assembly (SADA) was made for the Advanced Materials Applications to Space Structures (AMASS) Program flight experiment. This SADA, as shown in Figure 1, had both its inner and outer axis housings fabricated from silicon carbide particulate reinforced aluminum. Two versions of the housings were made. The first was machined from a solid billet of material. The second was plaster cast to a near net shape that required minimal finish machining. Both manufacturing methods were compared upon completion. Results showed a cost savings with the cast housing was possible for quantities greater than one and probable for quantities greater than two. For quantities approaching ten, casting resulted in a reduction factor of almost three in the cost per part.

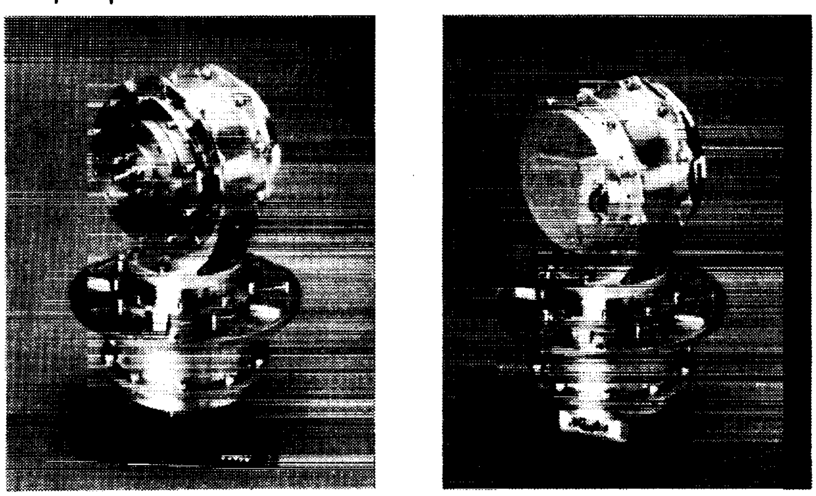

Figure 1. Metal Matrix Composite Solar Array Drive Assembly

INTRODUCTION

Changes in the spacecraft business have motivated a re-evaluation of low cost fabrication methods. Satellite metallic structures are typically machined from an oversized billet of raw stock. It is common in this industry to remark how a seemingly small, intricate part originated from a huge billet of material. This approach to fabrication yields a component with one appreciable value added feature: it is truly homogenous and monolithic. Problems from structural discontinuities are minimized. Nonetheless, the sheer number of cutting operations and potential of scrapping a part from machining errors makes this approach inefficient and risky, particularly in light of current customer production expectations.

Casting, injection molding, and forging are all viable alternate fabrication processes that we evaluated for this study. High reliability satellite manufacturers have historically shunned these approaches due to structure non-homogeneity, poor property predictability, poor mechanical strength repeatability, or because very small quantities were required. Advances in the last decade have resulted in the maturity of fabrication processes, especially motivated by commercial-world pressures to drive defects to zero. A recent trend prompting spacecraft builders to give a fresh look at alternative fabrication methods is government customer insistence that the cost of spacecraft hardware be dramatically reduced with no compromise in performance.

Advanced structural materials combined with a low cost fabrication approach can result in a significant cost efficiency improvement. One method for evaluating materials is to rank them based upon their *specific* strength and stiffness. Figure 2 shows these comparisons. Spacecraft mechanism structures tend to be located in regions of high elastic strain energy, such as at the root of appendages or in assemblies where bending is inevitable, but undesirable. Therefore, materials that exhibit high specific strength and stiffness are preferred.

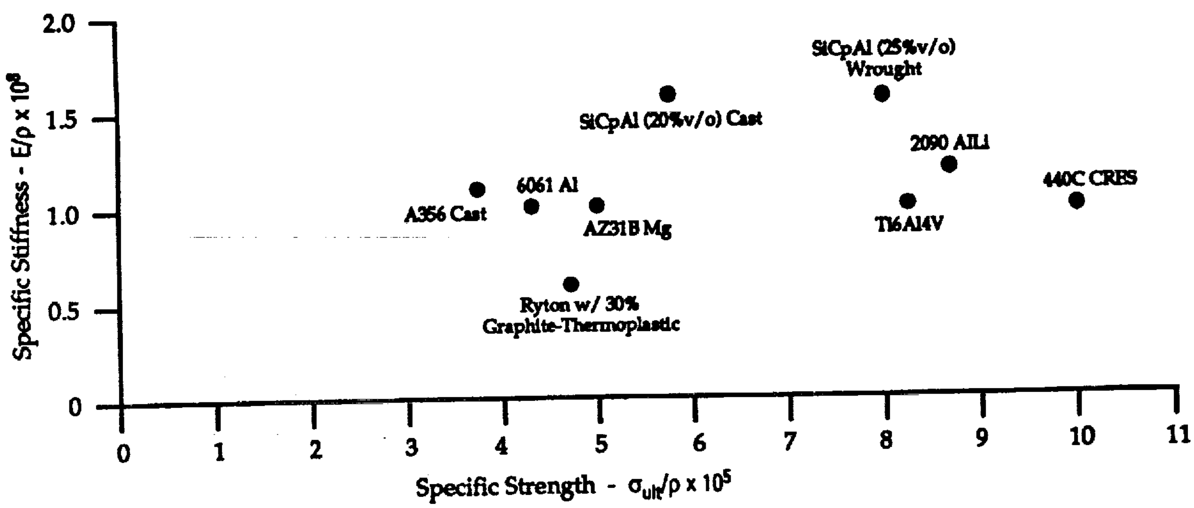

Figure 2. Comparison of Specific Strength of Aerospace Materials

Table 1 shows that when comparing metal matrix composites (MMCs) to metallic or plastic based systems, MMCs exhibit a low strain to failure and fracture toughness, but superior strength and stiffness. This failure strain and toughness issue was a reasonable concern because a design could be sensitive to inclusions acting as crack initiation sites, leading to ultimate, sudden failures. We addressed these problems by employing standard NDE methods of surface dye penetrant, and X radiography inspection (MIL-STD 2175, Class 2, Grade C), followed by static proof testing in three axes. If one looks closely at our cast MMC housings illustrated in Figure 3, generous radii and smooth load path transitions were intentionally included in the design. Inserts, although effective to distribute point concentrated fastener loads, were avoided altogether in favor of through-holes for bolted joints. Liberal tolerances and machinist drawing reviews were used to create a tolerant, forgiving design that minimized the number of secondary cutting operations.

Table 1. Mechanical Property Comparison for Aerospace Materials

	Density (kg/m^3)	Ultimate Strength (kPa)	Yield Strength (kPa)	Youngs Modulus (MPa)	Strain to Failure (%)	Thermal Expansion (10^{-6}/°C)	Thermal Conductivity (W/m·K)	Fracture Toughness (MN/m$^{-3/2}$)
SiCp/Al (20% v/o)								
Duralcan F3D-F Die Cast	2823	296-352	290-303	113.8	0.1-0.4	5.2	147	unknown
Duralcan F3S-20S Plaster Cast	2765	317-359	310-338	98.6	0.4	5.5	145	16
SiCp/Al (25% v/o)								
DWA 6013-T6 Machined Billet	2851	552	421	115.8	3.8	4.7	138	21
Reinforced Thermoplastic								
Ryton, 30% Chopped Gr Injection Molded	1412	163	N/A	24.8	0.6	4.4	0.36	unknown
Al-Li Alloy								
2090-T8 Machined Billet	2602	552	517	75.8	4-8	7.3	87	27
Aluminum								
6061-T6 Machined Billet	2713	310	276	68.9	12	7.3	166	29
A356 Plaster Cast	2685	255-276	200	75.1	6	6.6	151	17
Titanium								
6Al-4V Annealed and Machined	4429	896-1000	827-931	113.8	14	2.7	6.7	55
6Al-4V Cast and Annealed	4429	931	827	113.8	12	2.7	6.7	55

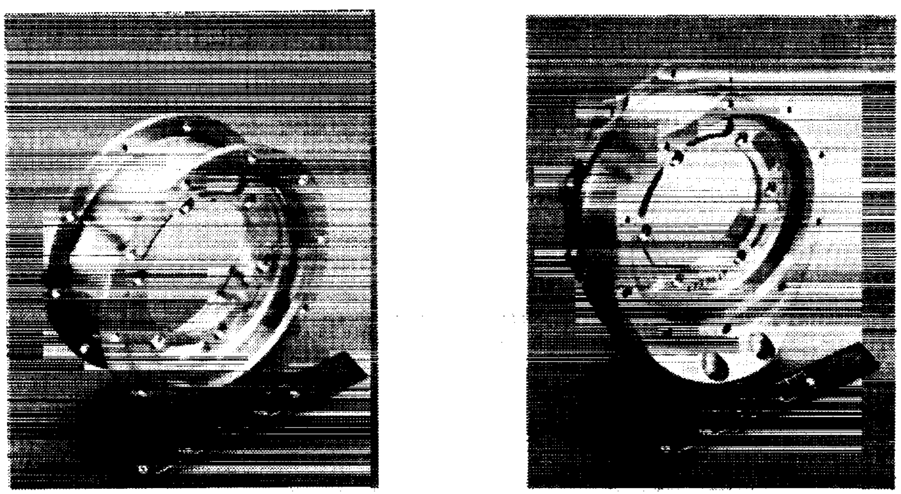

Figure 3. Cast MMC Inboard and Outboard SADA Housings

METHODS OF MANUFACTURING

When beginning the design of this SADA, we embarked on a technology survey to not only arrive at a low cost fabrication approach, but to conclude with a material system exhibiting superior yield and modulus properties. A third aspect under consideration was to take advantage of low volume or medium volume mass production: quantities of 10 to 100 units. This objective enabled the potential for an assembly line operation in contrast to a one-of-a-kind craftsman type assembly. Candidate approaches for fabrication included die and plaster casting, injection molding, forging and stamping of an aluminum or thermoplastic based composite material system.

The results of our survey concluded with choosing a SiCpAl/FDS-20S plaster cast aluminum fabrication process. We found there was a comparable cost to both injected molded graphite thermoplastic and plaster cast aluminum. Previous experience on other TRW programs showed MMC aluminum castings would likely achieve a superior design to injection molded thermoplastic. This was due to expected higher toughness, lower part attrition, higher attainable stiffness (independent of temperature), and less sensitivity to on-orbit thermal threat issues and atomic oxygen. Fabrication methods of forging and stamping involved an initial large capital expenditure (to develop dies and processes) which could only be recovered for production quantities approaching hundreds of units. These processes also resulted in parts more deviant from final dimensions, which would require significant finish machining.

Several casting approaches were considered. For large volumes, die casting the housing, as shown in Figure 4, resulted in the most economy and highest fabrication speed (approximately 50 seconds per unit). This approach would result with components containing exceptional part to part repeatability, low void density, excellent surface detail, and as a result of the high casting pressures, reduced structural shrinkage. Die casting would result in superior mechanical properties from quickly chilled, fine grained metallurgical structure. Expected accuracy in geometrical dimension were as follows:

Thinnest Sections	0.102 to 0.152 cm (0.040 to 0.060 in)
Tolerances	± 0.0016 cm (± 0.004 in) linear
	0.025 cm (0.010 in) concentricity
Surface Finish	127 μm (50 μ in)

Steel casting dies, although sufficient to produce 20,000 units without wear, proved too expensive in cost and schedule to be recouped over a 10 to 100 unit production run. Thus, we decided to investigate and alternate casting methods.

Rubber plaster mold casting was discovered to be ideal for our needs. Typical for quantities of 10 to 100, this process could readily produce units without the need of expensive dies. The compromise, however, would be in final surface dimensions and tolerances, which would require a minor finish machining operation. Comparing with die casting, accuracies were as follows:

Thinnest Sections	0.152 to 0.203 cm (0.060 to 0.080 in)
Tolerances	± 0.0127 cm (± 0.005 in) linear
	0.025 cm (0.010 in) concentricity
Surface Finish	318 μm (125 μin) typical for sand castings

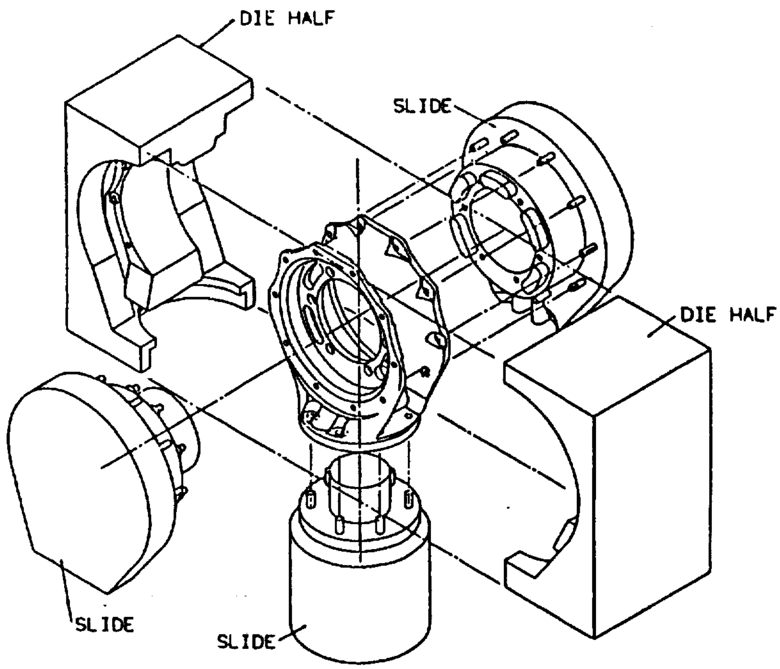

Figure 4. Conceptual Drawing of Outer Housing Die Assembly

To make a one-for-one cost/complexity evaluation with traditional fabrication methods, one set of SADA housings was machined from solid billets of SiCpAl and another set was plaster cast. Table 2 shows the cost results from these two approaches with actuals indicated. Unit costs for lots of one, ten, and one hundred are shown. From this table, two machined outboard units would have cost $12,136. This is approximately the same price as 10 cast units at $12,420. It became apparent that the cost effectiveness of casting would be realized at a quantity of approximately two or greater, with a cost avoidance of approximately 50% for a quantity of ten. This cost savings was realized with overall improved mechanical properties!

Table 2. Cost Comparison of Conventional Machining versus Casting

	Unit Cost for Lot of 1-9	Unit Cost for Lot of 10-99	Unit Cost for 100 or Greater
Outboard Solar Array Drive Assembly Housing:			
Machined Part Total	$6068.00†	$3138.00	$1979.00
Plaster Cast Part Total	$6510.00	$1242.00†	$374.00
Inboard Solar Array Drive Assembly Housing:			
Machined Part Total	$3925.00†	$1904.00	$905.00
Plaster Cast Part Total	$4571.00	$1021.00†	$284.00

† Costs taken from paid invoices, other costs quoted

SADA OVERVIEW

The two-axis SADA was the result of an effort to reduce size and weight of spacecraft mechanisms without sacrificing performance. This SADA uses two-phase, bipolar, 15-degree stepper motors with non-redundant windings coupled to 100:1 harmonic drive gear reducers in an extremely compact arrangement. Each axis contains potentiometer position feedback and uses preloaded duplex bearings for reaction loads. Hard mechanical stops were used on each axis to limit rotation range. Each housing had bonded strip heaters and individual thermostats for temperature control. Lubricant used was Penzane X2000 with a lead additive, that was previously life tested on other TRW programs. This SADA was originally designed for gimballing 48.9 N (11.0 lb) thin-film solar arrays on a micro-satellite. Minimum pull-out running torques of 2.94 N•m (26 in•lb) and unenergized holding torques of 4.97 N•m (44 in•lb) were measured for each axis. Drive voltage can vary, but is nominally approximately 26 volts for each axis, with potentiometer excitation of 10 volts DC.

LESSONS LEARNED

Inclusions in the cast MMC parts were the only significant fabrication problem encountered. These were discovered during X-ray NDE and were the cause of remaking one batch of castings. A quantity of 10 of each housing were initially requested. When inspected to the Mil standard, only 5 of 20 outboard housings passed within the grade C allowable. For the inboard housings, 2 of 10 housings were conditionally accepted. All housings contained small gas holes, but rejected ones had these near free surfaces, in violation of the specification. Conditionally accepted housings had near-surface gas holes, but in benign stress regions. Vast experience was claimed by vendors of standard cast aluminum. However, casting MMC's systems introduced unique problems due to silicon carbide particulate dispersion, flow characteristics, mold moisture, and humidity conditions during casting. Experience for MMC systems is improving. It was not a factor for the enthusiasm and cooperation of the vendor to resolve these difficulties.

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