Applications of Aluminum-Matrix Composites in Satellite: A Review

Zaigham Saeed Toor

***Abstract*—This paper attempts to review the potential applications of Aluminum-matrix composites in Satellite systems. Material selection is a very crucial part of space design due to extreme and diverse requirements of the outer space. There is always a requirement of lightweight materials in space launch. Aluminum Matrix Composites (AMCs) are potential candidates for such demanding applications and with the proper reinforcement selection, an effective state of the art satellite component can be developed. Diverse properties such as high stiffness, low Co-efficient of Thermal Expansion (CTE), high specific strength and low outgassing make these materials an attractive choice in various systems of Satellite. This review has focused on different combinations of AMCs being employed for the respective components of Satellite.**

***Index Terms*— Aluminum-matrix Composites, Material Selection, Satellite Structure, Space Technology**

I. Introduction

THE space exploration led the to the necessity and launching of satellites into space. Satellite is defined as an object sent into space to orbit the earth or a planet with a purpose of collecting information by navigation and communication.[1, 2] Today, satellite communication is a crucial part of the international infrastructure. Metrology, Agriculture, Mass communication and defense sectors largely benefit from the satellite network available globally for faster and effective communication. In simple words, no country in the modern era can develop economically as well as technologically without a proper satellite system[3, 4].

Generally all satellites have six major components namely Structure, Payload, Attitude control systems, Thermal control systems, Power systems and Propulsion systems. Structure is responsible for the complete integrity of the satellite components during the launch and in space since it sustains all the forces during the operation and mission of the satellite. Payload contains cameras, instruments, communication systems or anything else that defines or is involved in execution of the Satellite missions[5]. Attitude control systems use sensors, magnetometers and high profile compasses to position and change direction of the satellite in space. Thermal control systems are used for dissipating heat from the satellite in outer space because no air is present in space and conventional fanning systems cannot be used for temperature control of satellites. Power systems are dedicated for maintaining power supply to all the systems and components of the Satellite. Like any other electronic component, electricity is the major power contributor in satellites. In order to fulfil the electricity requirements for prolonged space missions there are two major power sources in satellites. The first one uses solar energy from the sun by using a combination of solar arrays and photovoltaic cells. The second source uses rechargeable batteries to power the systems in case the satellite is in such a position that sunlight is absent. Propulsion systems comprise of a combination of thrusters that facilitate in orbit control and changing the direction of satellite[6-8].

Space has a very extreme and challenging environment. The temperature can be below zero on one side and on the other side, it can reach to the direct exposure to the heat of sun. Apart from this, weight is a prime factor in any component that has to be launched in space since the launching cost increases with every pound of weight. Also during the launch, a lot of vibrational and gravitational forces act on the components which can rise up to three times their own weight and hence structural integrity is also a vital part of the satellite. In order to cope up with such diverse environment and stringent requirements, the materials to be used for space or satellite components must be light in weight, have good dimensional tolerance, exhibit high specific strength and conclude exceptional structural integrity.[9-11]

Aluminum-matrix composites along with other metal matrix composite(MMC) materials have potential applications in various aspect of engineering such as mountain bikes and golf clubs on one end to the diverse marine yacht fittings, automotive brake discs, drive shafts and extending to the defense and aerospace applications in the form of electronic housings and satellite structures[11-16]

Aluminum-matrix composites are preferred for space based applications due to their low density, high specific strength, high thermal conductivity and high wear resistance, making them an ideal candidate for diverse and robust engineering applications. Such remarkable properties are imparted by reinforcing the aluminum matrix with reinforcements in the form of fibers, particulates or whiskers. However, machining of the composite becomes more difficult due to the reinforcements involved making it a challenge for intricate component fabrication, leading to a higher cost[14-17].This

Engr. Zaigham Saeed Toor is a graduate of Materials Science & Engineering Department, Institute of Space Technology (IST), Islamabad, Pakistan. He is a registered engineer with Pakistan Engineering Council (PEC) (email: zaighamtoor93@gmail.com).

article attempts to focus the review on the research directed for specific material combinations of Aluminum Matrix Composite (AMCs) in terms of reinforcement selection and their potential use in satellite applications.

II. AMCs in Satellite Structure

Suraj [12] discussed the applications of discontinuously reinforced aluminum (DRA) composites using particulate and whisker reinforcements of Silicon-carbide(SiC) and Germanium (Gr).The author reported that due to their low density, light weight, tailorable Coefficient of Thermal expansion (CTE) which is match-able to electronic materials, high thermal conductivity and cost-effectiveness due to net-shape manufacturing, these composites have massive applications in satellite structures as thermal planes, truss nodes, housings, bushings, longerons, EMI shielding and electronic packages. Similar conclusions have been made by other authors on the subject[18-23].These applications have been qualified for space usage and have been used in Communication and Global Positioning System Satellites as shown in Figure 1 and Figure 2. Hocine et al.[22] has discussed a modelling-based approach for the material selection and design methodology of satellite structure components by the application of Transmission-Line Matrix (TLM) approach. This approach not only helps in the thermal management of the structure but also provides a comparison of the material combinations, thus providing a cost effective insight in housing and structure design of satellite components along with the analysis of complex geometry design provides the engineers with a tool of structure reliability for the satellite.

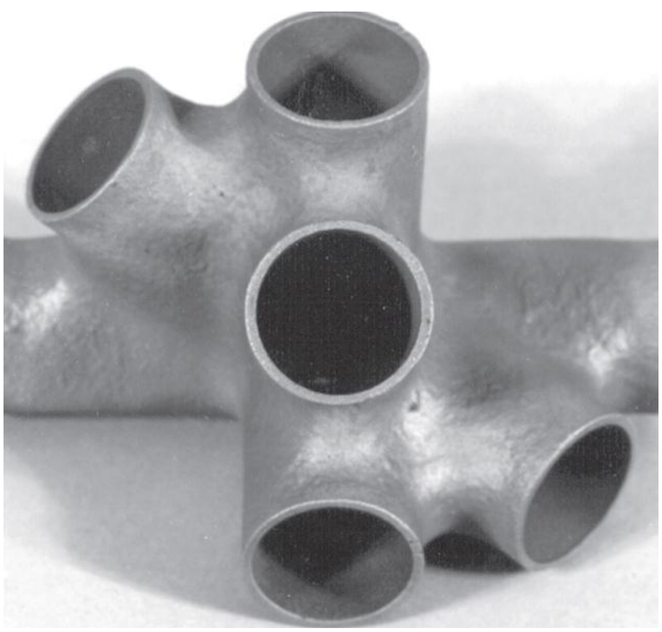

Fig. 1. Cast SiC_p(particulate)/Al(Aluminum) multi-inlet fitting for a truss node after Suraj [12] with permission from Springer.

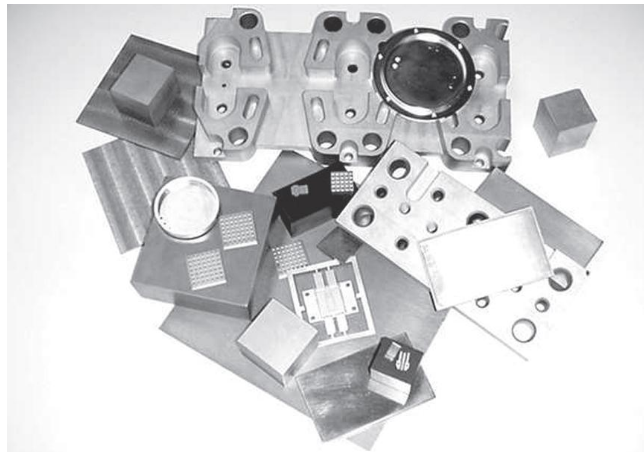

Fig. 2. Cast Gr_p (particulate Germanium)/Al(Aluminum) components using discontinuously reinforced aluminum MMCs for electronic packaging applications after Suraj [12] with permission from Springer.

Badiey et al. [21] discussed the optimization of satellite truss structure using Metal Matrix Composites. The authors reported that by replacing the initial Aluminum (Al-2024) structure with 6061-T6 Aluminum reinforced with 10% Germanium (Gr) composite, weight reduction of 42% was achieved and by replacing the former with 6061-T6 Aluminum reinforced with 30% particulate Silicon Carbide (SiC_p) composite, 70% weight reduction was achieved. Similar results have been supplemented by other authors on the subject [11, 12, 22-24]. Hocine et al.[22] has discussed the effective thermal management of the satellite structure by simulating and comparing metallic and composite material combinations. The author reports that Aluminum reinforced with Germanium provides an effective composite for heat spreader as shown in Figure 3.This is attributed to the resultant thermal properties of the combination that has a thermal conductivity close to copper and a CTE that matches silicon, which reduces the increase in temperature due to the heat generated in the structure.

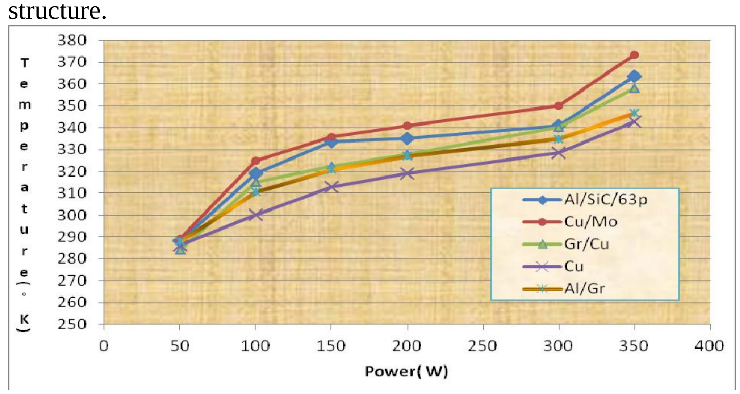

Fig. 3. Comparison of MMC heat spreader materials after Hocine et al.[22] with permission

Muley et al.[23] has discussed the overall enhancement of aluminum matrix composite properties by using nano and hybrid reinforcements. The author reports that by incorporating nano and hybrid reinforcements, the resultant properties are much better as compared to micro reinforcements and can give large results using small quantity and size of nano fillers as shown in Table 1.

Table 1
Properties of Al based metal matrix nano and hybrid composites after Muley et al.[23] with permission from Taylor & Francis

Materials	Particle size (µm/nm)	Vol.%/Wt.%	Elastic modulus (GPa)	UTS (MPa)	Yield strength (MPa)	% Elongation	Hardness
2024Al alloy/SiC_w + SiC_p	0.3-0.6µm,10–28 µm length 35 µm	20 vol.%, 0–7 vol.%	150-200	450-600	275-550		
Pure Al/WO_{3p} + ABO_w	18 µm, 0.5–1 µm, 10–30 µm	3 vol.%, 22 vol.%	96	287.30	250.7	1.66	
Pure Al/ABO_w + BPO_p	0.5–1 µm, 10–30 µm length 0.2–0.5 µm	20 vol.%, 5 vol.%	104	224		3.5	
Pure Al/MWCNTs		0.25–0.75 vol.%		198.5-330.8	126.1–230.5		57–77 Hv
Al/SiC_w + SiC_p T6	0.3–0.6 µm, 10–28µm length 35 nm	20 vol.%, 2–7 vol.%	124-127	513-620		0.77-0.83	

Although the properties achieved using nano and hybrid reinforcements are very promising but there is a major issue of homogeneous dispersion of these reinforcements, which is difficult to control, resulting in agglomeration of the particles and thus making bulk scale production difficult. Thus such structural components are in R & D phase and require further development in actual usage as component of satellite.

III. AMCs in Satellite Payload

Rudy [11] discussed the space applications of Graphite-Epoxy composites. The author reported that the hybrid horizontal cross arm of communication satellite Intelsat-IV constituted of Aluminum reinforced with graphite-epoxy tape. This combination was selected due to the low weight and minute deflections required from the arm in service. The antenna of Canadian communication satellite Anik was also developed using aluminum honeycomb with graphite-epoxy layer as reinforcement. This combination is validated for good structural stiffness, minimization of thermal distortions and controlling the effects of solar radiations. Similar reports have been made by other authors on the subject [22, 24].

Suraj [12] discussed the space applications of Metal Matrix composites. The author reported that Gr/Aluminum 6061 reinforced with P100 graphite fibers using diffusion-bonding was used for the high-gain antenna boom of Hubble Space Telescope (HST).This combination was selected due to good structural stiffness of the composite, low CTE for robust movements, good electrical conductivity for wave guidance, vibrational and flexural endurance as shown in Figure 4 and Figure 5.Other authors have reported similar conclusions on the subject[18-23].

Badiey et al. [21] discussed the optimization of vibrational transmission of Satellite Boom using Metal Matrix Composites. The authors reported that by incorporating 6061-T6 Aluminum reinforced with 10% Germanium (Gr) and 6061-T6 Aluminum reinforced with 30% particulate Silicon Carbide (SiC_p) composites in Satellite boom, filtering capability was enhanced for the entire 100Hz frequency range. The average vibrational filtering proficiency improved by 7.2 *dB* and 3.62 *dB* for Gr and SiC_p reinforced aluminum combinations respectively. Similar results have been supplemented by other authors on the subject [11, 12, 22-24].

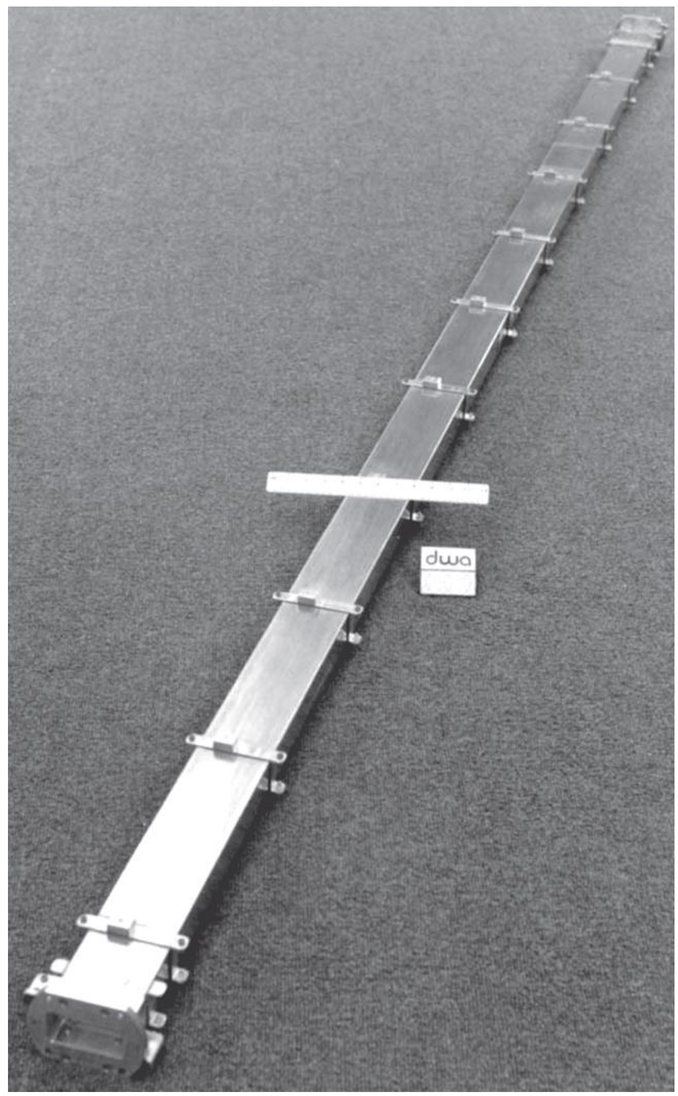

Fig. 4. The Gr/Aluminum 6061 reinforced with P100 graphite fibers antenna for HST after Suraj [12] with permission from Springer.

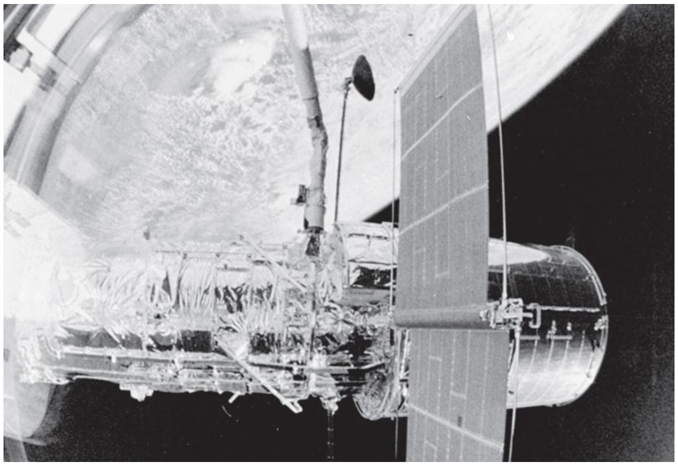

Fig. 5. The Gr/Aluminum 6061 reinforced with P100 graphite fibers antenna mounted on HST after Suraj [12] with permission from Springer.

IV. AMCs in Satellite Attitude control & Power systems

Babuska et al. [25] discussed the technological development of Flywheels for Attitude control and Power systems. The authors reported an Integrated Power/Attitude Control System (IPACS)[26] approach that suggests two composites systems namely Aluminum reinforced with Boron and Aluminum reinforced with SiC respectively for the Flywheel rotors which can be used for powering both the Attitude Control and Power systems of the Satellite. Similar results reported by other authors on the subject [27-29].

Ronald et al.[29] studied Flywheel storage technology for IPACS. The authors reported that with proper computational optimization Aluminum matrix reinforced with Boron, HS-graphite, SiC and Alumina can be used for Flywheel rotors for energy storage system. These composite systems are preferable due to their diverse nature in terms of material combinations and design optimization, synergistic properties, high specific strength, dimensional stability, high CTE, Stiffness and substantial weight reduction. Similar results were reported by other authors on the subject [23, 25-28, 30].

V. AMCs in Satellite Thermal control systems

Shinn et al.[31] has discussed the enhancement of thermal control in satellites using composite radiator panels. The authors reported that aluminum honeycomb core composite act as effective passive panels for thermal management of satellite and spacecraft which was implemented in Earth Orbiter program. Similar results were reported by other authors on the subject [23, 32-35].

Muley et al.[23] has reviewed applications of AMCs in various aspects. The authors reported that Aluminum reinforced with SiC can be effectively used in microwave system of satellite. Also, aluminum reinforced with Alumina (Al_2O_3), SiC and TiB_2 can be used for high performance thermal applications. Nanoparticles of SiC can be used for reinforcing aluminum for applications that oblige dimensional stability and exceptional thermal characteristics. Similar results were reported by other authors on the subject [31-38].

Sidhu et al.[32] has discussed thermal management prospects of MMCs. The authors reported that aluminum reinforced with copper (Cu) along with Beryllium oxide (BeO), Aluminum Nitride (AlN), diamonds or SiC as fillers can be used for thermal management systems of satellite. Such combinations are preferred due to diverse combination of properties such as effective dissipation, minimum thermal stress retention, dimensional stability at high temperatures and low CTE. It was also reported that aluminum reinforced with SiC can be utilized for thermal management of microwave housings while aluminum reinforced with Boron (B) can be used for thermal management of printed circuits. The relevant properties of the materials discussed are shown in Table 2. Similar results were reported by other authors on the subject [23, 31, 33-41].

TABLE 2
Thermal properties and densities of the selected materials after Muley et al.[23] with permission from Taylor & Francis

Materials	Density (g/cm^3)	CTE ($x\ 10^{-6}$/C)(25-150°C)	Thermal Conductivity (W/mK)
Si	2.3	4.2	151
Cu	8.96	17.8	398
SiC	3.2	2.7	200-270
Alumina	3.98	6.5	20-30
Diamond	3.51	0.9	2000
AlN	320	4.5	3.3
BeO	3	6	260

Silvain et al.[33] has discussed fabrication of Aluminum-Carbon and Copper-Carbon composites using powder metallurgy process. The authors reported that Aluminum reinforced with 5% volume Al-Si and 50 % volume reinforcement of Carbon fiber using powder metallurgy can result in effective composite materials for heat sink and heat transfer applications. These composites can be effectively utilized for thermal management systems of satellite due to their enhanced thermal conductivity (240W/m.K) and low CTE ($7.0\times10{-}6$/K).Similar results have been reported by other authors on the subject [23, 31, 32, 34-44].

Williamson et al.[35] has discussed the applications of Advance Materials for Spacecraft. The authors reported that Aluminum reinforced with Graphite and Aluminum reinforced with particulate or whisker SiC can result in excellent AMCs for thermal management systems of Satellite due to their Electromagnetic (EM) shielding, high heat dissipation, good thermal conductivity, no outgassing, high stiffness and strength respectively. Similar results have been reported by other authors on the subject [23, 31-34, 36-44]

VI. AMCs in Satellite Propulsion systems

Signorilli [45] has discussed the applications of MMCs in Satellite and Aircraft propulsion systems. The author reported that Aluminum reinforced with Boron is a cost-effective solution to replace titanium based turbine blades and compressor fan blades. These AMCs are not only lighter than the titanium counterparts, but also they significantly reduce the operation cost, have good impact resistance and provide dimensional stability at high temperatures. Similar results have been reported by other authors on the subject [46-49].

Halchak et al.[50] discussed Materials for Liquid Propulsion. The authors reported that AMCs are potential candidates for high performance housings of turbo pumps, since they provide an interesting combination of feasible fabrication, high specific strength, cost effectiveness, modifiable properties and propellant compatibility. Similar results have been reported by other authors on the subject [45, 51, 52]

VII. Conclusion

It can be inferred from the review that AMCs have diverse applications in spacecrafts and Satellite systems. Their diverse set of tailorable properties make them a potential candidate for research and development of space applications. With the right material selection a cost-effective, multi-functional and reliable engineering solutions can be developed for current problems and future design requirements.

Conflict of Interest

The author declares no conflict of interest

References

[1] Cambridge, in *Cambridge Advanced Learner's Dictionary & Thesaurus* ed. United Kingdom: Cambridge University Press, 2017.

[2] D. K. (1997). *HOW DO SATELLITES BENEFIT SOCIETY*. Available: http://www.stmary.ws/HighSchool/Physics/97/SATELIT1.HTM

[3] L. C. Rowan, "Application of Satellites to Geologic Exploration: Recent experiments in two spectral regions, the visible and near-infrared and the thermal-infrared, confirm the value of satellite observations for geologic exploration of the earth," *American Scientist*, vol. 63, pp. 393-403, 1975.

[4] H. SOFFAR. (2015). *What are the importance and uses of Satellites in our life ?* Available: https://www.online-sciences.com/technology/what-are-the-importance-and-uses-of-satellites-in-our-life/

[5] J. I. Inc. (2017). *Satellite Components* Available: http://www.jsati.com/why-satellite-how-Spacesegment3.asp

[6] D. A. McInnes. (2013). *Parts of a satellite*. Available: https://www.sciencelearn.org.nz/videos/123-parts-of-a-satellite

[7] K. G. (1997). *Major Components of a Satellite*. Available: http://www.stmary.ws/HighSchool/Physics/97/KGALLAG.HTM

[8] W. Cook. (1996). *The Anatomy of a Satellite*. Available: http://www.williamcraigcook.com/satellite/anatomy.html

[9] W. Wassmer. (2015). *The Materials Used in Artificial Satellites and Space Structures*. Available: http://www.azom.com/article.aspx?ArticleID=11443

[10] M. H. Heidt, P. J. Puig-Suari, P. A. S. Moore, P. S. Nakasuka, and P. R. J. Twiggs, "CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation," presented at the 14TH 1 Annual/USU Conference on Small Satellites, Utah, 2013.

[11] R. Lukez and M. Thiokol, "The Use of Graphite/Epoxy Composite Structures in Space Applications," presented at the Small Satellite conference, Utah, 1987.

[12] S. P. Rawal, "Metal-matrix composites for space applications," *JOM*, vol. 53, pp. 14-17, 2001.

[13] M. Ellis, "Joining of aluminium based metal matrix composites," *International Materials Reviews*, vol. 41, pp. 41-58, 1996.

[14] D. L. McDanels, "Analysis of stress-strain, fracture, and ductility behavior of aluminum matrix composites containing discontinuous silicon carbide reinforcement," *Metallurgical Transactions A*, vol. 16, pp. 1105-1115, 1985.

[15] M. O. Bodunrin, K. K. Alaneme, and L. H. Chown, "Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics," *Journal of Materials Research and Technology*, vol. 4, pp. 434-445, 2015/10/01/ 2015.

[16] D. R. Tenny, G. F. Sykes, and D. E. Bowles, "Composite Materials for Space Structures," in *Third European Symp. Spacecraft Materials in Space Environment*, ESTEC, Noordwijk, the Netherlands, 1985.

[17] A. F. Society. (2006). *Aluminum Metal Matrix Composites*. Available: http://www.afsinc.org/content.cfm?ItemNumber=6912

[18] C. Thaw, "Metal Matrix Composites for Microwave Packaging Components," *Electronic Packaging and Production*, pp. 27-29, August 1987.

[19] D. B. M. a. B. Maruyama, "Metal Matrix Composites for Space Systems: Current Uses and Future Opportunities," in *National Space and Missile Materials Symposium*, Dayton, OH: Anteon Corp., 2000.

[20] D. M. Goddard, P. D. Burke, and D. E. Kizer, "Continuous Graphite Fiber MMC's," in *Engineered Materials Handbook*. vol. 1, ed Materials Park, OH: ASM, 1987, p. 867.

[21] M. Badiey and A. Abedian, "APPLICATION OF METAL MATRIX COMPOSITES (MMCS) IN A SATELLITE BOOM TO REDUCE WEIGHT AND VIBRATIONS AS A MULTIDISCIPLINARY OPTIMIZATION," presented at the 27TH INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES Iran, 2010.

[22] R. Hocine, A. Boudjemai, A. Boukortt, and K. Belkacemi, "3D TLM formulation for thermal modelling of Metal matrix composite materials for space electronics systems," in *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, 2013, pp. 47-52.

[23] A. V. Muley, S. Aravindan, and P. Singh2, "Nano and hybrid aluminum based metal matrix composites: an overview," *Manufacturing Review*, vol. 2, pp. 1-13, July 12, 2015 2015.

[24] N. J. Mayer, "Carbon Composites in Space Vehicle Structures," presented at the International Conference on Carbon Fibers, London, 1974.

[25] V. Babuska, S. M. Beatty, B. J. deBlonk, and J. L. Fausz, "A review of technology developments in flywheel attitude control and energy transmission systems," in *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720)*, 2004, pp. 2784-2800 Vol.4.

[26] C. R. Keckler, "Integrated Power/Attitude Control System (IPACS)," V. NASA Langley Research Center; Hampton, United States, Ed., ed. United States: NASA. Langley Research Center Integrated Flywheel Technology, 1983, pp. 5-21.

[27] G. E. Rodriguez, P. A. Studer, and D. A. Baer, "ASSESSMENT OF FLYWHEEL ENERGY STORAGE FOR SPACECRAFT POWER SYSTEMS," N. A. a. S. A. (NASA), Ed., ed. Goddard Space Flight Center Greenbelt, Maryland 20771: NASA, 1983.

[28] R. S. Steele, *Composite flywheel balance experience*: ; Oak Ridge Y-12 Plant, TN (USA), 1981.

[29] R. E. Oglevie and D. B. Eisenhaure, "Advanced Integrated Power and Attitude Control System (IPACS) Study," N. A. a. S. A. (NASA), Ed., ed. Langley Research Center: NASA, 1985.
[30] F. T. Wallenberger, J. B. MacChesney, R. Naslain, and H. D. Ackler, *Advanced Inorganic Fibers: Processes — Structure — Properties — Applications*: Springer US, 2011.
[31] E. Shinn, D. H. Maahs, and D. S. Benner, "CARBON-CARBON COMPOSITE RADIATOR PANEL IMPROVES THERMAL CONTROL ON SATELLITES," NASA, NASAJune 1998.
[32] S. S. Sidhu, S. Kumar, and A. Batish3, "Metal Matrix Composites for Thermal Management: A Review," *Critical Reviews in Solid State and Materials Sciences,* vol. 0, pp. 1-26, 02 November 2015 2015.
[33] J.-F. Silvain, A. Veillère, and Y. Lu, "Copper-Carbon and Aluminum-Carbon Composites Fabricated by Powder Metallurgy Processes," *Journal of Physics: Conference Series,* vol. 525, 2015.
[34] R.-M. Wang, S.-R. Zheng, and Y.-P. Zheng, "Introduction to polymer matrix composites," in *Polymer Matrix Composites and Technology*, ed: WOODHEAD PUBLISHING, pp. 1-25.
[35] J. R. Williamson, "Advanced materials for space structures," *Acta Astronautica,* vol. 24, pp. 197-202, 1991/01/01/ 1991.
[36] D. B. Miracle, "Metal matrix composites – From science to technological significance," *Composite Science and Technology*, vol. 65, pp. 2526-2540, 2005.
[37] S. C. Tjong and Z. Y. Ma, "The high temperature creep behaviour of aluminium-matrix composites reinforced with SiC, Al2O3 and TiB2 particles," *Composite Science and Technology,* vol. 57, pp. 697-702, 1997.
[38] S. M. Zebarjad, S. A. Sajjadi, and E. Z. V. Karimi, "Influence of nanosized silicon carbide on dimensional stability of Al/SiC nanocomposite," *Research Letters in Materials Science,* p. 835746, 2008.
[39] H. S. Lee, K. Y. Jeon, H. Y. Kim, and S. H. Hong, "Fabrication process and the thermal properties of SiCAl metal matrix composites for electronic packaging applications," *Journal of Materials Science,* vol. 35, pp. 6231-6236, 2000.
[40] M. A. Occhionero, R. A. Hay, R. W. Adams, and K. P. Fennessy, "Cost-effective manufacturing of aluminum silicon carbide (AlSiC) electronic packages," *IMAPS Advanced Packaging Materials Symposium,* March 17 1999.
[41] D. C. Packard, "Kevlar epoxy substrate for interconnecting leadless chip carrier," *Sampe J,* pp. 6-14, 1984.
[42] A. Luedtke, "Thermal management materials for high-performance applications.," *Advanced Engineering Materials,* vol. 6, pp. 142-144, 2004.
[43] C. Zweben, "Advances in composite materials for thermal management in electronic packaging," 1998.
[44] C. Zweben, "High-performance thermal management material," *Advanced packaging*, 2006.
[45] R. A. Signorelli, "Metal Matrix Composites for Aircraft Propulsion Systems," presented at the International Conference on Composite Materials, Geneva, Switzerland, 1975.
[46] Krelder, K. G, Prewo, and K. M, "Boron-Reinforced Aluminum. Composite Materials," *Metallic Matrix Composites Academic Press,* vol. 4, pp. 400-480, 1974.
[47] Hancock, J. R, Swanson, and G. O, "Toughness of Filamentary Boron/Aluminum Composites," presented at the Composite Materials: Testing and Design, Second Conference, 1972.
[48] M. P, Toth, and i. J., "Development of Impact Resistant Boron/Aluminum Composites for Turbojet Engine Fan Blades," NASA, Ed., ed: NASA, 1974.
[49] H. J. R and G. G. Shaw, "Effect of Filament-Matrix Interdiffusion on the Fatigue Resistance of Boron/Aluminum Composites.," presented at the Composite Materials:Testing and Design, Third Conference, 1974.
[50] J. A. Halchak, J. L. Cannon, and C. Brown, "Materials for Liquid Propulsion Systems," ed.
[51] Lee, Jonathan, Elam, and Sandy, "Development of Metal Matrix Composites for NASA's Advanced Propulsion Systems," in *4th Conference on Aerospace Materials, Processes, and Environmental Technology*, Marshall Space Flight Center, Alabama, 2001.
[52] Effinger, M.Clinton, R.G, Dennis, Jay, Elam, *et al.*, "Fabrication and Testing of Ceramic Matrix Composite Propulsion Components," in *4th Conference on Aerospace Materials, Processes,and Environmental Technology*, Marshall Space Flight Center, Alabama, 2001.