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A Study on Recent Trends in the Applications of Metal Matrix Composites

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***Abstract:** In pursuit of lightweight materials with improved properties for various applications has been created, a new class of material family known as Metal Matrix Composites (MMC). On account of the excellent physical, mechanical and development properties of composite materials, they are applied widely in aircraft technology, automotive, defense, electronics and Space applications. Researchers are doing lots of work in the field of production technologies of MMC which has brought down their cost to an acceptable level. This is due to the significant advances in the development of fabrication routes of MMC. This paper aims both to summaries the present application status and the fabrication methods currently employed in the production of various Metal Matrix Composites,*

***Index Terms:** Applications of MMC, Production methods of MMC, Metal Matrix Composites.*

I. INTRODUCTION

Metal matrix composites (MMC) are a family of new materials which currently experiencing active development in various fields. The potential of MMC materials for significant improvements in performance over conventional alloys has been widely recognized. Besides performance, the other major factor in determining the applications for a material is cost. Raw materials cost is not the only factor determining the overall cost effectiveness of the material in a particular component application. It also depends on the processes through which the material advances.

II. COMPOSITE

A composite material is produced from two or more constituent materials with significantly different physical or chemical properties. The constituent materials, then work together to give the composite unique characteristics that are different from the individual components. The individual components remain separate and distinct within the finished structure as they do not blend or dissolve into each other. Wood is an example for natural composite, made from long cellulose fibers (a polymer) held together by a much weaker substance called lignin. The bone in the human and animals' body is also a natural composite. It is made from a hard but brittle material called hydroxyapatite (which is mainly calcium phosphate) and a soft and flexible material called collagen (which is a protein). The terms of matrix and reinforcement are very often used when talking about composites. Matrix is a relatively 'soft' phase with specific physical and mechanical properties, whose sole purpose is to bind the reinforcements together by virtue of its cohesive and adhesive characteristics, to transfer load to and between reinforcements. The reinforcement phase (or phases) is usually stronger and stiffer than the matrix and mainly carries the applied load to the composite [5]. Composite materials can be subdivided into three main groups: Polymer, Ceramics and Metals. Reinforcements added to these materials produce Polymer Matrix Composites (PMC), Ceramic Matrix Composites (CMC) and Metal Matrix Composites (MMC). Among different composites, Metal–matrix composites are the most widely used in the industrial scale due to its advantages compared to Polymer Matrix Composites and Ceramic Matrix Composites.

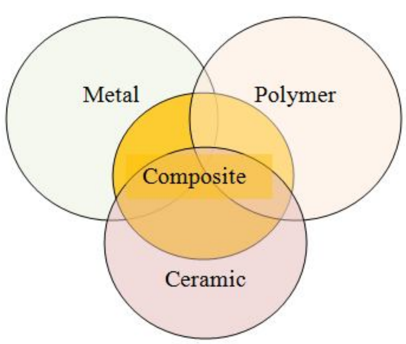

Figure 1: The family of composites

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III. METAL MATRIX COMPOSITE

Metal matrix composite materials are produced by combining tough metallic matrix with hard ceramic or soft reinforcement materials. The reinforcement materials systems can be generally divided into five major categories, i.e. particulates, wires, continuous fibers, discontinuous fibers, and whiskers [2]. Table 1 displays typical reinforcements used in MMCs. MMC can be defined as the materials whose microstructures comprise a continuous metallic phase into which a second phase, or phases, have been artificially introduced [10]. This is in contrast to conventional alloys in which the microstructures are produced during processing by phase transformations.

Table 1: Typical types reinforcements used in metal–matrix composites

Type	Aspect ratio	Diameter	Examples
Particle	1–4	1–25 μm	SiC, Al_2O_3, BN, WC
Short fiber (whisker)	10–10000	1–5 μm	C, SiC, Al_2O_3, $SiO_2 + Al_2O_3$
Continuous fiber	> 1000	3–150 μm	SiC, Al_2O_3, C, B, W, Nb + Ti, Nb_3Sn
Nanoparticle	1–4	< 100 nm	C, Al_2O_3, SiC
Nanotube	> 1000	< 100 nm	C

Source: Chawla, 2012 [24].

When the matrix material has high ductility, the cracks formed by the breakage of weak fibers can be arrested and if the matrix is not ductile enough, the cracks can propagate, and the strength of composite is determined then by the crack propagation [13]. MMC’s potential for achieving major jumps in property enhancement compared with the conventional alloy made it to widely use in various fields. Table 2 shows the advantages of metal matrix composites over metals and polymer matrix composites [16]. MMCs can be classified into different categories depending upon their matrix materials. From a recent market study, it is evident that among the different MMC’s aluminium based composites holds major share in the different applications (above one fourth). This is mainly due to its unique properties like less density, greater strength, good thermal properties, improved stiffness, controlled thermal expansion and improved wear resistance. Among all excellent aluminium alloys the precipitation hardenable alloys, such as AI-Cu-Mg and A1-Zn-Mg-Cu, are of special interest [20]. Figure 2 shows the usage volume of different matrix materials in the production of MMCs.

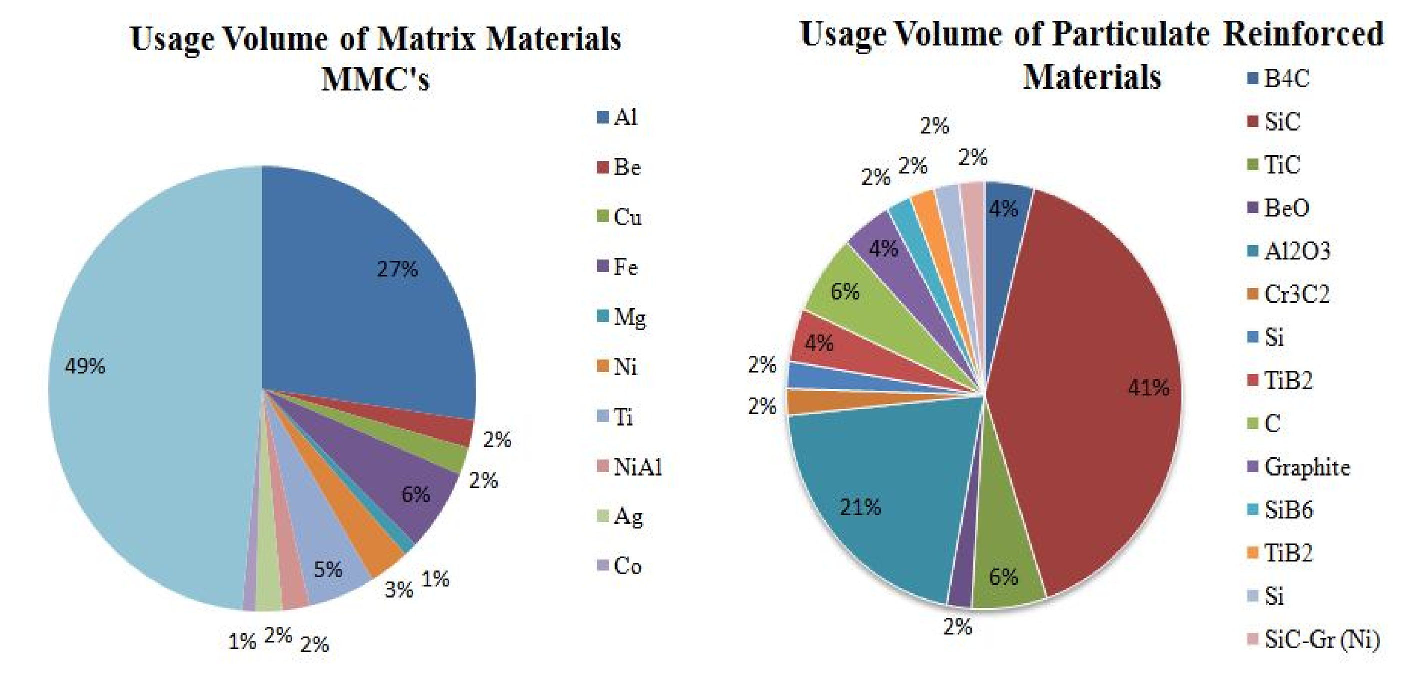

Figure 2: Usage volume of different matrix and reinforcement materials

Table 2: Advantages of metal matrix composites (MMCs) over metals and PMC

Metals	PMC
Major weight savings due to higher strength-to-weight ratio	Higher strength and stiffness
Significantly improved cyclic fatigue characteristics	Better transverse properties and radiation survivability (laser, UV, nuclear, etc.)
Exceptional dimensional stability (for example, SiC/Al to Al)	Higher thermal conductivity and service temperatures
Better wear resistance	Improved joining characteristics
Higher elevated temperature stability, i.e., creep resistance	Higher electrical conductivity (grounding, space charging)

Mainly particulate and whisker types reinforcements are used for the production of different MMCs. Liquid metal routes are generally the cheapest, although may not give the best properties. Stir casting is used, for example, to disperse coarse silicon carbide or alumina particles in aluminium alloys [17]. Table 3 represents typical mechanical and physical properties of typical reinforcement particles.

Table 3: Mechanical and Physical properties of various reinforcement particles

Ceramic	Density (g/cm^3)	Elastic Modulus		Compressive Strength (Mpa)		Thermal Conductivity (W/mK)	Co - efficient of thermal expansion (10^{-6} / K)
		(Gpa)	10^6 psi	(Mpa)	ksi		
Graphite	1.5-2.5	8-27.6	1.1-4	30-300	4-43	25-150	1.2-8.2
B_4C	2.52	450	65.3	3000	435.1	29	5
SiC	3.21	430	62.4	2800	406.1	132	3.4
TiC	4.93	345	50.0	2500	362.6	20.5	7.4
BeO	3.01	345	50	1655	240	270	8
Al_2O_3	3.92	350	50.8	2500	362.6	32.6	6.8
Cr_3C_2	6.68	373	54	4138	600	190	6
Si	2.33	140	20	3200	465	90-120	2.6
TiB_2	4.52	430 - 510	62-74	3735	542	25	8

IV. APPLICATIONS OF METAL MATRIX COMPOSITE

Most common metal matrix composite materials currently producing and applying practically are based on light metal alloys, especially on magnesium alloys, aluminium alloys and titanium alloy matrices, as well as high temperature superalloys based on nickel reinforced by stable ceramic dispersion particles [7]. These composite materials based on light metal alloys are reinforced with dispersion particles, platelets, short fibers or continuous fibers which enhance the mechanical properties and widely using in the fields of production technology of aircraft and cars, in defense technology and in astronautics etc. The principal market sectors which are looking to use MMCs are reviewed in Table 4.

Table 4: An overview of various applications of MMC

Market Sector	Components	Property requirement	Currently Using MMC	Literature
Automotive	Engines	Improved high temperature strength, fatigue and wear Better Match to CTE of steel in certain components	SiC_p/Al, SiC_w/Al, SiC_p Mg, Al_2O_3/Al, TiC_p/Al, etc.	17
	Brake callipers	Stiffness	SiC_p/Al	18
Aircraft	Engines	Improved high temperature strength, creep resistance, stiffness.	Nextel/Al, Cu–Nb, Cu–Nb3Sn	5,6
	Airframe	Improved strength and stiffness	B/Al	23
Defense	Missiles	Better high temperature strength, higher modulus.	Nextel/Al , Cu–Nb, Cu–Nb3Sn	5,6
	Armor	Complex high rate properties,	Bn / Steel	5,19,6
	Tank tracks	Lower density, higher wear resistance.	SiC/Al	19
	Torpedoes	Higher modulus and strength	Nextel/	6
Space	Satellites	Lower (zero) CIE, higher stiffness, self damping characteristics	B/Al	23
	SDI	Higher thermal conductivity with high temperature strength.	Gr/Al	23,22
	Space panels	Higher strength at temperature and low density.	Gr/Al, SiC_p /Al	23
Electronics	Substrates	Matched CTE of ceramic at low density	Al/B, Al/SiC_p, Al/graphite foam, etc	6
Sporting goods	Various	Higher stiffness, strength and high tech image	Al/SiC_p,	5

V. AUTOMOBILE AND RAILROAD APPLICATIONS

By far most of today's metal matrix composites for automotive applications are based on aluminium and its alloys. Generally MMC’s are used in the production of automotive engines is to lower the mass of reciprocating parts and hence generate less noise and vibration. Light weight and inexpensiveness are the prime factors for the wide use of aluminium and its alloys in the fields of automotive compared to other light metals, such as titanium and magnesium. The most commonly targeted part in the engine is the piston crown, where the improved hot strength of the MMC allows a lighter part to be used. Piston pins and connecting rods can similarly benefit in MMC. Among all excellent Al alloys the precipitation hardenable alloys, such as AI-Cu-Mg and A1-Zn-Mg-Cu, are of special interest. Toyota and Honda are one of the main automotive companies who commercially started to use Al based MMC’s in their engines. Toyota has used MMC pistons in its diesel engines and Honda has used steel wire reinforced aluminium connecting rods and Al–Si matrix MMC (with 12% Al_2O_3) for Cylinder block on cars [17]. Due to the improved wear resistance, toughness and thermal properties, MMC’s are widely used in the production of valve train components and light weight brake

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calipers [3]. To reduce the total weight of the bogey in Railway vehicles, a particulate-reinforced aluminum–matrix composite (AlSi7MgþSiC particulates, supplied by Duralcan) fabricated by a multi-pouring process are using. The most common MMC's now using are listed in the table 4. Earlier, the drawbacks of these MMC's are their expense and lack of experience in use, but due to the significant advances in the development of fabrication routes the final cost of MMC componentsis drastically reducedd.

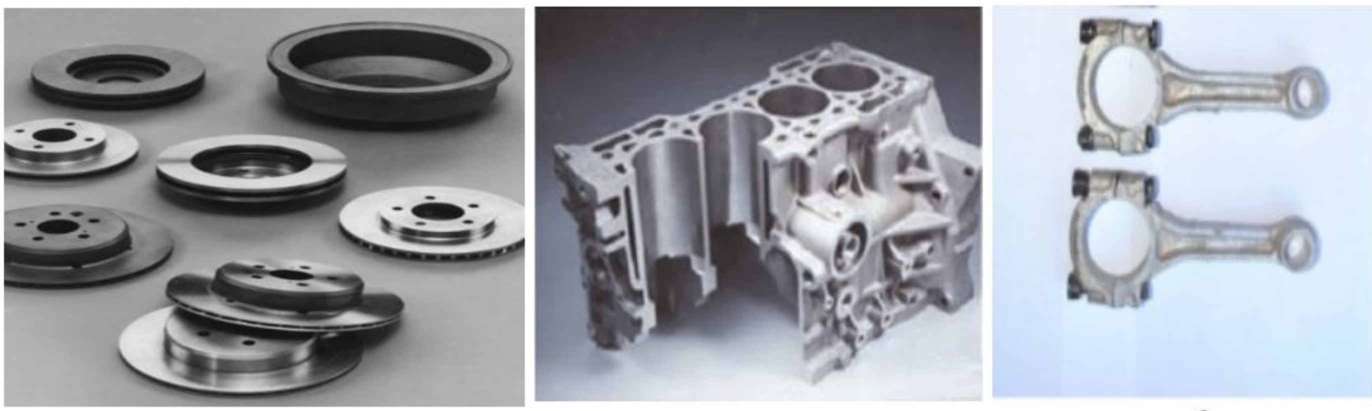

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Table 4: Common MMC applications in various automobile parts

Manufacturer	MMC system	Method of manufacture	Characteristics of applied MMC	Product
Toyota	AI203/ Al-alloy	Squeeze casting	Light weight, wear resistance at high temperature	Ring groove reinforced piston
Honda	SUS fiber/ Al-alloy	Squeeze casting	Specific strength	Connecting rod of gasoline engine
Mitubish	SiCp / Al-alloy	Compo-casting, Extrusion	Light weight, wear resistance, thermal diffusivity	Shock absorber cylinder
Niigata	SiCp Al-alloy	Compo-casting,	Light weight, wear resistance	Diesel engine piston
Audi, volkswagen	Aluminum–aluminum oxide (short fibers)	Squeeze casting, Compo-casting	Reduced weight, high strength and stiffness, Wear resistance, high running temperature	Sprockets, pulleys, and covers Piston ring Piston crown
Various Manufactures	Copper–graphite	Squeeze casting, Extrusion	Low friction and wear, low coefficient of thermal expansion	Electrical contact strips, electronics packaging, bearings
Honda	Al–Si matrix - Al2O3	Compo-casting,	Reduced weight, improved strength and wear resistance	Engine block
Audi	Aluminum–silicon carbide	Squeeze casting	Light weight, wear resistance	Brake rotor, Caliper

VI. AIRCRAFT PRODUCTION

Most of the research in aircraft manufacturing is to improve the thrust to weight ratio of their engines. This involves either increasing thrust or by reducing the weight. These will stress the materials more and also raises the working temperature which affects the whole range of engine parts, notably discs, blades and shrouds. Titanium-matrix composites with boron or silicon carbide reinforcement exhibits good properties at room and elevated temperatures, which made it a good material for fan blade applications for elevated temperatures [12]. The front running materials at present are monofilament reinforced, with matrices of titanium alloy or intermetallic (e.g. Titanium aluminide). Although titanium has substantially higher density than Al, it still shows excellent strength/weight and stiffness/weight ratios in comparison steels. Ti-MMCs reinforced by continuous SiC fiber are being developed for aerospace applications in several countries, including the USA, UK, France, and China [4].Lockheed, an American aerospace company is the one of the pioneers who started to use particle reinforced MMC in the military aircrafts. They used it for an instrument rack due to improved toughness [19] The Airbus Division of British Aerospace Commercial Aircraft has been involved in producing components of aircraft structures with aluminium 2124 matrix reinforced with 25% silicon carbide particulates by volume [9]. In the F-16 aircraft, for instance, aluminum access doors have been replaced with SiC-particle reinforced MMCs resulted in increased fatigue life. Continuous fiber-reinforced MMCs have also been used in military applications, due to high specific strength, stiffness, and fatigue resistance. SiC monofilament reinforced Ti–matrix composites have been used as nozzle actuator controls for the F119 engine in F-16 [11]. The MMC replaced a heavier Inconel 718 in the actuator links and stainless steel in the piston rods [5]. Boeing 787 makes greater use of composite materials in its airframe and primary structure than any previous Boeing commercial airplane. The figure 4 shows the percentages of materials used in Boing 787 aircraft [8] and Figure 5 represents various F-16 components made by MMCs.

The most important and recent improvement are in the precipitation hardenable aluminium alloys, however, A1-Li alloys. The particular effect of Li is that when it is alloyed to AI it simultaneously decreases the density and increases the elastic modulus of the alloy. It is, therefore, not surprising that the industry is interested in the possibilities of AI-Li matrix composites [20]. Oxide-fiber/nickel-based matrix composites are proven to be used as heat resistant materials up to 1200ºC. Large choice of entropy alloys (HEA) with a variety of the properties as a matrix and the availability of large number of oxide fibers produced by internal crystallization method make oxide-fibre/HEA-matrix composites highly prospective heat resistant materials [15].

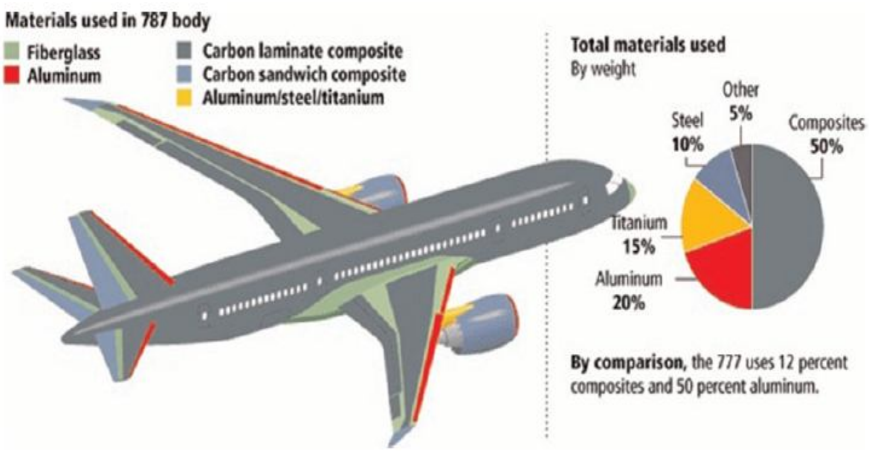
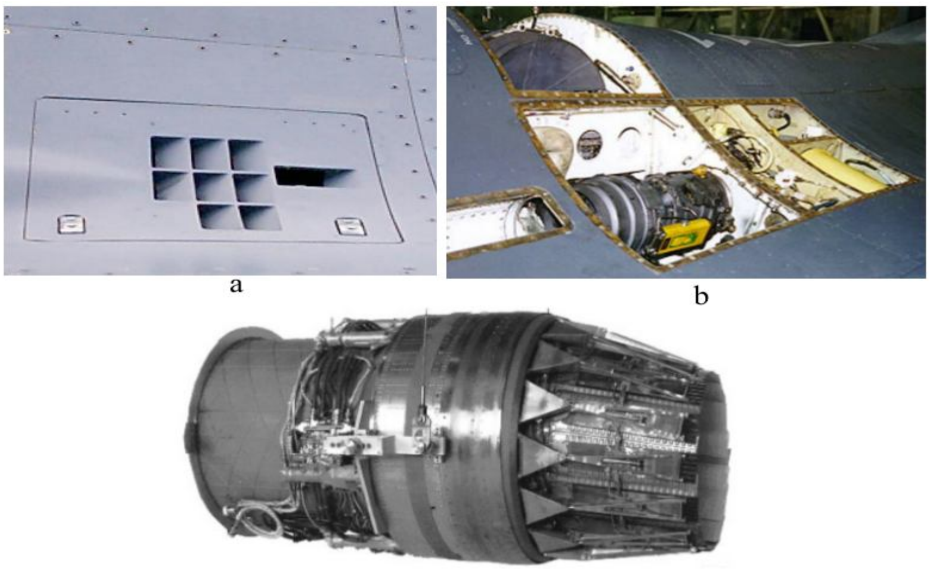


Figure 4: Percentages of materials used in Boing 787 aircraft.



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c

Figure 5: F-16 access doors (a) closed condition (b) Open condition (c) Nozzle of F119 engine

VII. DEFENSE APPLICATIONS

MMC's are started using in stiffness critical parts of missiles, which was earlier manufactured by using beryllium. The MMC used is a high volume fraction (40%) particle reinforced aluminium [17]. The MMC is both cheaper and avoids the toxicity problems associated with beryllium. Fins of a guided weapon are the other important parts which made by MMC's because of its high stiffness. This helps in reducing the flexing of fins thereby increases the accuracy of the weapon. A tank is an armored fighting vehicle designed for front-line combat, with heavy firepower, strong armor, tracks and a powerful engine. To increase the battlefield maneuverability, MMC's are started using for components such as track, engine parts, etc. Due to the reduction in overall weight the battlefield maneuverability and survival rates are drastically increased. Scram jet engines are widely used for the development of hypersonic missiles and aircrafts. A scramjet relies on high vehicle speed to compress the incoming air forcefully before combustion High temperature limits along with increased toughness and strength against ductility is the key features of choosing MMC's for the outside skin of a hypersonic aircraft. Normally Titanium-based materials are the prime candidates for large-scale structural use within the framework and engines. Magnesium alloys are being fortified with graphite strands to create composites, essentially for space applications such as scramjet where light weight, high particular stiffness, and near zero coefficient of thermal expansion are needed [19]. Figure 6 shows Fins, Figure 6 shows composite made Missile fins, armors, and tank track.

a b c

Figure 6: (a) Fin of Guided missile (b) Vehicle Armor (c) Tank Track

VIII. ELECTRONICS APPLICATIONS

New generation advanced integrated circuits are generating more heat than previous types. Therefore, the dissipation of heat becomes a major concern in electrical applications. There are potential applications in the electronics area where MMCs could find use as matched expansion substrates. A small mismatch of the coefficient of thermal expansion between the silicon substrate and the heat sink (molybdenum) will lead to thermal fatigue [5]. It is current practice to bond the ceramic to a low expansion metal such as Kovar. High volume fraction particle reinforced aluminium or chopped carbon fiber reinforced aluminium can adequately match expansion coefficients with the substrates and give better thermal conductivity at much lower weight.

Hermetic package materials are developed to protect electronic circuits from moisture and other environmental hazards. Due to the glass-to-metal seals these require materials with an 'adjustable' CTE. Al-based MMCs are fulfilling this condition, as the CTE is depending upon the volume fraction of the fibers or particles [5]. Copper-silver alloy matrix containing 55% by volume diamond particles, known as Dymalloy, is used as a substrate for high-power, high-density multi-chip modules in electronics for its very high thermal conductivity

IX. SPORTING GOODS

To meet the requirements of sports equipment, the materials of choice often consist of a mixture of material types—metals, ceramics, polymers, and composite concepts, which are fabricated into the desired equipment by making use of creative design concepts. The use of MMCs has been studied in many different kinds of sport equipment, for example, golf clubs, horseshoes, tennis racquets, bicycle parts (frames, wheel rims, etc). Aluminum, magnesium, titanium and carbon fiber based composites are widely used for the frame of sports bicycles. Carbon-fiber-reinforced composites are the prime considerations for most of the sports equipments because of its high strength to weight ratio and toughness. However, due to low cost aluminium and magnesium based MMC's are also using for the equipments like tennis rackets, Vaulting Pole, prosthetic limbs etc. [14].

Figure 7: (a) Prosthetic limbs (b) Bicycle frame (c) Golf club

X. SPACE APPLICATIONS

The extreme environment in space requires development of new materials with high specific stiffness and low coefficient of thermal expansion (CTE), lightweight and dimensionally stable structures. In the near earth orbit, typical spacecraft encounter naturally occurring phenomena such as vacuum, thermal radiation, atomic oxygen, ionizing radiation, and plasma, along with factors such as micrometeoroids and human-made debris [23]. Simultaneous reduction of weight and band averaged vibration transmission in a satellite boom structure is the major task of the present study [22]. Continuous-fiber reinforced B/Al MMC has been used as the frame and rib truss members in the mid-fuselage section, and as the landing gear drag link of the Space Shuttle Orbiter. High electrical conductive Gr/Al composite is used for the high-gain antenna boom (Figures 2a and 2b) for the Hubble Space Telescope. It was made with diffusion-bonded sheet of P100 graphite fibers in 6061 Al matrix. It also serves as structural radiators to perform structural, thermal, and EMI-shielding functions [26]. By replacing Kovar (used for microwave packaging) in the DSCS-III, a military communication satellite with Al/SiC$_p$ saves 13 kg of weight and cost of production. Functional properties including high structural efficiency and isotropic properties, offer the greatest potential for a wide range of space-system applications.

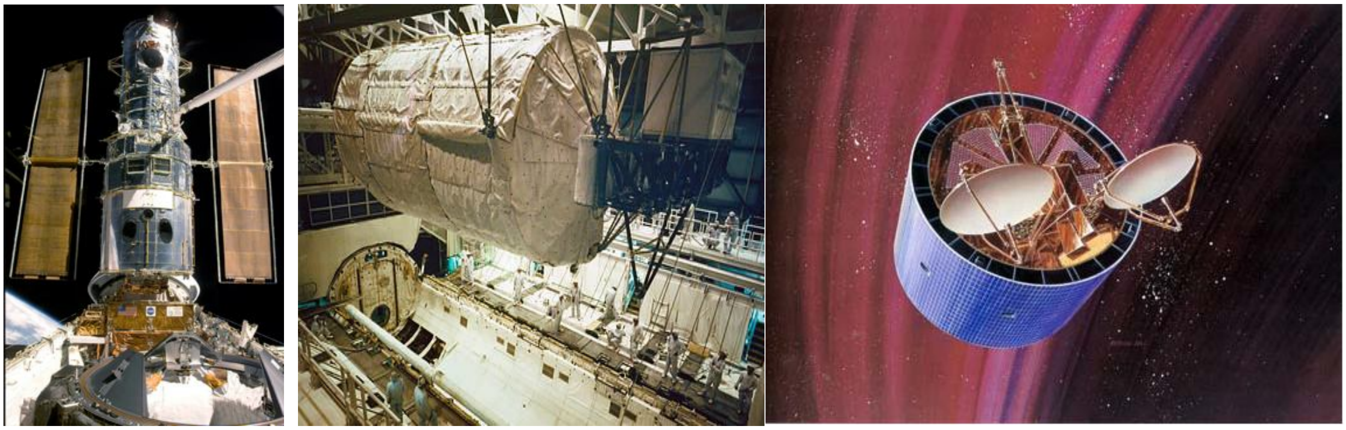

Figure 8: (a), (b) Space Shuttle Orbiter (c) Hubble Space Telescope [33}

XI. CONCLUSION

Materials research has been very active in the field of light metal matrix composites during the past two decades. This study revealed that currently, the major market for the MMC is the automobile field followed by the Electronics and thermal management systems. Gradual development of material and processing techniques have led to the creation of lighter weight, lower cost and higher performance Metal Matrix composites for various applications. For example, continuous fiber reinforced aluminium matrix composites are presently utilizing in some special applications requiring high strength/weight and stiffness/weight ratios in the aerospace industry and particle-reinforced metals provides very good specific strength and stiffness, isotropic properties, ease of manufacturing to near net shape, excellent thermal and electrical properties, and affordability. These make discontinuous MMCs suitable for a wide range of applications. During the development of MMCs, significant advancements were made on the fundamental science and technology front, including a basic understanding of composite behavior, fiber-matrix interfaces, surface coatings, manufacturing processes, and thermal-mechanical processing of MMCs. Subsequently, the technology experience benefited the latter development of high-temperature intermetallic- matrix composites. According to the global MMC market survey, more than 20% increase in the usage of MMC is predicted for next two years.

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