Lightweight Composite Materials for Automotive - A Review

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Abstract - *The weight saving requirement for automobiles has become more important, since the increase in the environmental issues. For boosting the fuel economy, maintaining safety and performance of modern automobiles; lightweight composite materials are essential. For acceleration of a lighter object, less energy is required as compare to acceleration of heavier one; so the lightweight composite materials offer the great potential for increasing vehicles efficiency. Decrease in fuel consumption gain by reduction in vehicle weight. By replacing steel & cast iron conventional components with lightweight composite materials such as Mg & Al metal matrix composite, carbon & glass fiber reinforced polymer composites can directly reduce the weight of the parts of an automotive i.e. engine block and chassis and results in reduction of fuel consumption by the vehicle. By the use of light composites in automotive can also carry additional advanced emission control system, safety devices, and integrated electronic system without increase in the overall weight of vehicles. It can reduce the exhaust emission and enhanced the fuel economy.*

Key Words: Composite, Fiber, Matrix, Automotive, Metal, Polymer etc.

1. INTRODUCTION

1.1 Composite

The word composite in the term composite material signifies that two or more materials are combined on a macroscopic scale to form a useful third material [1]. It consists of two or more constituents and that are not soluble in each other. One constituent is called the reinforcing phase and another one in which it is embedded is called the matrix phase. The reinforcing phase available in the form of particles, fibers or flakes and it is harder than matrix phase. The matrix phase materials are generally ductile and continuous [2].

1.2 Classification of Composites

On the basis of the matrix phase, composites can be classified into-
Metal matrix composites (MMCs), Ceramic matrix composites (CMCs), and Polymer matrix composites (PMCs).
Classifications according to types of reinforcement-
Particulate Composites (composed of particles), Fibrous Composites (composed of fibers), and Laminate Composites (composed of laminates) [3].

1.3 Composites in Structural Applications Having Following Characteristics

- Composite generally consist of two or more physically distinct and mechanically separable materials.
- MMCs are developed by mixing the separate materials in such a way that to achieve controlled and uniform dispersion of the constituents.
- Composite has superior mechanical properties and sometimes their properties are uniquely different from the properties of their constituents [3].

Table-1: Comparison of mechanical properties between conventional & composite materials [4].

Material	Density (g/cm^3)	Tensile strength σ (Mpa)	Tensile Modulus E (GPa)	Specific strength (σ/ρ)	Specific Modulus (E/ρ)
Steel	7.8	1300	200	167	26
Al	2.81	350	73	124	26
Titanium	4	900	108	204	25
Mg	1.8	270	45	150	25
E glass	2.10	1100	75	524	21.5
Aramid	1.32	1400	45	1060	57
IM Carbon	1.51	2500	151	1656	100
HM Carbon	1.54	1550	212	1006	138

1.4 Why We Use Composite Materials in Place of Conventional Metals?

The composites materials have some advantages over conventional materials are as follows:
- Lightweight,
- High specific stiffness and strength,
- Easy mouldable to complex forms,
- Easy bondable,
- Good dumping,
- Low electrical conductivity and thermal expansion,
- Good fatigue resistance,
- Part consolidation due to lower overall system costs,
- Low radar visibility,

- Internal energy storage and release [5].

2. COMPOSITES FOR AUTOMOTIVE

In Automotive, composites are being considered to make safer with low weight and more fuel-efficient vehicles. The fiber-reinforced composite is composed of a high strength fiber (i.e. carbon or glass) in a matrix material (polymer and metals i.e. Al, Mg etc.) and it can provide magnify properties compared with the individual materials by themselves. Many components like seat, roof, steering wheel, hatch, dashboard, mats, energy absorber, interior and exterior panel, wheels, leaf spring, engine cover etc. are fabricated by composite materials [6]. For example, reducing a car mass by 100kg saves about 0.7litre fuel each 100km (directly and indirectly). For the lightweight composite structures manufacturing process, the technologies which are based on fiber-reinforced thermoplastic materials can be integrated. The main motivators for the lightweight materials applications are weight savings and possible cost savings. Significant weight reductions with improved performance will mean less fuel consumption and CO_2 emissions. The transport industries are customer sensitive and currently, the customers are pushing for the cost-effectiveness and the more environmentally friendly transport system. By using low cost, eco-friendly, and reliable materials the economic burden would be reduced for both the customer and the automotive industry [3]. The demand for better fuel efficiency and reduced emissions developed the demand for weight reduction in order to comply with EU legislation (from <130g CO_2/km in 2015 down to <95g CO_2/km by 2021). Composites can offer lightweight benefits from 15-25% for glass-fiber reinforced composites (GFRP) to 25-40% for carbon-fiber reinforced composites (CFRP) in comparison to other structural metallic materials that are presently dominant, such as steel, iron, and aluminum [7].

2.1 Obstacles to Use Composites in Automotive

Industry inexperience with polymer and Al-based composites materials, low production rate due to undeveloped processes, the new techniques need for joining, lack of knowledge about material responses to automotive environments, immature recycling technologies, a small supplier base and lack of crash models; these are the main obstacles for an automotive industry implementation of composites. Due to the high current cost of carbon fiber as compared to other structural materials for a vehicle is the additional factor for the carbon fiber based composites are restricted in industry use. By weight, about 8% of today's automobile parts are made of composites including bumpers, body panels, and doors. Several research and development efforts are needed for increasing the application of lightweight composites in the automotive sector [8]. The relation between the cost reduction and weight reduction in automotive is shown in Figure 1.

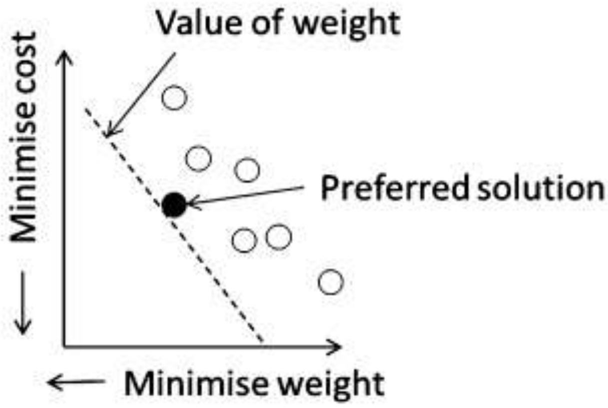

Fig-1: Weight reduction is inversely proportional to cost reduction [9].

2.2 Polymer Matrix Composites for Automotive

Polymer matrix reinforced with fiber or whiskers is the most common form of composite that has been used in the automotive industry. The first application of such materials was the fiber-glass body of the Chevrolet Corvette in 1953 [8]. The key advantages of polymer materials over the conventional metallic materials are their specific strength properties with weight saving of 20-40%, lower thermal expansion properties, potential for rapid process cycles, ability to meet stringent dimensional stability and excellent fatigue and fracture resistance. Automobile's segment of composites accounts for about 50% of the thermoplastic and 24% of the thermoset composite market in the world. For weight reduction, the glass fiber reinforced thermoplastic polymer is a promising material due to its relatively low cost, fast cycle time and ability to facilitate parts integration. Carbon fiber reinforced polymer is another composite but will require breakthroughs in the cost and manufacturing techniques to be cost-effective for high volume production. For the automotive sector, it is a favorable option for reductions in energy uses and lower emissions levels by making advanced composites. In automotive sector future business opportunities are as follows.

- RTM panel,
- Glass fiber/epoxy springs for heavy trucks or trailers,
- Valve guides,
- Rocker arm covers, wheels, and engine shrouds, suspension arms,
- Filament-wound fuel tanks,
- Electrical vehicle body components and assembly units,
- Automotive racing brakes and train brakes,
- Clutch plates [3].

A polymer composite body has significant implications for vehicle light-weighting and improved fuel efficiency; these results come at a time when they are particularly pertinent [10]. Potential benefits of the PMCs structure for the automotive industries are as follows:

- Weight reduction, which may be translated into improved fuel economy and performance,
- Improved overall vehicle quality and consistency in manufacturing,
- Corrosion resistance,
- Part consolidation resulting in lower vehicle and manufacturing costs,
- Improved ride performance (reduced noise, vibration, and harshness),
- Vehicle style differentiation with acceptable cost,
- Lower cost of vehicle ownership,
- Lower investment costs for plants, facilities, and tooling-depends on cost/volume relationships.

However, there are areas where major uncertainties exist that will require extensive research and development prior to resolution. For example:

- High-speed, high-quality manufacturing processes with acceptable economics,
- Repairability,
- Satisfaction of all functional requirements,
- Particularly crash integrity and long-term durability,
- Recyclability and customer acceptance [11].

2.2.1 Fibers Used for Reinforcement of Polymer Matrix for Automotive

a) Carbon Fibers (CF) -

Carbon fibers, also known as graphite fibers, can be based on three chemical sources: poly acrylo nitrile (PAN method is led by Japanese manufacturers), rayon (from the Indian manufacturer Grasim) and petroleum pitch. About 90% of the carbon fibers are produced or made from PAN. The exact composition of each precursor varies according to the recipe of manufacturers. The PAN based fibers give excellent mechanical properties for structural applications and the pitch fibers present higher modulus values and favorable coefficients of thermal expansion. The main benefits of carbon fibers are their low density and its high strength-to-weight ratio and stiffness. Its cost and brittleness is the main downsides as compared to the other fibers. At 46,500 tonnes of global annual demand for CF in 2013 has seen a growth of 15.1% CAGR since 2009 (26,500t). Global demand of CF is estimated to continue to grow to reach 89,000t by 2020. Regarding production capacities, the most important regions are North America (30%), Europe (24%) and Japan (20%). The top five CF manufacturers according to production volumes in 2013 were Toray, Toho, MRC, and SGL in that order [7]. The composites design, analysis, and manufacturing tools will help for a reduction in the engineering cycle time and costs. Also, improve the quality while maintaining repeatability of parts being manufactured [12].

The decrease in the projected cost of the carbon fibers will be mainly driven by-

- The development of a less expensive precursor material to produce the CF (textile PAN precursors or even lignin-based precursors instead of oil/gas based precursors to decouple the material price from oil price developments), results in 30% to 50% cost decrease for the raw material,
- A reduction in the processing cost for pre and part forming of 60% to 80% due to radical reductions in cycle times, for example; the development of fast curing resins and the resulting reduction of investment and labor costs per part.

Carbon fiber is the highest weight reduction potential (50% lighter than steel) but also has the highest cost (570% the cost of steel today). The effect of carbon fibers percentage on the weight of medium size car is shown below in Figure 2 [13]. The major techniques for cost reduction and their areas are shown in Figure 3.

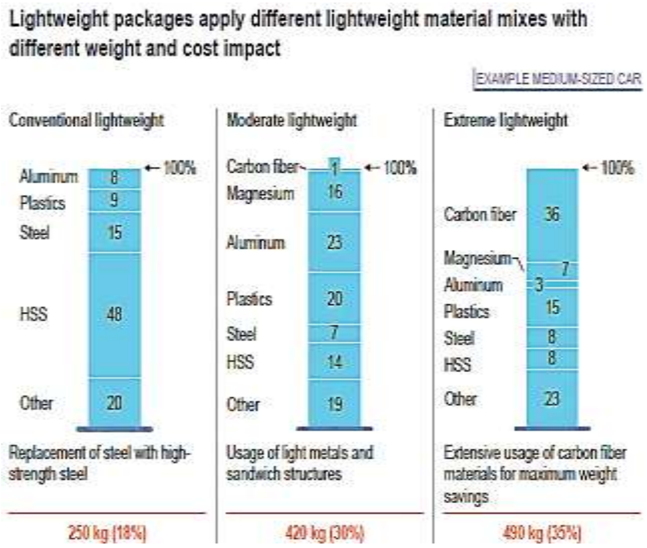

Fig-2: Weight saving in percentage by using lighter materials [13].

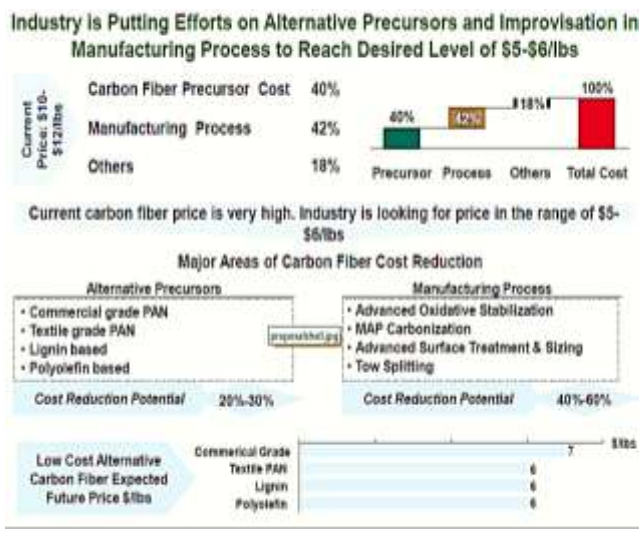

Fig-3: Reduction of cost of carbon fiber [14].

b) Glass Fibers (GF) –

Glass fiber is based on an alumina-lime-borosilicate composition. The recipe can be varied resulting in different commercial compositions: E-glass (electrical), C-glass (chemical), R-glass, S-glass, and T-glass. In GF market, **E-glass** accounts for 90% and it is used in a polyester matrix and providing high electrical insulation properties, low susceptibility to moisture and high mechanical properties. **C-glass** fibers have the best resistance to chemical attack and **S-glass** has higher strength, heat resistance, and modulus. Overall, the Glass Fiber Reinforced Polymer (GFRP) exhibit very good thermal insulation and electrical properties and are also transparent; however, they are heavier than CF and due to the lower modulus, they require special design treatment in applications where stiffness is critical [7].

	Design 1: carbon fiber	Design 2: glass fiber	Design 3: steel
Design parameters			
Wheelbase (cm)	274.3	274.3	261.6
Length x Width (cm)	472.4 x 180.3	472.4 x 180.3	469.9 x 170.2
Height (cm)	137.2	137.2	144.8
Components	25	25	120
Inserts	37	37	130
Material composition			
Primary material	Two-component polyurethane	Two-component polyurethane	Mild-grade steel
Brand	Bayer AG's Baydur 420	Bayer AG's Baydur 420	Varies
Price ($/kg)	$2.65	$2.65	$0.77
Reinforcement	Carbon fiber	Glass fiber	NA
Spray price ($/kg)	$20	$2.53	
Lay-up brand	Hexcel Fabric (Woven 24 K)	Owens Corning F2 Matt	
Lay-up price ($/kg)	$13.20	$3.08	
Resin: Reinforcement	65:35 vol%, 50:50 wt%	65:35 vol%, 41:59 wt%	NA
Inserts	Mild-grade steel	Mild-grade steel	Mild-grade steel
Assembly joining	Two-component adhesive	Two-component adhesive	Spot welding
Brand	SIA's Plastilock 731SI	SIA's Plastilock 731SI	NA
Price	$17.50/kg	$17.50/kg	NA

Fig-4: Comparison between carbon fiber, glass fiber and steel [10].

Because glass fiber is less stiff, less strong and denser than carbon fiber, glass fiber reinforced parts are typically thicker and heavier than the carbon fiber reinforced parts. The price of glass fiber is 5-10 times less than that of the carbon fiber [10]. The most suitable natural fiber to be hybridized with glass fiber reinforced polymer composites used for the design of a passenger vehicle center lever parking brake components [15]. The comparison between carbon fiber, glass fiber and steel are shown in Figure 4.

2.3 Metal Matrix Composites for Automotive

The materials can be tailored to be lightweight and with various other properties including are as follows:

- High specific strength and specific stiffness,
- High hardness and high wear resistance,
- Low coefficient of thermal expansion and High thermal conductivity,
- Low coefficients of friction,
- High energy absorption and a damping capacity.

In addition to these above-mentioned properties, new MMCs are being developed which have self-healing, self-cleaning and self-lubricating properties, which can be used to enhance energy efficiency and reliability of automotive systems and their components [16]. The MMC system is generally designated simply by the metal alloy designation of the matrix then the material type followed by weight or volume fraction and form of the ceramic reinforcement. For example, 6061Al/30 vol. % SiC-p designates a discontinuously reinforced 6061 aluminum alloy with 30 volume % fraction of silicon carbide particulate. MMCs differ from the polymer or ceramic matrix composites in several ways. Some of these general distinctions are as follows:

- The matrix phase of an MMC is either a pure metal or alloy as compared to a polymer or ceramic.
- MMCs have higher ductility and toughness than the ceramics or ceramic matrix composites (CMCs) and also their respective unreinforced matrix.
- The reinforcement in the MMCs is increased the strength and modulus as is the case with PMCs. Reinforcement in CMCs generally provides improved damage tolerance.
- The MMCs have a temperature capability generally higher than the polymers and PMCs but less than the ceramics and CMCs [3].

a) Al or Al alloy metal matrix composite –

Aluminium based metal matrix composites (MMCs) are "engineered materials" for automotive. This composite is composed by the addition of non-metallic (generally ceramic) particles and/or fibers in 5-50% by weight fraction to the metal. The additions non-metallic material can produce a considerable alteration in the mechanical and tribological properties of the base alloy. Tensile strength, yield strength and in some case fatigue strength can be significantly improved over the entire range of temperature. The Al MMCs also have enhanced physical property characteristics i.e. higher modulus, lower coefficient of thermal expansion, improved tribological characteristics and higher hardness versus unreinforced aluminum. Over the past 10 years, low-cost particulate reinforcements i.e. SiC, $A1_2O_3$, fly ash and graphite have been developed to reduce the cost of MMC materials. Also, there has been significant progress in the development of low-cost processing technique [17].

b) Magnesium Alloy Metal Matrix Composite –

Magnesium is one of the lightest structural metals. The major advantage of Mg is its ability to reduce vehicle weight and enhance the performance of the vehicle. Magnesium parts can be tuned to those critical frequencies where noise, vibration, and harshness are reduced [8]. At room temperature, Mg alloys have very low formability [18], but today's interest in Mg alloys for automotive applications is based on the combination of high strength and low-density property and for this reason, Mg alloys are very attractive as a structural material in all applications where weight savings are the main requirement. In automotive applications, the reduction in weight will improve the performance of a vehicle by reducing the rolling resistance and energy of acceleration, thus reducing the fuel consumption and moreover a reduction of the greenhouse gas CO_2 can also be achieved [19].

3. PARTS OF AUTOMOTIVE FABRICATED BY COMPOSITE MATERIALS

3.1 Engine Block Cylinder Liners –

In modern aluminium engine blocks, grey cast iron cylinder liners are used to protect the block. These weight about 9kg per block but MMC liners weight 3.5kg less. Al MMC liners can improve engine operating efficiency by reducing knock (heat transfer from the cylinder to water jacket is improved due to increased thermal conductivity). Blocks with MMC liners have increased rigidity as compared to the blocks with coated bores, which may be translated into increased cylinder roundness and reduced engine friction. Honda has successfully used in situ formation of an MMC cylinder via die-casting non-metallic cylinder preforms [17]. In a new approach to achieve a further weight reduction, researchers will developed a new aluminium engine block which has the cylinder bore surface reinforced with short hybrid fibers of alumina and carbon [20].

3.2 Main Bearings –

Copper-lead bearings are used in crankshaft main bearing caps can be replaced with lead free aluminium or copper matrix composites containing graphite particulates. Gr is nontoxic and the use of Gr reinforced Al or Cu composite bearings as a replacement for leaded copper reduces weight. The Gr reinforced MMC bearings also improve the wear characteristics because deformation of the Gr particulates results in the formation of a continuous graphite film, which provides self-lubrication of the component, allowing for improved component longevity [16].

3.3 Connecting Rods –

With the advent of nanostructured materials, new materials have been developed with exceptional properties exceeding those expected for monolithic alloys or composites containing micron-scale reinforcements. For example, carbon nanotubes reinforced composites have ultrahigh strength and modulus. In another example reinforcements of only 10 vol. % of 50nm alumina (Al_2O_3) particulates to an Al alloy matrix using the powder metallurgy process increased yield strength to 515MPa. This is 15 times stronger than the base alloy, 6 times stronger than the base alloy containing 46 vol. % of 29μm Al_2O_3 and over 1.5 times stronger than AISI 304 stainless steel [16].

3.4 Accessories –

For components not exposed to extreme loading, further cost and weight reductions can be realized by reinforcing of fly ash (a waste by-product of coal power plants) in metal (e.g., aluminum, magnesium, lead, and zinc) matrix. Replacing components such as A/C pump brackets, alternator housings, timing belt/chain covers, valve covers, transmission housing and intake manifolds with Al reinforced with fly ash composites can reduce the vehicle cost and weight. Fly ash reinforced Al MMCs used for accessories can reduce emissions and save energy. It also reduces its coefficient of thermal expansion and increases its wear resistance along with making lighter and less expensive material [16].

3.5 Chassis –

The performance of vehicle can affect by the strength and toughness of the chassis. Hollow ceramic micro-spheres reinforced metal matrix results in a syntactic foam product. Its density is about one half as compared to the matrix and it can able to absorb large amounts of energy per unit weight upon impact as compared to the monolithic alloys and open cell foams. Al-fly ash chemosphere syntactic foams being developed at UWM can be used in crumple zones to both increase torsional rigidity and increased energy absorption upon vehicle impact. In advanced automotive vehicles, syntactic foam also serves as a core material to increase the rigidity of thin gage sheet metal sandwich structure. High-performance material like Kevlar honeycomb core material is cost prohibitive [16].

3.6 Bumper –

Bumper is the one of the main part of an automotive vehicle having slightly more weight. We can employ composite materials in the bumper without sacrificing the safety. Polymers composite have been a major part of the automotive industries for several decades but the technical barriers and economic have constraint their use. At present, carbon fiber reinforced and glass fiber reinforced polymer composite are commonly used for automotive bumpers [21].

3.7 Leaf Spring –

The Corvette was fitted with glass fiber reinforced epoxy polymer composite leaf springs, whose fatigue life is more than five times that of steel. Leaf springs developed by composite, give a smoother ride than steel leaf springs and also give more rapid response to stresses caused by road shock. Moreover, composite leaf springs have less chance of catastrophic failure and excellent corrosion resistance property [8].

Another component i.e. brake drum, disc brake, bearing etc. can also be developed by the metal matrix composite which has good mechanical and tribological properties with lower weight.

4. MANUFACTURING AND ASSEMBLY COST ESTIMATION

The cost estimation models must consider both the part manufacturing and assembly line. The total part cost (C_{tot}), including both manufacturing and assembly lines, is described as follows

$$C_{tot} = C_{invest} + C_{tot-material} + C_{tool} + C_{running}$$

ϵ Assembly, manufacturing
Where:
C_{invest} = f (machines, presses, robots)
$C_{tot-material}$ = f (material utilisation and scrap)
C_{tool} = f (tool cost)
$C_{running}$ = f (electricity, service, facilities, labor, etc.)

The initial material and process selection phase aims to estimate the cost of part manufacturing for a structure with low complexity and a set weight (normally comparison is done comparing the cost of a 1 kg structure). For the analysis of integral and differential design solutions, more detailed cost estimation is required by taking into account geometry, size, complexity etc. A manufacturing line is designed for each process considered in the above equation. Based on the operational time ($t_{operation}$) for each station, the annual work time (t_{annual}) and the annual planned volume (V), the specific number of annual operations available can be assessed for each station (n_{annual}) by

$$n_{annual} = \frac{t_{annual}}{t_{operation} \times V}$$

The annual volume planned (V) for the production governs the number of robots and machines required in the process and for each station. In the cost models, a parallel line design must be considered due to the slow cycle times for composites and the often high annual volumes demanded by the automotive industry [9].

5. CONCLUSION

The objective of this review paper is to find out the materials for automotive which are commonly used and to give an overview on the optimized composite materials. The cost of lightweight composite materials in which carbon fiber, Al and Mg are used is much higher than the conventional materials. So it is essential for research and development in the field of lowering their cost, increasing their recyclability, enabling their integration and maximizing fuel economy benefits of automotive vehicles. By the use of composite materials instead of traditional heavy cast iron & steel we can reduce the weight by 10-60%. Researchers already work on the composites to find out the properties of these composite materials and the associated manufacturing processes. They also work on the natural composites to find out cost-effective composites. Advanced material such as magnesium matrix composite and carbon fiber reinforced composites can gives optimum level of weight reduction at same strength level. Lightweight automotive gives better fuel efficiency and low emission which is the main required issue of present era, these issues can be fulfil by the use of light composites.

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