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Advanced Materials for Light Weight Body Design

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ABSTRACT: With the emergent industrial development and dependence on fossil fuels, Green House Gas (GHG) emission has become most important problem. However, car manufacturers have to remain in competition with peers and design their products innovatively that fulfil the new regulations too. Nevertheless of various different approaches to improve fuel economy such as enhancing fuel quality, development of high performance engines and fuel injection system, weight reduction is one of the encouraging approaches. With 10% weight reduction in passenger cars, the fuel economy improves by as much as 6–8%.

KEYWORDS: Carbon Fibre, Magnesium, Aluminium, Titanium, light-weight body materials, poly-acrylonitrile

I. INTRODUCTION

Car body design in view of structural performance and weight reduction is a challenging task due to the various performance objectives that must be satisfied such as vehicle safety, fuel efficiency, endurance and ride quality. Applications of lightweight materials not only allow the potential for car manufacturers to reduce the car weight but also concurrently satisfy the new regulations. In this paper, material replacement as design optimization strategy is proposed to develop a lightweight car body structure that enhances performance. Even though in this paper, the focus is on automotive industry, the applications of light weight advanced materials expand to other industries too.

Advanced materials are essential for enhancing the fuel efficiency of modern automobiles while maintaining safety and performance. Lightweight materials offer great potential for increasing vehicle efficiency as it takes less energy to accelerate a lighter object than a heavier one. Substituting cast iron and traditional steel components with lightweight materials such as carbon fiber, magnesium alloys, aluminum alloys, and polymer composites can reduce the vehicle's body weight by up to 50 percent and consequently reduce its fuel consumption.

Utilizing lightweight structural materials, cars can carry additional integrated electronic systems, advanced emission control systems, and safety devices without adding to the overall weight of the vehicle. This makes lightweight materials particularly important for hybrid electric and electric vehicles. Using lightweight materials in these vehicles can counterweight the weight of power systems such as electric motors and batteries, improving the efficiency and increasing their travel range. On the other hand, the use of lightweight materials could enable the utilization of smaller and lower cost battery.

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II. RELATED WORK

A few lightweight materials have been introduced in automotive industry such as carbon fibre composites, aluminium and its alloys, magnesium, titanium, glass fibre composites, advanced high strength steels, polypropylene, polyamides (PA 6 and PA 66), polyurethanes, Acryl-Nitrile Butadiene Styrene (ABS), thermosetting composites and other composite materials.

LIGHTWEIGHT MATERIAL	MASS REDUCTION
Magnesium	30-70%
Carbon fiber composites	50-70%
Aluminum and Al matrix composites	30-60%
Titanium	40-55%
Glass fiber composites	25-35%
Advanced high strength steel	15-25%

Table 1. *Lightweight Materials with % Mass Reduction (Source : www.energy.gov)*

Table 1 represents a few lightweight materials with their contributions in mass reduction. The carbon fibre composites are the major impacting materials.

There are various factors that affect the selection of materials. Some of the prominent factors are:

- Properties of materials (Physical, Chemical, Structural and Thermal): It involves material's strength, plasticity, elasticity, thermal behaviour, chemical stability, manufacturability, endurance, and others. These are the deciding properties that determines the suitability of a material for application)
- Availability: It decides the quantity that can be produced, scrap affordability and thus cost.
- Cost: This decides the target market segment. Advanced materials are costly and so unaffordable to use for economic scale applications.

Materials	GFRP	CFRP	Steel	Aluminum	Magnesium	Titanium
Specific Strength (kNm/kg)	150	400	38	130	158	120
Density (kg/m ³)	1800	1590	7870	2700	1800	4500
Domestic Production Cost (\$/kg)	2.5	27	0.47	2	3.31	9

Table 2: *Material comparison (G=Glass; C=Carbon; FRP=Fibre Reinforced Plastic)*

Table 2 provides the comparison of three impacting factors- specific strength, density and cost for six advanced materials. CFRP has the highest specific strength followed by magnesium.

Amongst the various advanced materials, the three most promising materials are described in this paper in subsequent sections:

1. Carbon Fibre
2. Magnesium and its alloys
3. Aluminium and its alloy

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III. CARBON FIBRE

Carbon Fiber is a polymer, also known as graphite fiber. It is a strong lightweight material that is five-times stronger than steel and twice as stiff, thus making it ideal manufacturing material for many parts. These are few reasons why carbon fiber is preferred by engineers and designers. Carbon fiber is very popular in many industries such as aerospace, automotive, military, and recreational applications.

Carbon fiber is made of thin, strong crystalline filaments of carbon that is used to strengthen material. It can be thinner than a strand of human hair and gets its strength when twisted together like yarn. Then it can be woven together to form cloth & if needed to take permanent shape & can be laid over a mold & coated in resin or plastic.

Brief History:

In 1879, Thomas Edison baked cotton threads / bamboo silvers at high temperatures that carbonized them into an all-carbon fiber filament. By 1958, high-performance carbon fibers were invented just outside of Cleveland, OH. Although inefficient, these fibers contained around 20% carbon and had low strength and stiffness properties. In 1963, carbon fiber's strength potential was realized in manufacturing process developed at a British research center.

Carbon Fiber Manufacturing Process:

Carbon fiber is made from partly chemical and partly mechanical process. It starts by drawing long strands of fibers and then heating them to a very high temperature without allowing contact to oxygen to prevent the fibers from burning. Now, the carbonization takes place, when the atoms inside of the fibers vibrate violently, expelling most of the non-carbon atoms. This leaves a fiber composed of long, tightly inter-locked chains of carbon atoms with only a few non-carbon atoms remaining. A typical sequences used to form carbon fibers from polyacrylonitrile (PAN) involves spinning, stabilizing, carbonizing, treating the surface and sizing.

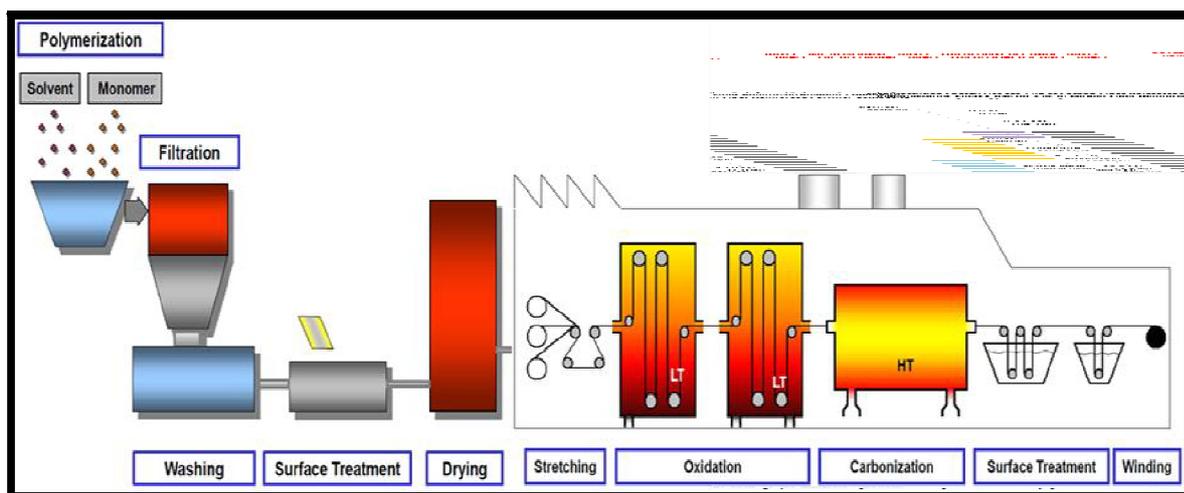


Figure 1. Current Basic Manufacturing process of Carbon Fibre

Figure 1 above shows the basic manufacturing processes to create carbon fibre. It is as follows:

1. The precursor is produced through the polymerization process, where the monomers of the selected materials combine chemically forming stable covalent chemical bonds between the monomer sets.
2. After polymerization, filtration process is performed followed by washing to remove any excess solvents and impurities.

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3. The transformation of the precursor (PAN) into high performance carbon fibres involves consecutive stages of oxidative stabilization: where the (PAN) precursor is initially stretched and simultaneously oxidized in a temperature range of 200-300°C. This treatment transforms thermoplastic PAN to a non-plastic cyclic or ladder compound.
4. Fibres are then carbonized at about 1000°C without tension in an inert atmosphere (generally nitrogen) for a few hours. During this process the non-carbon elements are removed as volatiles to give carbon fibres with a yield of about 50% of the mass of the original PAN precursor material.
5. Depending on the final fibre property requirements, the fibres are treated at temperatures between 1500-3000°C at the next graphitization step, which improves the ordering, and orientation of the crystallites in direction of fibre axis.
6. The fibres are then wound into appropriate size and packed for further processing⁶

Manufacturing Technologies for Carbon Fiber Reinforced Polymer		
<i>Technology</i>	<i>Polymer type</i>	<i>Forming type</i>
<i>Widely used Technologies</i>		
Thermoset Pre-preg	Thermoset and Thermoplastic	Semi-Finished Fabrication
Thermoset Sheet Molding Compound (SMC) / Bulk Molding Compound (BMC)		
Hand Lay Up	Thermoset and Thermoplastic	Open Stage
Spray Up		
Robotic Lay Up		
Filament Winding		
Pultrusion		
Honeycomb Core		
Injection Molding	Thermoset and Thermoplastic	Closed Forming
Resin Transfer Molding		
Vacuum Assisted Resin Infusion		
Compression Molding		
Autoclave Forming		
Cold Press		
<i>R & D purpose and Developing technologies</i>		
Fused Deposition Modeling (Additive Manufacturing)	Thermoplastic	Open Stage
Balanced Pressure Fluid Molding (“Quickstep”)	Thermoset and Thermoplastic	Closed Forming
Thermal Press Curing	Thermoset	

Table 3: Different Manufacturing Technologies for Carbon Fibre reinforced polymers

The table 3 above gives a petite idea about the different manufacturing technologies available for manufacturing carbon fibre reinforced polymer with reference to specific Forming and Polymer types as per applications.

Applications: Bike frames; Aircraft Wings; Automotive components; Tubing; Containers; Propeller blades;

Advantages: High Stiffness & Tensile Strength; Low weight to strength ratio; High chemical stability; Low thermal expansion

Disadvantages: Excessive cost; Low and costly reparability

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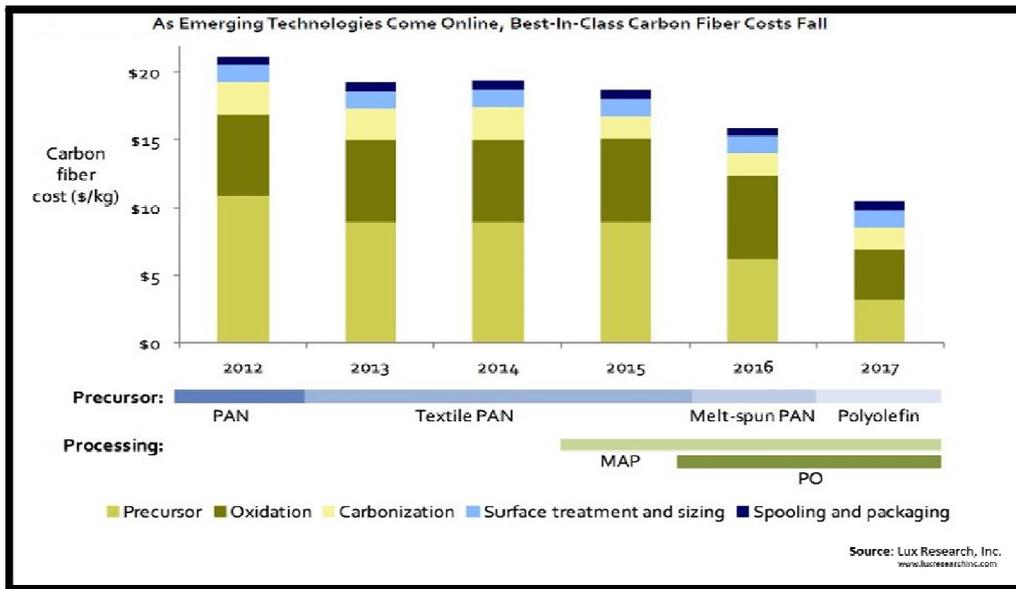


Figure 2. Carbon fibre cost variation

Figure 2 shows the trend of cost of carbon fibre from 2012-2017. The cost is constantly falling with maximum drop in 2016-2017. The costs of all individual process have been reduced significantly over the period of 5 years.

IV. MAGNESIUM AND MG-ALLOYS

According to Dieringa and Kainer et al., magnesium is considered to be a forefront material among other lightweight materials. A magnesium car body structure with equal stiffness can be 60% or 20% lighter than steel or aluminum design, respectively^[1]. The performance of the optimum design with magnesium parts demonstrates significant weight reduction and better performance. The future vision for magnesium estimates use of magnesium in cars will increase by 15% (about 227 kg) by 2020^[2]. The disparity between rigidity for vibration and softening for crash responses addresses important considerations for magnesium application in car body structure.

Previous works:

Prior works on the application of magnesium alloys in car body structure include Parrish et al.^[3] where 22 steel parts were replaced with magnesium (AZ31) counterparts. This replacement combined with structural optimization saved 54.5 kg in weight while most of the crashworthiness characteristics of the new design remained similar to the baseline design. Logan et al.^[4] show that magnesium body structure not only offers more than 40% weight reduction as compared to a conventional steel structure but it also significantly improves the structural performance.

Magnesium (Mg) Properties:

• Atomic number : 12	• Atomic mass : 24.305	• Elastic modulus E = 45GPa
• Melting point : 650°C	• Boiling point : 1090 °C	• Density (r) : 1.736 g/cm ³
• Specific modulus = 26	• Crystal structure hcp: a = 0.32094 nm, c = 0.52107 nm	
• 1m ³ of sea water contains 1.3 kg magnesium		

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Magnesium alloys:

Magnesium alloys are mixtures of Mg with other metals often aluminium, zinc, manganese, silicon, copper, rare earths and zirconium. Magnesium is the lightest structural metal. Mg alloys have a hexagonal lattice structure. Major types of Mg alloys are: Mg-Al-base alloys; Zr-containing alloys; Cast Mg alloys.

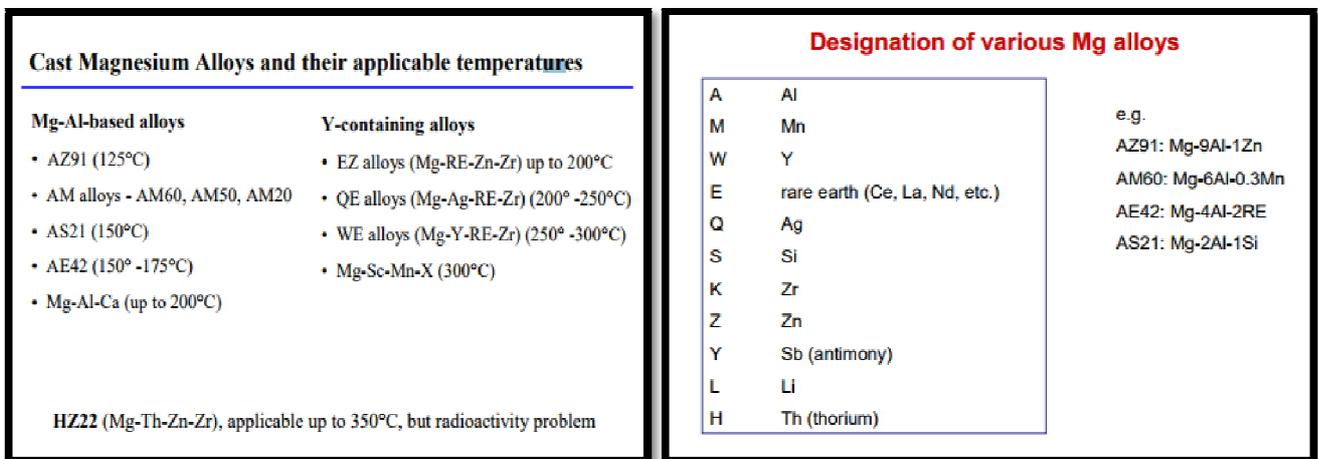


Figure 3 & 4: Magnesium alloys

The figures 3 and 4 above provides a basic understanding of the magnesium alloys mainly with their designation. Also, it provides the suitable temperature applications range.

Fabrication Techniques:

Hot & cold working; casting; welding, soldering, and riveting; machining; hot extrusion

Advantages:

Lowest density (~1.8 g/cm³) of all metallic constructional materials • High specific strength • Good cast ability & machinability • High thermal conductivity • High dimensional stability • Good electromagnetic shielding property • High damping characteristics • 100 % recyclability

Disadvantage:

Low elastic modulus • Limited cold workability and toughness (hcp structure) • Limited creep resistance at elevated temperatures (T_m = 650°C) • High thermal expansion • High chemical reactivity

Applications:

- Automotive components like intake manifolds, door panels, radiator parts instrument panel, support & seat frame, steering wheel core parts, cylinder block heads, transmission cases, clutch housings, lower crank cases, brake and gas pedal-stand other structural components. Mostly used in electric and advanced cars.
- Electronic equipment parts and telecommunication industries.

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Magnesium Price Trend:



Figure 5: Magnesium Price Trend

The figure 5 represents the variation of Magnesium prices over a span of 5 years. The price for Mg showed drop until 2016, but for recent year there has been a significant price rise.

V. ALUMINIUM AND AL-ALLOYS

Aluminium is an abundantly available and well-established material in the automotive industry for many years. Its low density and high specific energy absorption performance and good specific strength make it most important. Al is also resistant to corrosion and can be easily recycled in its pure form. Thus, it is foremost demanded material in advanced cars and light weight application machineries.

Aluminium has lower Modulus of elasticity and therefore, parts need to be engineered to achieve the mechanical strength equivalent to steel or replaced material. It is alloyed to achieve those properties making it suitable for most applications. Thus, Al will play an increasingly significant role for the automotive industry in the future

Aluminium (Al) Properties:

• Atomic number : 13	• Atomic mass : 26.982	• Elastic modulus E = 70 GPa
• Melting point : 660°C	• Boiling point : 2520 °C	• Density (r) : 2.7 g/cm ³
• Specific modulus = 26	• Crystal structure fcc: a = 0.4041 nm	

Aluminium Alloys:

The typical alloying elements are copper, magnesium, manganese, silicon, tin and zinc. There are two major classifications, viz. *casting* alloys and *I* alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of aluminium is used for wrought products.

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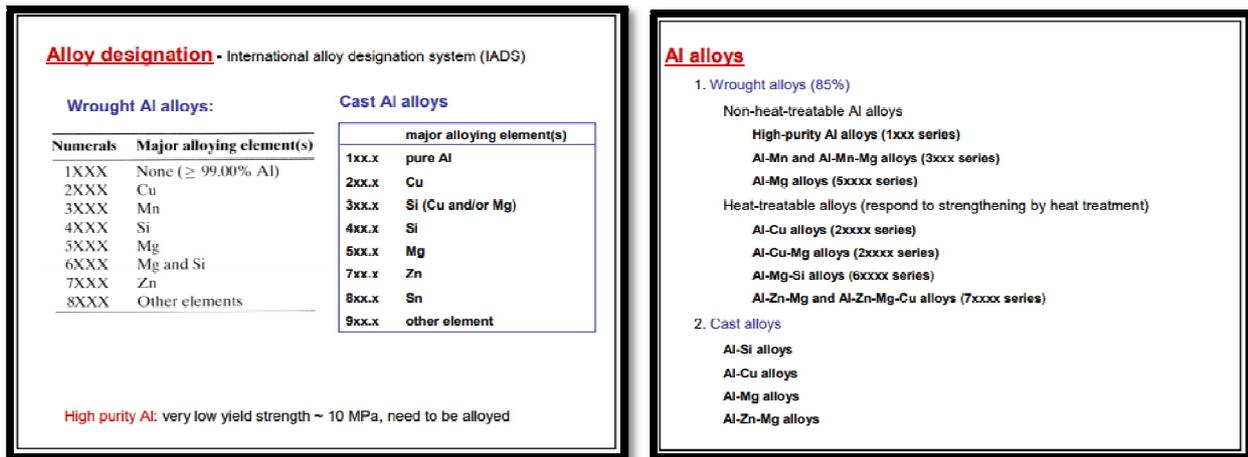


Figure 6 & 7. Aluminium Alloys

Other Named Al alloys are: Alferium; Alclad; Birmabright; Duralumin; Hindalium; Pandalloy; Magnalium; Magnox; Silumin; Titanal; Y alloy; Hiduminium, R.R. Alloys specifically named after their manufacturers.

Casting Processes: Cast processes; Sand casting; Permanent mould casting (gravity die casting); Die casting

Advantages:

High Strength to weight ratio; excellent heat and electrical conductivity; corrosion resistance; high reflectivity; low density, 100% recyclability

Disadvantages:

Expensive than steel; difficult to weld; low strength in pure form, needs alloying.

Applications:

- Non-Automotive Applications: Building & construction; Containers & packaging; Transportations; Electrical conductors;
- Automotive applications:
 - Body structures, closures and exterior attachments such as crossbeams, doors or bonnets. They are used for luxury cars, such as the Audi A8, & niche vehicles, such as BMW Z8.
 - 6111 aluminium & 2008 aluminium alloy are extensively used for external automotive body panels, with 5083 and 5754 used for inner body panels. Bonnets have been manufactured from 2036, 6016, and 6111 alloys. Truck & trailer body panels have used 5456 aluminium.
 - Automobile frames often use 5182 aluminium or 5754 aluminium formed sheets, 6061 or 6063 extrusions.
 - Wheels have been cast from A356.0 aluminium or formed 5xxx sheet.
 - Cylinder blocks & crankcases are often cast made of aluminium alloys. The most popular aluminium alloys used for cylinder blocks are A356, 319 & to a bit 242.
 - 6061 aluminium and 6351 aluminium are widely used in breathing gas cylinders for scuba diving & SCBA.

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Aluminium Price Trend:



Figure 8: Aluminium Price Trend

The figure above represents the statistics for aluminium prices for the previous 5 years. There has been an oscillating curve similar to sine curve. For last 2 years the price has been increasing.

VI. CONCLUSION

Given the advantages and applications, carbon fibre, magnesium alloys and aluminium alloys are the most promising advanced materials dominantly in automotive industry

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