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Materials in Automotive Application, State of the Art and Prospects

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1. Introduction

This chapter gives a comprehensive account of the materials used in manufacturing vehicles. In the first section it explains the properties and characteristics that a suitable material should have to be accepted in automotive production. In later sections it reviews the history of development of the materials in automotive from the most traditional to the most recent ones. In the class of the metallic materials, steel, aluminium and magnesium and the most recent alloys of these used in the automotive are explained. Some of the properties, manufacturing and joining processes for these metals are described. The advantages and problems of using each of these materials are also reported. The potential application of these materials in different parts of a vehicle is identified. The other class of materials considered is composites and plastics with synthetic or natural fibre as reinforcement. Whilst the synthetic fibres are more traditional type of composites used, the natural fibre composites hold a relatively new place with substantial potential for growth due to the growing environmental concerns. With regard to the composite the cost is one of the most important barriers in use of these materials. Therefore a cost analysis is presented. Also the second barrier is a suitable manufacturing process for producing complex automotive parts. A review of the manufacturing process therefore is also offered for the composites with both synthetic and natural fibres. s

2. Requirements of the materials in automotive

The materials used in automotive industry need to fulfil several criteria before being approved. Some of the criteria are the results of regulation and legislation with the environmental and safety concerns and some are the requirements of the customers. In many occasions different factors are conflicting and therefore a successful design would only be possible through an optimised and balanced solution.

2.1 Lightweight

As there is a high emphasis on greenhouse gas reductions and improving fuel efficiency in the transportation sector, all car manufacturers, suppliers, assemblers, and component producers are investing significantly in lightweight materials Research and Development and commercialization. All are moving towards the objective of increasing the use of lightweight materials and to obtain more market penetration by manufacturing components and vehicle structures made from lightweight materials. Because the single main obstacle in application of lightweight materials is their high cost, priority is given to activities to reduce costs through development of new materials, forming technologies, and manufacturing processes.

Yet the weight reduction is still the most cost-effective means to reduce fuel consumption and greenhouse gases from the transportation sector. It has been estimated that for every 10% of weight eliminated from a vehicle's total weight, fuel economy improves by 7%. This also means that for every kilogram of weight reduced in a vehicle, there is about 20 kg of carbon dioxide reduction.

To achieve lightweight construction, without compensating on rigidity, automakers have been investigating the replacement of steel with aluminium, magnesium, composites, and foams. The recycling and recovery of end-of-life vehicles, which involves recovery targets of 85%, are driving the auto industry to adopt lightweight materials technology to meet these recovery targets.

Some of the facts about the lightweight materials are as follows: [McWilliams, 2007]

- The total global consumption of lightweight materials used in transportation equipment was 42.8 million tons/$80.5 billion in 2006 and will increase to 68.5 million tons/$106.4 billion by 2011, at a compound annual growth rate (CAGR) of 9.9% in tonnage terms and 5.7% in value terms between 2006 and 2011.
- High strength steel accounts for the largest percentage of total tons of lightweight materials consumed, followed by aluminium and plastics. In value terms, plastics with their relatively high unit prices are the largest market segment. Aluminium and high strength steel are the second and third largest product segments.
- Motor vehicles, particularly passenger cars and light trucks, are by far the largest end-user segment. Shipbuilding was the second largest consumer of lightweight materials, while the aircraft industry ranks second in the value of the lightweight materials consumed.

Car manufacturers are investigating the reduction of the weight in a viable economical way. For example study by Lotus Engineering concludes that a vehicle mass improvement of 38% versus a conventional mainstream vehicle can be achieved at only 3% cost. Comparison of weight reduction and associated costs for two future models are shown in Table 1. [Lotus Eng. Co., 2010]

Also a report from Corus indicates that the main structure – known as the Body In White (BIW) – is usually made of steel pressings welded together to form a strong and stiff frame.

This method of construction accounts for 99.9 per cent of all the cars produced in the world. The remaining 0.1 per cent is mostly constructed with aluminium BIW, while a very small number (less than 0.01 per cent) are constructed from carbon-fibre composite.

The material properties of steel (with its wide range of yield strength combined with high modulus) together with ease of manufacture and low cost, mean that steel intensive vehicles have by far the largest share of the market. The high cost of alternative materials such as aluminium or composites mean that steel's position as the first-choice material could be still secure. [Corus Automotive Eng., 2010] The BIW of a vehicle accounts for 20 per cent of the vehicle mass. The weight of the closures (doors, bonnet and boot/rear hatch), chassis (suspension parts) and driveline bring the total amount of steel and other ferrous metals to more than 60 per cent. In recent years, the amount of ferrous metal has declined, mostly driven by manufacturers replacing iron with aluminium for engine castings. The percentage of sheet steel per car has also dropped, mainly due to:

- Higher levels of equipment, trim and soundproofing.
- More aluminium used in wheels and suspension parts.
- More moulded plastics, especially under the bonnet.

Base Toyota Venza Excluding powertrain		Lotus Engineering Design			
System	Weight (kg)	2020 Venza		2017 Venza	
		% Mass Reduction	% Cost Factor	% Mass Reduction	% Cost Factor
Body	383	42%	135%	15%	98%
Closures/Fenders	143	41%	76%	25%	102%
Bumpers	18	11%	103%	11%	103%
Thermal	9.25	0%	100%	0%	100%
Electrical	23.6	36%	96%	29%	95%
Interior	252	39%	96%	27%	97%
Lighting	9.90	0%	100%	0%	100%
Suspension/Chassis	379	43%	95%	26%	100%
Glazing	43.7	0%	100%	0%	100%
Misc.	30.1	24%	99%	24%	99%
Totals	1290	38%	103%	21%s	98%

Table 1. An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program by Lotus, [Source: Lotus Engineering, 2010]

The weight reduction versus the price increase by replacing steel by aluminium or magnesium for some of the parts is reported in Table 2.

	steel (kg)	Aluminium (kg)	Magnesium (kg)	% weight (part)	reduction (vehicle)	% cost increase (part)
Body In white (BIW)	**285**	**218**	**N/A**	**23.5**	**3.90** Examples vehicle mass of 1700 kg	**250**
Bonnet (assembly)	**14.8**	**8.3**	**N/A**	**44**	**0.48** Examples vehicle mass of 1350 kg	**300**
Door (assembly)	**15.7**	**9.5**	**N/A**	**39**	**0.40** Examples vehicle mass of 1550kg	**275**
IP Beam (instrument panel support)	**11.4**	**N/A**	**6.3**	**45**	**0.33** Examples vehicle mass of 1550kg	**350**

Table 2. Alternative materials, potential weight savings versus cost, [Source: Corus Automotive Eng., 2010 with permission]

2.2 Cost

One of the most important consumer driven factors in automotive industry is the cost. Since the cost of a new material is always compared to that presently employed in a product, it is one of the most important variables that determines whether any new material has an opportunity to be selected for a vehicle component. Cost includes three components: actual cost of raw materials, manufacturing value added, and the cost to design and test the product. This test cost can be large since it is only through successful vehicle testing that the product and manufacturing engineers can achieve a ‘level of comfort” to choose newer materials for application in a high-volume production program.

Aluminium and magnesium alloys are certainly more costly than the currently used steel and cast irons that they might replace. The ability to approach the total cost of the competition, therefore, must be associated with lower component manufacturing costs. Compared to cast irons and steel, cast aluminium and magnesium components are potentially less costly. This is based on their reduced manufacturing cycle times, better machinability, , ability to have thinner and more variable wall dimensions, closer dimensional tolerances, reduced number of assemblies, more easily produced to near net shape(thus decreasing finishing costs, and less costly melting/metal-forming processes). However, wrought aluminium and magnesium components are almost always more costly to produce than their ferrous counterparts. Since cost may be higher, decisions to select light metals must be justified on the basis of improved functionality. Government regulations mandate reductions in exhaust emissions, improved occupant safety, enhanced fuel economy, reductions in workplace emissions, increased safety requirements, and requirements for toxic materials handling and disposal. Also the high cost is one of the major barriers in use of the composite materials.

2.3 Safety, crashworthiness

The ability to absorb impact energy and be survivable for the passengers is called the ‘‘crashworthiness’’ of the structure in vehicle. There are two important safety concepts in automotive industry to consider, crashworthiness and penetration resistance. Crashworthiness is defined as the potential of absorption of energy through controlled failure modes and mechanisms that provides a gradual decay in the load profile during absorption. However, penetration resistance is concerned with the total absorption without allowing projectile or fragment penetration. [Jacob et al, 2002]

The current legislation in design of the automobiles requires that, in the case of an impact at speeds up to 15.5 m/s (35 mph) with a solid, immovable object, the occupants of the passenger compartment should not experience a resulting force that produces a net deceleration greater than 20g.

The current trend of materials in car industry is towards replacing metal parts more and more by polymer composites in order to improve the fuel economy and reduce the weight of the vehicles. The behaviour of composite failure in compression is the opposite to metals. Most composites are generally characterized by a brittle rather than ductile response to load. While metal structures collapse under crush or impact by buckling and/or folding in accordion (concertina) type fashion involving extensive plastic deformation, composites fail through a sequence of fracture mechanisms involving fibre fracture, matrix crazing and cracking, fibre-matrix de-bonding, de-lamination and interply separation. The actual mechanisms and sequence of damage are highly dependent on the geometry of the structure, lamina orientation, and type of trigger and crush speed, all of which can be suitably designed to develop high energy absorbing mechanisms.

Several aspects are considered in design for improved crashworthiness including the geometrical and dimensional aspects which have key role in different stages of crash. However the materials deformation and progressive failure behaviour in terms of stiffness, yield, strain hardening, elongation and strain at break are also very important in the energy absorption capacity of the vehicle. [Witteman, 1999].

Thin-walled columns are basic components in the concept and design of automotive body structures. Their crashworthiness behaviour is of fundamental importance in the safety design of the whole vehicle because their plastic collapse is the mechanism that is used to dissipate the kinetic energy of the vehicle in an accident. The mechanism of plastic collapse should be reliable and its evolution during the crash regular so that the desired quantity of absorbed energy, a low load uniformity and the required level of deformation load can be achieved without increasing danger for the vehicle passengers. [Wallentowitz & Adam, 1996] To predict the characteristic values of automotive front structures energy absorption, e.g. weight specific energy absorption, load uniformity and structural effectiveness, the buckling of thin-walled columns, representing body front side members, normally are investigated. Geometries used for front side members like closed-hat, double-U and octagonal columns made by conventional steel, high-strength steel and light alloys could be joined with different joining methods e.g. spot-welding, press-joining and structural adhesive. The design parameters of the specimen (t/a-ratio, flange width, joining width, material thickness, etc.) are varied in a wide range. Axial and non-axial quasi-static tests and even dynamic tests with different collision speeds are normally carried out to evaluate the crash behaviour.

2.3.1 Crashworthiness tests

Apart from the test at the design stage explained above, there are more tests to be performed at the later stage of product evaluation. To determine crashworthiness — how well a vehicle protects its occupants in a crash — the Institute of highway safety rates vehicles good, acceptable, marginal, or poor based on performance in high-speed front and side crash tests, a rollover test, plus evaluations of seat/head restraints for protection against neck injuries in rear impacts. To earn Top Safety Pick for 2010 a vehicle must have good ratings in all four Institute tests. In addition, the winning vehicles must offer electronic stability control. [Insurance institute of highway safety, 2010]

Frontal offset crash test details

Today's passenger vehicles are designed to be more crashworthy than they used to be. Still, about 30,000 passenger vehicle occupants die in crashes on US roads each year. About half of the deaths occur in frontal crashes.

Since the late 1970s, the federal New Car Assessment Program has compared frontal crashworthiness among new passenger vehicles. This program, which involves 35 mph crash tests into a full-width rigid barrier, has been highly successful in providing consumers with comparative crashworthiness information. It also has been a major contributor to the crashworthiness improvements that characterize recent passenger vehicle models.

The very success of the New Car Assessment Program means remaining differences in performance among most new vehicles in full-width tests are small. This doesn't mean important crashworthiness differences no longer exist. They do exist, and additional crash test configurations can highlight these differences. One such test is the frontal offset crash.

Side impact crash testing/ratings criteria

Today's passenger vehicles are more crashworthy than they used to be, especially in frontal crashes. As occupant protection in frontal crashes improves, the relative importance of protection in side impacts increases. From the early 1980s until 2000, driver death rates per million cars registered decreased 47 percent. Most of this improvement was in frontal crashes, in which driver death rates decreased 52 percent. In contrast, the decrease in side impacts was only 24 percent.

These changes are attributable to two effects. There have been significant improvements in frontal crash protection — standard airbags, improved structural designs, and higher belt use rates, for example.
Since 1997 the federal New Car Assessment Program, which compares crashworthiness among new passenger vehicles, has included side impacts. In these tests, an impactor with a deformable front end representing the front of a car is used to strike the sides of the vehicles being assessed.
The Institute's side impact test is severe. Given the designs of today's vehicles, it's unlikely that people in real-world crashes as severe as this test would emerge uninjured. But with good side impact protection, people should be able to survive crashes of this severity without serious injuries.
Side impact crash test ratings can be compared across vehicle type and weight categories, while frontal crash test ratings will be compared only within weight categories.

Rollover evaluations

Rollover ratings assess vehicle roof strength for protection in rollover crashes. Roof strength is a new component of the *TOP SAFETY PICK* criteria for 2010 models.
To measure roof strength, a metal plate is pushed against one corner of a vehicle's roof at a constant speed. The maximum force sustained by the roof before 5 inches of crush is compared to the vehicle's weight to find the strength-to-weight ratio. This is a good assessment of vehicle structural protection in rollover crashes.
Other tests on the safety of the vehicle include the Rear crash protection/head restraint ratings which focus on how well seat/head restraint combinations protect against whiplash injury. The necessary first attribute of an effective head restraint is good geometry. If a head restraint isn't behind and close to the back of an occupant's head, it can't prevent a "whiplash" injury in a rear-end collision.
Also Electronic stability control (ESC) significantly reduces crash risk, especially the risk of fatal single-vehicle crashes, by helping drivers maintain control of their vehicles during emergency manoeuvres.

2.4 Recycling and life cycle considerations

One of the major growing concerns in all the industries including automotive, is an increased awareness for environment. Issues such as ‘protection of resources’, ‘reduction of CO2 emissions’, and ‘recycling’ are increasing the topics of consideration.
While the United States has not issued regulations concerning automotive end-of-life requirements, European Union (E.U.) and Asian countries have released stringent guidelines. European Union legislation implemented in 2006 dictates that a significant percentage of the vehicle should be re-used or recycled.
The End of Life Vehicles (ELV) Directive from environment agency aims to reduce the amount of waste produced from vehicles when they are scrapped. Around **two million vehicles** reach the end of their life in the UK each year. These vehicles are classed as hazardous waste until they have been fully treated. The directive requires ELV treatment sites to meet stricter environmental standards. This would mean that the last owner of a vehicle must be issued with a **Certificate of Destruction** for their vehicle and they must be able to dispose of their vehicle free of charge. Vehicle manufacturers and importers must cover all or most of the cost of the **free take-back system**. It also sets higher reuse, recycling and recovery targets and limits the use of hazardous substances in both new vehicles and replacement vehicle parts. [Environment agency, 2010]

As the results of the new legislations, no discussion of new materials in the automotive industry should conclude without a consideration of recycling. Considerable R&D efforts are now focused on developing materials with greater potential of recycling and re-use or developing ways of recycling and re-use of the current materials. This includes both metal and composite materials. The composition and forming processes of the metal materials are changing to accommodate this recycle and re-use demand. This also justifies the great attention towards natural fibre based composites and new high temperature resistant thermoplastic resins.
Figure 1 shows a simplified diagram of the vehicle life cycle. [Kumar & Sutherland, 2008] After the raw material is extracted, it is processed, manufactured into parts and products, and then sold to the consumer. It should be noted that there is a chain of part and component suppliers that contribute to the final manufacturing/assembly stage performed by the original equipment manufacturers (OEM). Traditionally the design of the part/components has mainly been the responsibility of the OEMs. Recently, however, manufacturers have begun to shift design responsibility to part/component suppliers. After the manufacturing stage, the vehicle spends a long period of time in the use phase of the life cycle. In the past, the median life of a vehicle has been reported to be 12–13 years [Libertiny, 1982, 1993]. Lately, the median life has increased to around 16 years with as many as 5% of the vehicles still remaining on the road after 30 years of operation [Davis, 2004].

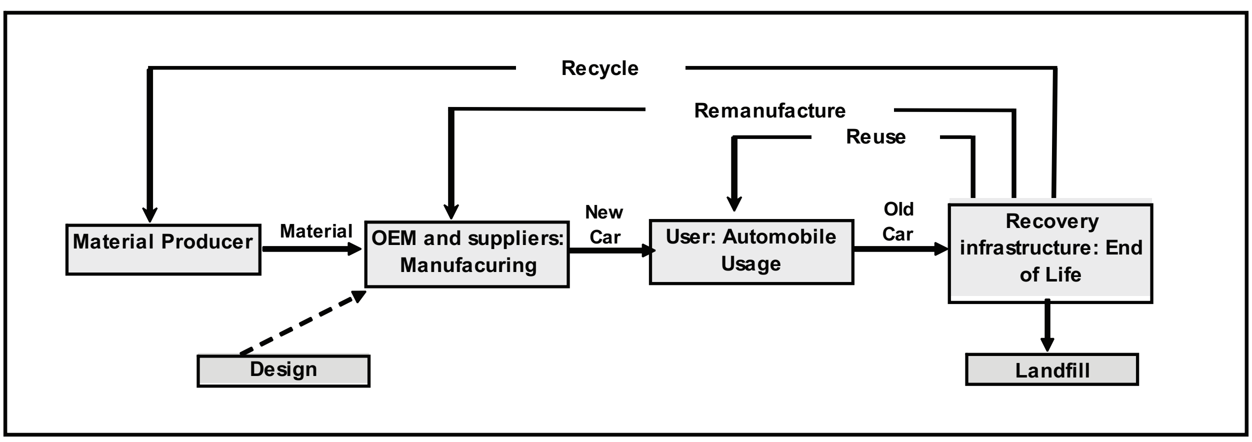

Fig. 1. Life cycle of automobile [Source: Kumar & Sutherland, 2008]

When a consumer decides that they no longer wish to use a given vehicle, there are a number of options available to them:
1. sell the whole vehicle to another user
2. disassemble the vehicle with some components/modules reused
3. remanufacture the vehicle
4. recycle the vehicle for material content, and/or
5. dispose the vehicle to a landfill (Zussmann et al., 1994; Kumar et al., 2005).

The option selected depends on the economic benefit to the parties/entities associated with each option. It should be noted that often times a vehicle undergoes multiple use cycles (i.e., the first option is selected repeatedly) before the user considers the other options. After multiple use cycles, the value of the vehicle to the user (and other potential users) approaches zero. This is because the vehicle no longer functions as desired – the vehicle is said to have reached the end of its life. However, from the perspective of a dismantler or shredder, the value of the vehicle is not zero because they are not directly interested in the vehicle function; rather, they are interested in the value of the vehicle subassemblies, parts, and materials (Kumar et al., 2007). It should be noted that the expression end of use product 'EOUP' is preferred over the commonly used end of life vehicle 'ELV' phrase, because as a whole the vehicle may no longer be functional, but certain subassemblies or parts may be functional and of course the material can always be recycled for the secondary materials market. Each life cycle stage shown in Figure 1 consumes certain amount of energy, and produces air/water emissions and municipal solid waste.

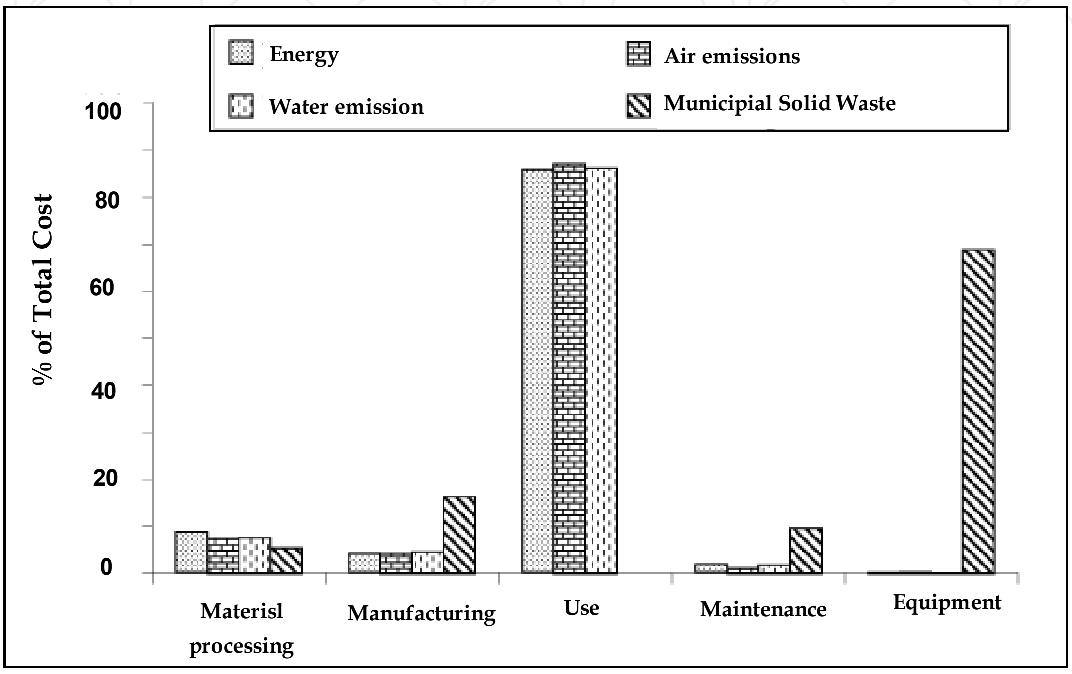

Fig. 2. Comparison of energy, air emission, water emission and municipal solid waste across the life cycle of 1995 generic vehicle [Source: Sullivan et al, 1998]

Figure 2 shows the contribution of each stage in terms of energy consumption, air and water emissions, and municipal solid waste. As can be seen from the figure 2, use stage is the most significant contributor in terms of energy consumption, and air and water emissions. This justifies the effort of the automotive manufacturers to use lighter-weight material and new powertrain technologies in its vehicles. However, while analysing the impact of use stage on the environmental performance of a vehicle, it is important to note that the associated energy consumption and emissions are distributed over a larger period of time as opposed to a shorter time periods during the other stages (Field et al., 2001). Thus, any conclusion with respect to the environmental performance should carefully include the temporally distributed nature of emissions. It can also be seen from the figure 2 that in terms of municipal solid waste, the EOUP stage was found to be the significant contributor.

It should be noted that the choice of material plays an important role on the fuel economy of the vehicle. For example, use of lighter-weight material such as aluminium as opposed to steel is usually considered a positive choice in terms of fuel economy (Ungureanu, 2007a). As an approximation, a 10% reduction in mass produces a 5% improvement in fuel economy. However, it should also be noted that lighter-weight materials might not always be the most sustainable choice from a total life cycle perspective. For example, in a study to determine the potential benefits of lighter materials such as aluminium, it was found that substantial change in the existing manufacturing and assembly technologies would be needed. It was found that the current equipment and processes are well suited for steel-based components and a complete redesign of this equipment and processes would be needed to manufacture aluminium components (Ungureanu, 2007b). Selection of material and manufacturing technology also impacts the automotive recovery infrastructure. It is suggested that replacing steel with aluminium or a composite material not only increases the fuel economy but also reduces the overall life cycle emissions and energy consumption. However, it is also likely that the total solid waste, which is usually landfilled will increase with such material substitutions. It is largely unknown what effect such substitutions will have on the generation of solid waste and thus, the environmental sustainability of the recovery infrastructure. Further detail analysis with consideration of interactions regionally is needed for better understanding of the life cycle issues.

3. Current materials in use and their future

The current materials used in automotive industry both categories of metals and composites are reviewed. The advantages and disadvantages of each material are discussed. Also the most recent topics of research on development of new compositions, manufacturing and characterisations of these materials for the specific purpose of use in automotive is presented.

3.1 Metals

3.1.1 Steel

Advanced iron and steel technologies have seen considerable development over the past decade and are frequently included into new designs and redesigns by all automakers. The steel industry and component suppliers are investing heavily in innovation. The result of the investment is numerous examples of successful, cost-effective use of stainless steel, new formulations of iron, high-strength steels, and an associated variety of new design, fabrication, and assembly techniques. Applications include not only vehicle bodies, but also engine, chassis, wheels and many other parts. The usages commonly demonstrate weight reduction plus simultaneous improvements in strength, stiffness, and other structural performance characteristics. Thus, a clear potential exists to affordably make vehicles lighter and safer at the same time. [DeCicco, 2005]

While body, chassis, engine and other powertrain components made of ferrous materials comprise the largest part of a vehicle by mass, lightweight steel and iron technologies compete with potential substitutes in all of these applications.

Mass reduction through advances in the use of iron and steel is significant (ferrous materials), because they are the dominant material (64% of a typical family vehicle).

Iron and steel form the critical elements of structure for the vast majority of vehicles, and are low-cost

materials with an extensive experience base and familiarity to the industry.

The past several years have seen steady increases in the use of high-strength steels (HSS), many versions of which are referred to as high-strength, low-alloy (HSLA) steels. These materials plus their associated advanced design and fabrication techniques (as well as improved design and fabrication using traditional steels) formed the basis of the American Iron and Steel Institute (AISI) Ultralight Steel Auto Body (ULSAB) series of studies and demonstration projects. The ULSAB car body demonstrated a 19% mass reduction in a body structure that had superior strength and structural performance (including crashworthiness) along with a reduced parts count and net manufacturing cost savings compared to a conventional steel body. [USAB, 1998] Comparable mass reductions and other benefits were achieved for doors, hoods, decklids, and hatchbacks. [Opbroek & Weissert, 1998] Improved steel materials and forming processes allow a significant optimization of vehicle body structures and components. [DeCicco, 2005]

The prime reason for using steel in the body structure of an automotive is its inherent capability to absorb impact energy in a crash situation [Marsh, 2000]. This, in combination with the good formability and joining capability, makes these materials often a first choice for the designer of the body-in-white (BIW) structure. [Magnusson et al, 2001]

New grades of steel and alloys

Materials are often described by properties such as yield- and tensile strength, elongation to fracture, anisotropy and Young's modulus but shape is not a material property. A sheet metal component is a material made into a certain shape through a forming process. Depending on loading condition, a material-and-shape combination resists the applied load best. Components in a BIW structure should also be able to absorb or transmit impact energy in a crash situation. Certain tests should be performed to decide about the suitability of the materials for automotive application.

In axial tensile loading of components, the shape is not as important as the cross-sectional area since all sections with the same area will carry the same stress. The strength of a component that should be under axial loading is related to the mechanical properties of the material [Meyers & Chawla, 1999].

In bending and torsion, both material and shape are important parameters for the efficiency of the component to carry the applied load [Ashby, 2000]. For bending, the elastic-plastic transition is a combination of shape and material properties. The strength of a beam under bending is related to the materials yield stress and Young's modulus. The stiffness is correlated to the materials Young's modulus and the shape of the component.

High-strength steel (HSS) is based on alloys that are categorized on the basis of yield strength. Standard HSS has a yield strength between 210 MPa and 550 MPa; ultra-high-strength steel (UHSS) has a yield strength higher than 550 MPa. High-strength steels can cost as much as 50% more than traditional mild steels, but they allow use of lower thicknesses than milder steels for achieving needed part performance specifications. Also, different grades of steel can be combined in tailored blanks (see below), so that the more costly or thicker materials can be placed only where needed. With HSS, there can be a trade-off between strength and formability; in other words, the stronger a steel is, e.g., in resisting stretching (tension), the more difficult it can be to forge into shapes, particularly the stylistically and aerodynamically optimized shapes needed for new vehicles. Steel suppliers are therefore developing steels with a range of properties that give engineers more flexibility in selecting an ideal grade of steel for any given application.[Heckelmann et al, 1999]

Stainless steel is a material of choice due to passivity and resistance to corrosion. Some of the stainless steel grades suggested for automotive are as follows: [Cunat, 2000]

a. Duplex austenitic-ferritic stainless steel

The most commonly used duplex grade is 0.02% C – 22% Cr – 5.5% Ni – 3% Mo – 0.15% N alloy, whose standard European designation is X2CrNiMoN22-5–3 / 1.4462.

b. Austenitic stainless steel

These steels have chromium (18 to 30 per cent) and nickel (6 to 20 per cent) as the major alloying elements. The austenitic phase is stabilised by the presence of a sufficient amount of

nickel. The principal characteristics are the ductile austenitic condition, rapid hardenability by cold working and excellent corrosion resistance.
One of the most commonly used grade for structural applications is the 0.02% C – 17.5% Cr – 7% Ni – 0.15% N alloy, whose standard European designation is X2CrNiN 18-7/1.4318.

Property	Duplex Stainless Steel (1)	Austenitic Stainless steel			6061 Aluminium Alloy		High Strength Steel HSLA
		Annealed	C850(2)	C1000(3)	T4(4)	T6(5)	
Density: $\rho(g/cm^3)$	7.8	7.9	7.9	7.9	2.7	2.7	7.83
Yield Stress: σ (N/mm^2)	640	370	600	880	130	275	410
Specific Strength $(N/mm^2/g/cm^3)$	82	46.8	76	111.4	48.1	100	52.4

(1) In the solution annealed condition, (2) In the cold worked condition C 850 ($850<UTS\ (N/mm^2)<1000$) (3) In the cold worked condition: C 1000 ($1000<UTS\ (N/mm^2)<1150$), (4) In the solution heat treated condition, (5) In the precipitation heat treated condition

Table 3: Specific Strength of Stainless Steels, 6061 Aluminium and High Strength Steel [Source: Cunat, 2000]

The specific stiffness of Stainless Steel is very similar to that of aluminium alloy and the HSLA steel, which means that the three materials can all be considered as "light materials".
The specific strength of the austenitic Stainless Steel in the cold worked condition, is much higher than the one for the other materials. The specific strength of different steel and aluminium are compared in the Table 3.
Crashworthiness energy absorption is a key property of the material used for structural components or complete structures so-called "space frames". Austenitic Stainless Steels i.e. Fe – Cr – Ni containing alloys have the advantage over aluminium alloys and carbon steels of being highly strain rate sensitive. This means that the faster the loading is applied the more the material will resist deformation. In addition to that, Stainless Steel has the capability to collapse progressively in a controlled and predetermined manner which is desirable in automotive application.

Advances in manufacturing and joining technique

Advances in fabrication and assembly technique are just as important as advances in materials. For lightweight steel technology, key process advances include *laser welding, hydroforming,* and *tailored blanks.* Both tailored blanks and hydroforming allow parts counts to be reduced, providing significant savings on tools and dies, simplifying later stages of assembly, and improving the integrity of components, subassemblies, and body structures. These processes can be combined in the production of any one component or subassembly. Compared to conventional welding processes, ***laser welding*** creates a very clean and strong weld seam with minimum excess material. It is an important enabling technology used for multiple stages of steel materials fabrication and assembly. Laser welding permits production of new process input materials, such as tailored blanks, with smooth, high-integrity seams and minimal distortion or change in material properties surrounding the weld zone. It also improves strength, aesthetics, and overall quality of final assembled structures. As automakers gain experience with laser welding and the structural design improvements it permits, they are reaping significant productivity savings as well A recently reported example is VW's use of the technology on the 2004 redesign of the Golf. [Kochan, 2003] Compared to the previous model, they reduced production time per car body by 25% while reducing weight.

A related innovation is greater use of steel tubes in place of shapes based on stampings of sheet steel. High-quality tubes are formed by bending sheets into a tubular shape with a laser welded seam. In addition to direct uses (e.g., in cross members and door beams), steel tubes also find broader use when further manipulated by hydroforming.

Hydroforming involves shaping a part in a die through the use of fluid pressure as opposed to stamping. Tube hydroforming permits the construction of relatively complex shapes with a single part that is stronger and lighter than the same part made as an assemblage of stampings. Although a number of challenges were identified, methods for overcoming them were found, with optimizations achieved using advanced CAD tools. Eight bodies were built for validation and testing purposes; the results demonstrated a small mass reduction with a 25% increase in torsional stiffness. Such results suggest that a lighter structure could have been built without as great an increase in stiffness. An economic analysis showed that the demonstrated hydroformed design could be implemented within pre-defined financial targets, in other words, would be cost-effective for the given application. Hydroforming is now coming into widespread use and is particularly valuable for optimizing the frames of light trucks. GM and Ford have both used hydroforming for frame components in their full-size pickups and vehicles sharing those platforms; again, however, the potential mass savings were sacrificed to provide further increases in stiffness and other structural performance attributes.

Tailored blanks combine different grades and thicknesses of steel into a single blank, referring to a piece of material that is inserted into a stamping press or other piece of forming equipment. They allow optimizations of strength, crash performance, and dent resistance with minimal material use and therefore lower weight than attempting to make a similarly performing part from a blank of uniform grade and thickness.[Kuroda, 2033] Tailored blanks also permit reduced major parts counts and simplified assembly. Instead of two or more different gauges being welded together to achieve the desired component, an integral component can be stamped or hydroformed from a tailored blank. This technique pushes some of the complexity upstream in the assembly process, but can do so with net cost savings and often substantial improvements in component performance (in terms of mass, stiffness, strength, etc.). Sandwich materials, involving a plastic core between thin sheets of a steel skin, are another innovation that can be used to save weight. Although sandwich steel cannot be welded, it can be formed and joined through many other common processes and is used in applications where bending stiffness is the principle performance need. One branded version of this material is "Quiet Steel®," which uses viscoelastic cores in a laminated steel composite to offer significant cost reduction opportunities and enhanced noise, vibration and hardness performance. [Materials science Co., 2004] A notable recent application is in the 2004 upgrade of Chrysler's Town & Country and Dodge Grand Caravan minivans. Driven by competition, Chrysler needed to add a stowable third-row seat and other refinements; steel sandwich material was used to make the tubs into which the foldable seats were stowed. [Kelly & Priddle, 2004] An overarching area of progress that enables further refinement in all aspects of iron and steel use is the major improvements in materials science, component characterization and modelling, and computerized simulation and design methods. Better techniques for measuring and modelling the properties of steels enable highly optimized designs. [Mahadevan et al, 2000] Such advances give engineers greater confidence in part performance, minimizing the "margin of error" that otherwise results in a larger or heavier part than needed. Extensive computer modelling development and validation work yields CAD/CAE/CAM34 techniques that enable many fewer adverse trade-offs in design, resulting in simultaneous progress in weight reduction, strength, stiffness, and energy absorption as needed, while cutting materials costs and waste and enhancing productivity in both design and manufacture. [Yoshimoto et al, 1999]

3.1.2 Aluminium

There are a broad range of opportunities for employing aluminium in automotive powertrain, chassis, and body structures. The use of aluminium offers considerable potential to reduce the weight of an automobile body. In current steel construction, the vehicle consists of stamped body panels spot welded together (body-in-white) to which stamped steel fenders, doors, hood, and deck lid are bolted. There are two methods of designing and manufacturing an aluminium body structure; one is similar to the current steel construction using stamped option and the other system which involves castings, extrusions, and stampings welded together, known as spaceframe. [Cole et al, 1995]
Adequate formability is one of the requirements for aluminium sheets to produce complex stampings at acceptable economical rates. This involves appreciation of the interaction of the crystallographic texture, sheet thickness and stamping die/lubricant parameters. In addition, the aluminium alloys chosen for exterior panels must have the ability of age hardening to provide suitable strength for dent resistance during the oven paint baking.
In order to use the Aluminium in automotive intake manifolds and transmission housings, it is essential that material shows the ability to be cast into leakproof components with well-defined inner passages for water and air flow, provides suitable thermal conductivity, and sufficient resistance to the mechanical forces at temperatures near 145'C. On the other hand, the components are exposed to high mechanical stresses from engine vibration and the thermal expansion loads. This can lead to thermal fatigue if the metallurgical structure is not sufficiently small and if the casting contains inclusions, oxide films, and porosity. This has initiated considerable research to aluminium castings with no defects to avoid fatigue and reduced impact resistance. Also control of solidification microstructure, dendrite arm spacing, grain size, and eutectic silicon morphology are the other areas that have become more and more under investigation. In addition to alloy chemistry and melt temperature, dissolved gas and nonmetallic inclusions must be controlled to limit porosity and stress-raising oxide films. Foundry practice to eliminate turbulence during pouring that can cause such films can be enhanced by computer-based heat-flow fluid flow and solidification modelling to design the location and geometry of sprue, ingates, and risers.
Aluminium usage in automotive applications has grown substantially within past years. A total of about 110 kg of aluminium: vehicle in 1996 is predicted to rise to 250 or 340 kg, with or without taking body panel or structure applications into account, by 2015 [Sears, 1997]. There are strong predictions for aluminium applications in hoods, trunk lids and doors hanging on a steel frame. Recent examples of aluminium applications in vehicles cover power trains, chassis, body structure and air conditioning. Aluminium castings have been applied to various automobile parts for a long period. As a key trend, the material for engine blocks, which is one of the heavier parts, is being switched from cast iron to aluminium resulting in significant weight reduction. Aluminium castings find the most

widespread use in automobile. In automotive power train, aluminium castings have been used for almost 100% of pistons, about 75% of cylinder heads, 85% of intake manifolds and transmission (other parts-rear axle, differential housings and drive shafts etc.) For chassis applications, aluminium castings are used for about 40% of wheels, and for brackets, brake components, suspension (control arms, supports), steering components (air bag supports, steering shafts, knuckles, housings, wheels) and instrument panels. Recently, development effort to apply wrought aluminium is becoming more active than applying aluminium castings. Forged wheels have been used where the loading conditions are more extreme and where higher mechanical properties are required. Wrought aluminium is also finding applications in heat shields, bumper reinforcements, air bag housings, pneumatic systems, sumps, seat frames, side impact panels, to mention but a few. Aluminium alloys have also found extensive application in heat exchangers. Until 1970, automotive radiators and heaters were constructed from copper and brass using soldered joints. The oil crisis in 1974 triggered are-design to lighter-weight structures and heralded the use of aluminium. The market share of aluminium has grown steadily over the last 25 years and is now the material of choice for use in the automotive heat exchanger industry. Modern, high performance automobiles have many individual heat exchangers, e.g. engine and transmission cooling, charge air coolers (CACs), climate control. [Miller et al, 2000]

Aluminium alloys for body-in-white applications

Up to now the growth of aluminium in the automotive industry has been in the use of castings for engine, transmission and wheel applications, and in heat exchangers. The cost of aluminium and price stability remains its biggest impediment for its use in large-scale sheet applications. Aluminium industry has targeted the automotive industry for future growth and has devoted significant resources to support this effort. The body-in-white (BIW) offers the greatest scope for weight reduction with using large amount of aluminium.

Recent developments have shown that up to 50% weight saving for the BIW can be achieved by the substitution of steel by aluminium [Scott, 1995]. This can result in a 20–30% total vehicle weight reduction when added to other reduction opportunities. There are two types of design each of which has a different form philosophy in the use of aluminium. One is the extruded space frame exemplified by the Alcoa- Audi A8 , and the other is the conventional sheet monocoque architecture as used in most steel structures as by the Alcan-Ford aluminium intensive vehicle (AIV). Each type has its merits: the space frame offers lower tooling costs by eliminating some stampings, whereas the conventional sheet monocoque offers established processes and low piece costs. The updated examples of these two types are Ford P2000 and Audi AL2. Both of them could reduce weight about 40% on the BIW basis. The extruded space frame developed for Audi A8 is believed most appropriate for low volume production. The structure of Audi AL2 is a modified space frame with aluminium extrusions already developed for A8. Audi AL2 model is produced with an all aluminium body structure. In the AL2, there are fewer aluminium cast joints, which were extensively used in A8 since they are replaced with direct bonds. Aluminium extrusions in the AL2 are also made into as straight shape as possible. It is also clear that, as the automotive companies work more and more with aluminium, simplification of design results in lower overall cost.

Determining the right alloy for the body structure and hang-on panels has been the subject of considerable development effort [Bull, 1992] and most of the activity is now concentrated on a relatively small number of alloys.

For skin sheet material the emphasis is on achieving a good balance of formability, strength after the paint-bake, and a high surface quality after pressing and paint finish. Consequently, the bake hardening 6xxx alloys are the primary choice for these applications. For structural sheet materials, strength may be a limiting factor in certain areas, impact energy absorption and good deep drawing behaviour are often the most important.
To meet these requirements, 5xxx alloys are mostly used in North America. In Europe, 6xxx-T4 materials are still widely used. One obvious and significant difference between aluminium and steel is the outstanding bare metal corrosion of the 5xxx and 6xxx aluminium materials. Increasingly large amounts of steel are supplied zinccoated to achieve acceptable paint durability, this is not necessary for aluminium. However, the aluminium coil or sheet can be supplied with a range of pre-treatment and primer layers which can improve formability, surface quality and may eliminate the need for E-coating.
There is a wide range of aluminium materials and surface qualities, which can be chosen, and the growing design and process experience is enabling the aluminium industry to help the customer specifying the right material for the application.
There is a clear difference [Bottema et al, 1998] in the alloy choice and treatments for these applications between Europe and North America.

Aluminium alloys for brazing sheet applications

As mentioned earlier brazed aluminium components are used extensively in modern vehicles for engine and transmission cooling, charge air coolers and climate control. It consists of a core alloy which provides the strength and life cycle requirements of the heat exchanger and a clad layer which is of a low melting point aluminium silicon alloy. During the brazing process the Al–Si alloy melts and seals joints in the heat exchanger between the different sheet components. The brazing sheet can be clad on one or both sides with the Al–Si alloy and in some cases one side is clad with a different alloy to provide corrosion protection on the inner (water-side) of the a radiator.
During 1970 vacuum brazing [Miller, 1967] was developed to solve the problems associated with old techniques of dip brazing. It was an environmental friendly approach but requires significant capital investment. It became the main method for manufacturing heat exchangers in the 1980s and still remains the preferred brazing method for evaporators and charge air coolers. It is gradually being superseded by controlled atmosphere brazing (CAB). A main advantage of vacuum brazing over controlled atmosphere brazing is that high (0.3%) magnesium containing alloys can be used. Although, now in use for several decades the complete mechanisms behind the technique are still not fully understood. Since the introduction of Nocolok process by Alcan in 1978 [Cooke et. al, 1978], this process has become the workhorse in the brazing industry. It is a very attractive process since it can be operated continuously at low costs [Fortin, 1985]. Although the CAB process is very popular it has some constraints like, the flux can not tolerate high magnesium alloys [Bollingbroke, 1997] and the uniform application of the flux on the heat exchanger to be brazed can be very difficult to control.

3.1.3 Magnesium

Magnesium is 33% lighter than aluminium and 75% lighter than steel/cast-iron components. The corrosion resistance of modern, high-purity magnesium alloys is better than that of conventional aluminium die-cast alloys. As well, porosity-free die-cast AM501 AM60 can achieve 20% elongation, or over three times that of Al A380, leading to higher impact strength; but magnesium components have many mechanical/physical property disadvantages that require unique design for application to automotive products. Although its tensile yield strength is about the same, magnesium has lower ultimate tensile strength, fatigue strength, and creep strength compared to Aluminium. The modulus and hardness of magnesium alloys is lower than aluminium and the thermal expansion coefficient is greater. However, it should be noted that suitable ribbing and supports often can overcome the strength and modulus limitations.

Property	Magnesium	Aluminium	Iron
Crystal Structure	hcp	FCC	BCC
Density at 20^{0}C (g/cm^3)	1.74	2.70	7.86
Coefficient of thermal expansion 20-100^{0}C (*10^6/C)	25.2	23.6	11.7
Elastic modulus (10^6 MPa)	44.126	68.947	206.842
Tensile strength (MPa)	240	320	350
Melting point (^{0}C)	650	660	1.536

Table 4: Properties of Mg, Al, Fe [Source: Davies, 2003]

Despite the above issues Magnesium alloys have distinct advantages over aluminium that could not be dismissed. These include better manufacturability, longer die life and faster solidification due to lower latent heat. Therefore more castings can be produced per unit time compared to aluminium. Magnesium components have higher machinability. Magnesium components can be produced with improved dimensionality and surface quality, and smaller draft angles compared to aluminium. The capability of magnesium to be hot chamber die cast can reduce casting scrap by reducing dross and can limit gas and oxide inclusions while allowing more consistent melt temperature. A comparison of the properties of the Mg, Al and Fe is made in Table 4.

Mechanical properties of Mg alloys

Specific strength and specific stiffness of materials and structures are important for the design of weight saving components. Weight saving is particularly important for automotive bodies, components and other products where energy consumption and power limitations are a major concern [Tkachenko et. al, 2006]. The specific strength and specific stiffness of magnesium are compared with aluminium and iron in Figure 3. There is little difference between the specific stiffness between Mg, Al and Fe as seen in Figure 3. The specific stiffness of Al and Fe is higher than Mg only in the ratio of 0.69% and 3.7%, respectively. On the other hand, the specific strength of Mg is considerably higher than that of Al and Fe in the ratio of 14.1% and 67.7%, respectively. [Kulekci, 2008]

Because of its too low mechanical strength, pure magnesium must be alloyed with other elements, which confer improved properties. The Mg-Al-Zn group of alloys contains aluminium, manganese, and zinc. These are most common alloying elements for room temperature applications. Thorium, Cerium, and Zirconium (without aluminium) are used for elevated temperatures and form the Mg-Zn-Zr group. Thorium or cerium is added to improve strength at the temperatures of 260°C to 370°C. Mg-Al alloys are one major group among magnesium-based alloys. The strength of these alloys is improved [Aghion et al 2003, Pekguleryuz et al, 2003 a-b]. But they suffer from poor coherency, and high creep deformation at elevated temperature of >150 ^{0}C for long periods of time, the supersaturated Mg solid solution transforms to Mg matrix with coarsely dispersed Al (g) precipitates and contributes to grain boundary migration and creep deformation. Furthermore Al (g) is also prone to aging and has poor metallurgical stability, which limited its application in higher temperatures. Early developments in improving the creep properties of magnesium were made in the 1960s by Volkswagen [Medraj & Parvez, 2007]. It was based on Mg-Al-Si system. These alloys exhibit marginally improved creep resistance but are difficult to die-cast. Magnesium components are generally in the form of magnesium alloys. The addition of other alloying elements can strengthen and harden magnesium as well as alter its chemical reactivity.

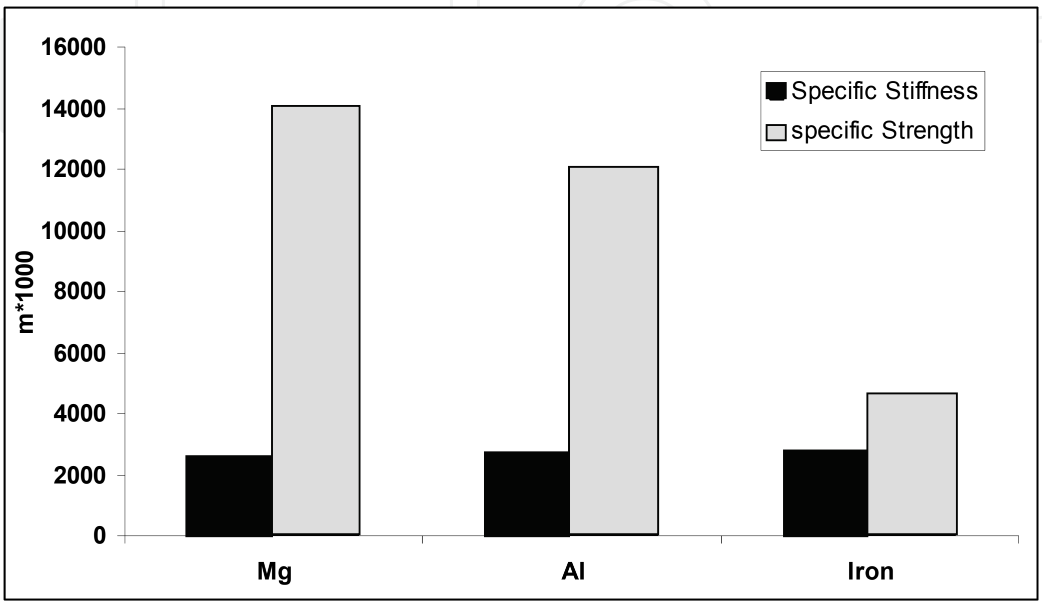

Fig. 3. comparison of specific stiffness and strength of the Mg, Al and Fe [Source: Kulekci, 2008]

AZ91D magnesium alloy has been shown to creep at ambient temperature under initial applied stress of only 39% of its yield stress [Grieve 2001]. The commonly used die-casting alloy AZ91, starts creep at temperatures above 100°C and has a maximum operating temperature at 125°C [Aghion et al, 2001].
Because of its creep behaviour, it is not convenient to use this alloy for power train and engine castings. Both of them operate at temperatures of 100°C or more and are fixed together with threaded fasteners so creep becomes a key issue for these applications [Pekguleryuz, 2003 a-b]]. The studies on AE42 alloy showed that AE42 has a greater percentage of initial compressive load than AZ91D as seen in Figure 4 [Aghion et al 2003, Pekguleryuz, 2003]. AE series alloys have better creep resistance with respect to AZ91D. Magnesium alloys for automotive applications must have good creep resistance property. These alloys should be thermally and metallurgically stable and resistance to flow during creep loading. Moreover, it should have adequate corrosion resistance, castability and strength. The AE42 (Mg-4 atomic percent Al-2 atomic percent rare earths) magnesium alloy has improved creep resistance over the other alloys as seen in Figure 4. Magnesium-thorium alloys display excellent creep properties at elevated temperature (350°C). However, these alloys have cast disadvantages due to expensive rare earth additions [Pekguleryuz, 2003, a-b]. The Mg-Al-Sr system is a recently developed alloy for the heat-resistant lightweight Mg alloys. The Mg- Al-Sr system is used by BMW for the manufacturing of die-cast engine blocks. This system has excellent mechanical properties, good corrosion resistance and excellent castability. Mg alloys with Sr addition have better creep resistance

than other alloy systems as seen in Figure 4. Corrosion resistance of the Mg- Al-Sr alloys is similar to AZ91D and better than AE42, which indicates that strontium does not have adverse affect on corrosion properties [Medraj, 2007]. The addition of Al to Mg alloys provides good fluidity which adversely affects the creep resistance. Wrought alloys exhibit significantly better combination of strength and ductility compared with casting alloys. However wrought alloys are currently used to a very limited extent due to a lack of suitable alloys and some technological restrictions imposed by the hexagonal crystal structure of magnesium [Eliezer et al, 1998].

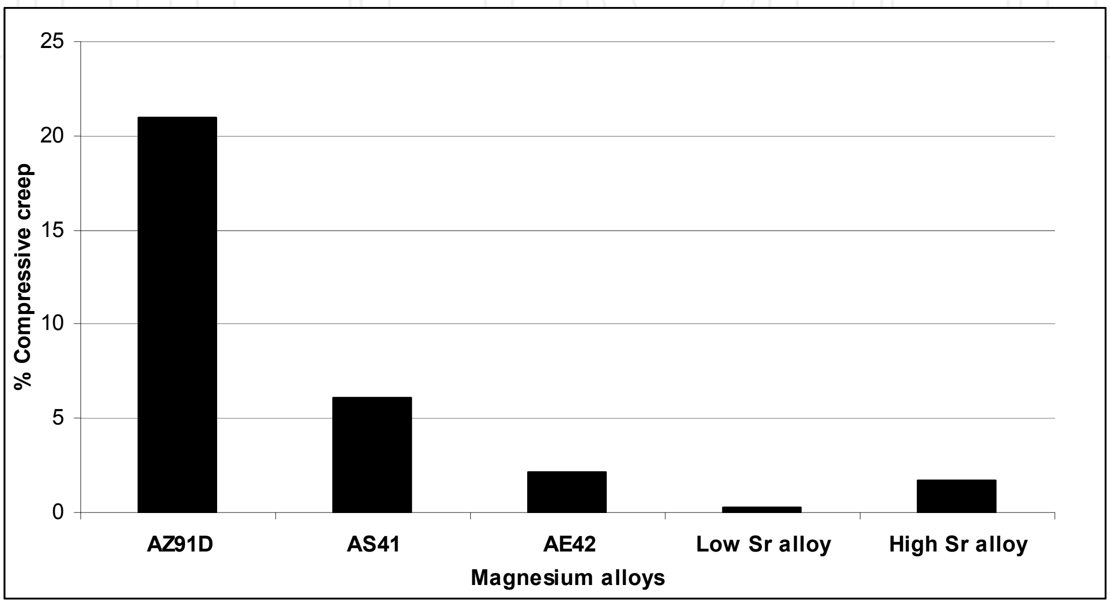

Fig. 4. Compressive creep of the magnesium alloys at 70 MPa, 150 ^{0}C after 200 hrs, [Source: Pekguleryuz et al, 2003]

Technical problems and solutions for use of magnesium alloys in automotive industry

The disadvantages of Mg alloys are high reactivity in the molten state, inferior fatigue and creep compared to aluminium and galvanic corrosion resistance. The problems in using magnesium alloys stem from their low melting points 650°C and their reactivity (inadequate corrosion resistance) [Haferkamp et al, 2001]. The main problem for Mg alloys encountered during fabrication and usage is the fire hazard/risk, especially in machining and grinding processes due to their relatively low melting point [Sreejith & Ngoi, 2000]. In roughing cuts the chips are generally thick and not likely to get hot enough to ignite. However, the thin chips produced in the finishing cuts are more likely to heat up and ignite. Similarly, the dust in grinding can ignite, even explode, if heated to melting temperatures. The fire hazard can be eliminated by avoiding fine cuts, dull tools, high speeds; using proper tool design to avoid heat build up; avoiding the accumulation of chips and dust on machines and cloths; and using coolants.

Magnesium is a reactive metal, so it is not found in the metallic state in nature. It is usually found in nature in the form of oxide, carbonate or silicate often in combination with calcium. Because of this reactivity the production of magnesium metal requires large amounts of energy. This situation makes magnesium an expensive metal. To prevent reactivity problems, protective finishes, such as anodic coating or paint are used [Shi et al, 2006]. Magnesium is attacked by inorganic acids. It is not attacked by alkalis and caustic soda.

Welding of Mg alloys can also present a fire risk if the hot/molten metal comes in contact with air. To overcome this problem, the welding region must be shielded by inert gas or flux. A larger amount of distortion relative to other metals may arise due to high thermal conductivity and coefficient of thermal expansion in welding of magnesium alloys if required precautions are not taken [Robots 4 welding, 2007]. Service temperatures must be well below the alloy melting points; otherwise the fire hazard might materialize. For example, it caused an engine fire in a DC-3 aircraft, resulting in a fatal crash. This particular aircraft was built during World War II, when aluminium shortages forced manufacturers to use of magnesium alloys as a replacement in some applications. The low creep properties of magnesium alloys limits the application of magnesium alloys to be used for critical parts, such as valve covers [Medraj, 2007]. The following are the main issues that need attention to increase creep properties of magnesium alloys: stress relaxation in bolted joints, the potential for creep at only moderately elevated temperatures, corrosion resistance, and the effects of recycled metal on properties.

Significant research is still needed on magnesium processing, alloy development, joining, surface treatment, corrosion resistance, and mechanical properties improvement.

Different coating methods are used to increase the corrosion resistance of magnesium alloys. Problems with contact corrosion can be minimized, on the one hand, by constructive measures and, on the other hand, by an appropriate choice of material couple or the use of protective coatings [Blawert et al, 2004]. Chromate coating of Mg alloys is hazardous and not environmentally friendly. A newly developed Teflon resin coating has been developed for Mg alloys [AIST, 2007]. The coating is obtained with an aluminium vapour deposition and finish treatment with a Teflon resin coating. The newly developed Teflon resin coating is a low cost, chromium-free corrosion resistant coating for magnesium alloys. The coating not only has corrosion resistant properties, but also good lubricity, high frictional-resistance and non-wetting properties. The main future of the coating is in the application of Teflon coating on Magnesium alloys.

3.2 Plastics and composites

Polymer composite materials have been a part of the automotive industry for several decades, with early application in the 1953 Corvette. These materials have been used for applications with low production volumes, because of their shortened lead times and lower investment costs relative to conventional steel fabrication. Important drivers of the growth of polymer composites have been the reduced weight and parts consolidation opportunities the material offers, as well as design flexibility, corrosion resistance, material anisotropy, and mechanical properties. Although these advantages are well known to the industry, polymer composite use has been impeded by high material costs, slow production rates, and to a lesser extent, concerns about recyclability. Several factors have hindered large scale automotive applications of polymer composites. Amongst these are concerns about crash energy absorption, recycling challenges, competitive and cost pressures, the industry's general lack of experience and comfort with the material.

The cost of composite materials is usually much higher (up to 10 times higher when using carbon fibres) than those of conventional metals. A comparison of the cost elements for the glass fibre composites and carbon fibre composites are made with the steel in figure 5. Therefore, the main targets for future development must be the use of hybrid composites (low-cost fibres to be used where possible and aramide and carbon fibres to be used only where they are required for damage tolerance or stiffness reasons), the evaluation of highly automated and rapid manufacturing processes including the application of intelligent preforms or half-finished goods, and the full use of the potential of composites for parts integration. Either glass or carbon, reinforced in the matrix of thermoset or thermoplastic polymer materials. The glass-reinforced thermoset composites are the most commonly used composite in automotive applications today, but with the development of very high

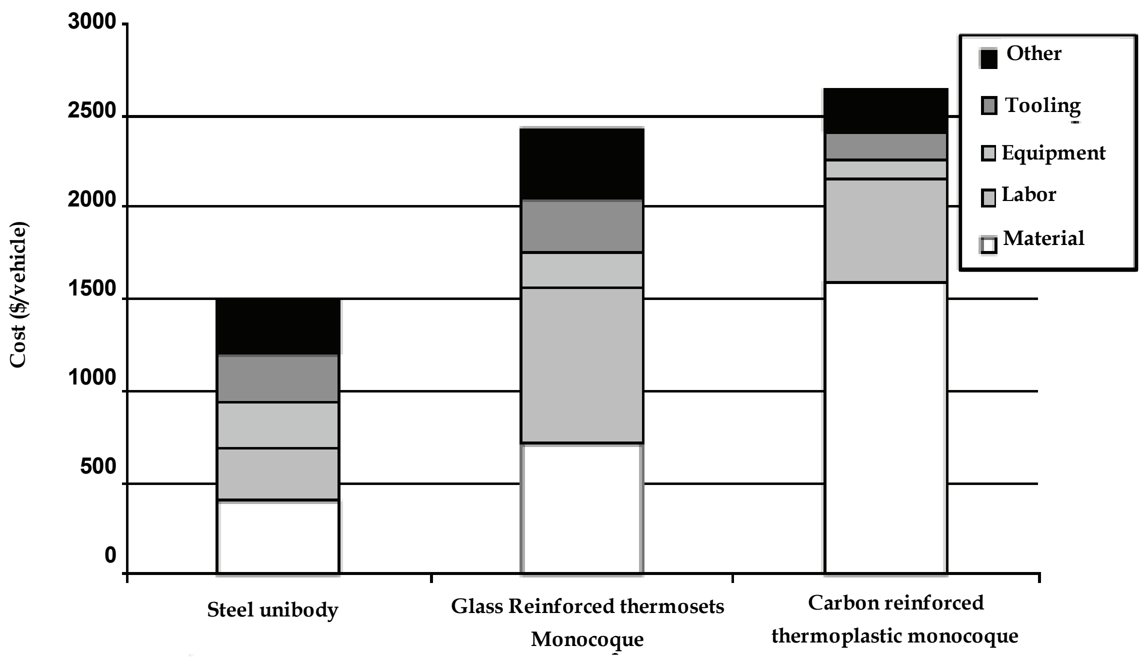

Fig. 5. Cost structure comparison of BIW designs [source: Dieffenbach et. al, 1996)]

3.2.1 Fabrication

The choice of a specific fabrication method depends on the costs and on the technical requirements of the component to be produced. In order to guarantee economic production, methods with a high throughput are absolutely necessary. High throughput can be achieved by means of low clock times or by means of high integrative parts. Table 5 compares the most commonly used composite fabrication processes available today, addressing their advantages, disadvantages, and cycle time.

The use of prepregs, which are reinforced with carbon or glass in fibre and fabric forms coated with epoxy resins, may be suitable for only limited automotive applications because of lower productivity. One of the chief obstacles in the way of achieving higher production volumes for structural composites is the time at the preforming stage required to place complex, properly oriented reinforcement in the moulding tools. This requirement results in long cycle times, high labour cost, and low productivity of the moulding tool investment. A recent study indicates that the cost of preforms contribute about 35% to the total composite BIW cost, compared to 50% for moulding and 15% for assembly (Mascarin 2000). Some of the approaches that are used for making preforms are specially knit fabric designed to drape properly for a given component; braided reinforcement over moulded foam cores; multiple ply vacuum preforming; and robotically applied chopped fibres known as P4 process The most broadly accepted reinforced thermoset composites used by automakers in today's market include sheet moulding composite (SMC), bulk moulding composite (BMC), reinforced reaction injection moulding (RRIM), and liquid composite moulding processes such as structural reaction injection moulding (SRIM) and resin transfer moulding (RTM).

SMC and RRIM are most widely used today, contributing to 48% and 40%, respectively to the total thermoset components used in the 2000 model year passenger cars (ACA 2000). RTM and SRIM composite moulding processes have been considered to provide the best economic balance for the automotive structural products. These processes have favourable cycle times with large parts and produce a surface quality corresponding to the automotive standard

Moulding process	Adavantages	Disadvantages	Cycle time
Prepreg	Better resin/fibre control	Labour intensive for large complex parts	5-10 hrs
Preforming	Good mouldability with complicated shapes and the elimination of trimming operation	Cost-effective only for large complicated shape parts and large scrap generated when fibre mats used	45-75 secs. (compform process) 4-5 mins (vacuum forming)
RTM	Inside and outside finish possible with thickness control, more complex parts possible with vacuum assisted	Low viscosity resin necessary and the possibility of voids formation without vacuum assisted	8-10 mins for large parts: 3-4 mins for vacuum assisted
Liquid compression moulding	Favoured method for mass production with high fibre volumes	Expensive set p cost for low production	1-2 mins
SMC	Cost effective for production volume 10K-80K/year	Minimum weight savings potential	50-100 secs
RIM	Low cost tolling where prototypes can be made with soft tools	Difficult to control the process	1-2 mins
BMC	Low cost base material	Low fibre content randomly oriented, low structural quality, poor surface finish	30-60 secs
Extrusion compression moulding	Fully automated variety of polymers and fibres can be used with fibre volumes up to 60% by weight	Not for surface finish parts without paint film or similar process	3-6 mins
Structural reaction injection moulding	Low tooling cost with the good finish capability	Difficult to control the process particularly with low viscosity resin and longer cure cycle time	4 mins

Table 5: A Comparison of the Most Commonly Used Composite Moulding Processes [Source: Das, 2000]

3.2.2 Cost

Reducing the cost of manufacturing automotive structural components from lighter weight composite materials so that they are competitive with the component (including life cycle) costs of other materials is a major focus. Although cost reduction is a pervasive factor in all composites R&D activities, most of the activities in this area are related to materials, the major factor affecting the viability of composites in automotive applications today.

3.2.3 Manufacturability

Methods for high-volume production of automotive components from lightweight materials have not been adequately developed. Composite processing technologies need to be developed that yield the required component shape and properties in a cost-effective, rapid, repeatable, and environmentally conscious manner. For instance, technologies for high-rate forming and moulding of composites for large structural components and high-volume production of continuous fibre preforms are needed.
It is essential that high-rate preforming techniques be developed to obtain chopped-fibre preforms with consistent fibre distribution and density at the volumes required by the automotive industry.

3.2.4 Design data/test methodologies

One of the major challenges for the commercialization of polymer composites is the lack of adequate design data (e.g., material property databases), test methods, analytical design tools (i.e., models), and durability data. DOE is focusing on the development of enabling technologies and property data to predict the response of materials in a given structural design after long-term loading, under exposure to different environments, and in crash events.
Theoretical and computational models are being developed for predicting energy absorption and dissipation in automotive composites. These models are tools designers need to minimize component weight while maximizing occupant safety.

3.2.5 Joining and inspection

High-volume, high-yielding technologies for joining composites to each other and to metal structures in an automotive assembly environment do not currently exist but are being developed. Current efforts concentrate on adhesive formulation, modelling, and processing. Significant work is being conducted to understand the synergistic effects of environmental stressors on adhesive joint integrity. The next five-year research focus is on the development of non-adhesive joining techniques such as chemical bonding of thermoset composites and the joining of carbon fibre based composites to a variety of materials. Fast, reliable, and affordable methods to test bond integrity and assembled structures are needed.
One of the major drawbacks in the use of composites for automotive applications is that technologies for cost-effective recycling and repair of advanced composite materials do not exist. Cost-effective methods for the separation and recycling of composite materials into high-value applications, as opposed to using them only as filler, need to be developed. Methods are being pursued for separating glass and carbon fibre from thermoset and thermoplastic resin systems. Efforts are also underway to identify alternate uses for post-consumer automotive grade composites.

3.3 Renewable materials, barriers and incentives in use of biocomposites

The lightweight, low cost natural fibres offer the possibility to replace a large portion of the glass and mineral fillers in several automotive interior and exterior parts. In the past decade, natural-fibre composites with thermoplastic and thermoset matrices have been embraced by European car manufacturers and suppliers for door panels, seat backs, headliners, package trays, dashboards, and interior parts. Natural fibres such as kenaf, hemp, flax, jute, and sisal are providing automobile part reinforcement due to such drivers as reductions in weight, cost, and CO2, less reliance on foreign oil sources, recyclability, and the added benefit that these fibre sources are "green" or ecofriendly. As a result, today most automakers are evaluating the environmental impact of a vehicle's entire lifecycle, from raw materials to manufacturing to disposal. At this time, glass-fibre-reinforced plastics have proven to meet the structural and durability demands of automobile interior and exterior parts. Good mechanical properties and a well-developed, installed manufacturing base have aided in the insertion of fibreglass-reinforced plastics within the automotive industry. However, glass-reinforced plastics show shortcomings such as relatively high fibre density (approximately 40% higher than natural fibres), difficulty to machine, and poor recycling properties, not to mention the potential health hazards posed by glass-fibre particulate.

Blast	Leaf	Seed	Fruit	Stalk	Wood Fibres
Flax **Hemp** **Jute** **Kenaf** **Ramie** **Banana** **Rattan**	**Sisal** **Manila** **Curauna** **Banana** **Palm**	**Cotton** **Kapok**	**Coconut** **Coir**	**Bamboo** **Wheat** **Rice** **Grass** **Barley** **Corn**	**Hardwood** **Softwood**

Table 6. A list of vegetable and cellulose fibre classifications [Source: Holbery & Houston, 2006]

An ecological evaluation, or eco-balance, of natural-fibre mat as compared to glass-fibre mat offers another perspective. The energy consumption to produce a flax-fibre mat (9.55 MJ/kg), including cultivation, harvesting, and fibre separation, amounts to approximately 17% of the energy to produce a glass-fibre mat 54.7 MJ/kg). [Patel et al, 2002] Though natural-fibre-reinforced plastic parts offer many benefits as compared to fibreglass, several major technical considerations must be addressed before the engineering, scientific, and commercial communities gain the confidence to enable wide-scale acceptance, particularly in exterior parts where a Class A surface finish is required. Challenges include the homogenization of the fibre's properties, and a full understanding of the degree of polymerization and crystallization, adhesion between the fibre and matrix, moisture repellence, and flame retardant properties, to name but a few. Technology for implementing natural fibre composites into interior trim continues to be developed by Tier I and Tier II automotive suppliers, typically in partnership with producers of natural fibre- based processing capabilities for mat or other material forms. Compression moulding, injection moulding, thermoforming, and structural reaction injection moulding are all processes utilized to process natural-fibre composites. [Holbery & Houston, 2006]

3.3.1 Thermoplastic/ thermoset polymers

The manufacture of natural-fibre composites includes the use of either a thermoset or thermoplastic polymer binder system combined with the natural fibre preform or mat. In automotive applications, the most common system used today is thermoplastic polypropylene, particularly for nonstructural components. Polypropylene is favoured due to its low density, excellent processability, mechanical properties, excellent electrical properties, and good dimensional stability and impact strength. [George et al, 2001], However, several synthetic thermoplastics are utilized including polyethylene, polystyrene, and polyamides (nylon 6 and 6, 6). The development of thermoplastic natural-fibre composites is constrained by two primary physical limits: the upper temperature at which the fibre can be processed and the significant difference between the surface energy of the wood and the polymer matrix. Process temperature is a limiting factor in natural fibre applications. The generally perceived upper limit before fibre degradation occurs is on the order of 150°C for long processing durations, although fibres may withstand short-term exposures to 220°C.

The result of prolonged high-temperature exposure may be discoloration, volatile release, poor interfacial adhesion, or embrittlement of the cellulose components. Therefore, it is important to obtain as rapid a reaction rate as possible during both surface treatment and polymer processing to limit exposure to cell wall components preventing degradation. The development of low-process-temperature surface

treatments with high service capabilities are viewed as enabling technology for the application of natural fibres in composite materials. Because the interfacial adhesion between the natural fibre and polymer matrix determines the composite physical properties, it is usually necessary to compatibilise or couple the blend. [Baille, 2004] Compatibilisation is any operation performed on the fibre and polymer that increases the wetting within the blend. Coupling is a process in which dissimilar polymers or fillers are made into an alloy by use of external agents called coupling agents. [Bledzki & Gassan, 1999] The result of properly applying a compatibiliser or coupling agent to the composite is an increase in physical properties and environmental durability. [Mohanty et al, 2005] The primary thermoset resins used today in natural-fibre composites for automotive applications are polyester, vinylester, and epoxy resins. [Mohanty et al, 2005] In natural fibres, polar groups are the main structural units and the primary contributor to mechanical properties; these also render cellulose more compatible with polar, acidic, or basic groups, as opposed to nonpolar polymers. Polyester resins are widely used, particularly the "unsaturated" type capable of cure from a liquid to a solid under a variety of conditions. Epoxy resins offer high performance and resistance to environmental degradation. Epoxies have wide appeal in industry, although in the automotive industry epoxies have not gained broad use due to longer cure schedules and high monomer cost. Vinylester resins is a relatively new addition in the family of thermosetting resins which combine excellent chemical resistance, good thermal and mechanical properties, and the relative ease of processing and rapid cure characteristics of polyester resins. These have better moisture resistance than epoxies when cured at room temperature. Vinylester resins are similar in their molecular structure to polyesters, but differ in that the reactive sites are positioned at the ends of the molecular chains, allowing for the chain to absorb energy. This results in a tougher material when compared to polyesters.

3.3.2 Composite processing

The primary drivers for the selection of the appropriate process technology for natural-fibre composite manufacture include the final desired product form, performance attributes, cost, and ease of manufacturing. Several factors must be considered in selecting a process. One must insure: that the fibre is distributed evenly within the matrix, that there is adequate compatibility between the hydrophobic matrix and hydrophilic fibres, that fibre attrition is minimized due to processing to insure reinforcement, that the desired fibre orientation effects will be imparted, that thermal stability of the fibre is maintained throughout the processing step, and that the moisture inherent within the fibre is at the desired level, minimizing problems with swelling or part distortion. The control of moisture in the fibre and the effect of moisture after moulding are primary considerations in natural-fibre composites in automobiles. Similarly, the ability to eliminate water absorption during service of natural-fibre-based composite components is paramount in industrial applications. For example, it has been shown in sisal fibre/unsaturated polyester composites that storage in water will result in a reduction of up to 50% in flexural modulus. [Zafeiropoulous et al, 2002]

Compounding processes that blend the natural fibres with a thermoplastic matrix are gaining wide acceptance due to the high degree of consistency feasible in the pellet form. The purpose of a compounding operation is to produce a pelletised feed stock that can be processed further, similar to any other thermoplastic processing technique, such as injection moulding, extrusion, or thermoforming. There are several types of compounding processes, including extrusion, kneading, and high-shear mixers.

Injection moulding is a versatile process and is the most widely used processing technique for making composite products, particularly where intricate shapes are needed in cyclic, high-volume production. The benefits include excellent dimensional tolerance and short cycle times coupled with few post-processing operations. According to BMW, it is possible to manufacture bio-based composites that are as much as 40 percent lighter than equivalent injection-moulded plastic parts.[Singh 1998] One of the challenges posed by injection moulding natural-fibre composites is to produce pellets of a consistent quality. This has been explored by both North American and European injection moulding equipment suppliers through a process called direct long-fibre thermoplastic (D-LFT) moulding. In this continuous process, first developed for glass fibres, the fibres are spooled and fed into a heating zone, where the thermoplastic is integrated with the fibre bundles. These bundles are then cut at a desired length and fed continuously into an injection moulding hopper, and parts are moulded continuously. It is reasonable to assume that the recent developments in producing continuous natural-fibre roving could be integrated on a large scale into the D-LFT process. Several companies are working in this development area.

Thermoforming is mainly used to produce natural-fibre-mat thermoplastic composites. The process takes pre-cut layers of fibre (or preformed mats that could comprise random fibres or roving) and polymer sheet that are inserted in a heated mould, and consolidates the material as heat is transferred through conduction to melt the thermoplastic. The thermoplastic flows to penetrate the fibre component, with pressure applied during the heating and cooling phases. After reaching the melt temperature in a hot press, the molten hybrid material is consolidated into a composite in a cold press, with very rapid processing times possible via combined heating-cooling presses in parallel. Compression moulding using thermoset polymer matrices is another major platform used to manufacture large parts for the automotive industry, producing light, strong, and thin panels and structures. The primary advantage of this process is low fibre attrition and process speed. A comparison of compression moulded unsaturated polyester composites reinforced with glass fibre and with natural fibres (flax) is provided in Table 7.

Property	Glass fibre (30% wt)	Natural Fibre (35% wt)
Flex Strength (MPa)	80	70
Flex Modulus (GPa)	6.0	6.0
Elongation at Break (%)	2.2	1.9
Impact Strength (KJ/mm^2)	38	20
Density (g/cm^3)	1.54	1.42

Table 7: Comparison of the properties of the flax fibre and glass fibre.

This indicates that the properties are comparable with properties with similar fibre loadings. Another method of compression moulding is the sheet moulding compound (SMC) process which has been used for glass composites for years. Many variations of compression moulding have been developed that are suitable for automotive application, and recent developments to combine extrusion and compression of thermoplastic composites, initially with glass fibres, are beginning to enter into the automotive industry. This process extrudes large thermoplastic fibre bundles, or pre-heated plugs, into a compression mould in-situ, and then the compression moulds the part. However, high capitalization costs will preclude this process from large-scale insertion into the Tier 1 supply chain in the near future. The foaming technique produces foamed products that can be used in upholsteries and in insulation applications. Finally, thermoset polymer composite manufacture via resin transfer and vacuum-assisted resin transfer moulding has gained interest from the automotive industry. The primary benefits of this processing platform include compounding at low shear and temperatures with minimal degradation of the cellulose fibre. Higher fibre loadings to 70% are possible, as well as good devolatilization. However, these processes are meeting resistance due to the high capital expenditure requirements.

4. Conclusions

The competition in the market of materials for automotive applications is substantial. This is due to the size and value of the market. In the more recent years the environmental concern has opened the need for lighter vehicle for lower fuel consumption and also for the need of recycling. These recent pressures have opened the door for introduction of new materials to the automotive market such as alternative metals and composites. However there are yet significant barriers in large scale use of these materials mainly due to the cost of the raw materials or the large capital investment need for transformation of the forming processes. Therefore the need for further research for suitable processes, properties and lower cost materials in this lucrative industry is at its peak. The more traditional materials such as steel producers are trying hard to keep their market by further innovations and improvements in their alloying and their processes in order to offer lighter material and structure option. But at the same time the newer materials such as alternative metals and composites are at the heart of the research and innovation for opening the possibility of the lighter and more environmentally friendly future vehicles.

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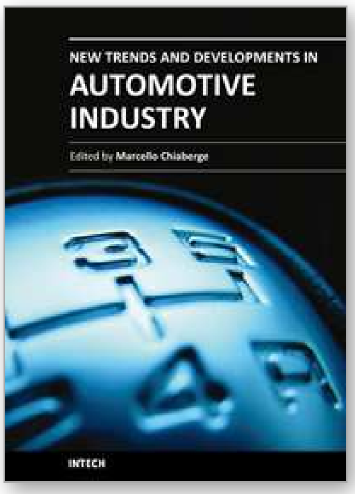

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