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INTENSIVE USE OF ALUMINIUM IN CAR BODY CONSTRUCTION

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ABSTRACT

The developments in materials over the last decade have been considerable within the automotive industry, being one of the leaders in innovative product applications. Sustainable product development of an automotive structure requires a balanced approach towards technological, economical and ecological aspects. The introduction of new materials and processes is dependent on satisfying different factors. Competitive and legislative pressures, creating the need for change, affect these factors considerably. The process, direction and speed of change are often reactive. Current paper shows the application of aluminium alloys, for the use in the bottom structure of a car to face the problem for the weight of the entire bottom structure under static load conditions, including stiffness, strength and buckling constraints. In addition to minimized mass and materials' price, the assessment of an environmental impact of materials-candidates during the entire life cycle of the structure is considered.

KEYWORDS: Vehicle engineering; Body construction; Structural optimisation; Light weight body

INTRODUCTION

The modern motor vehicle is an excellent and accessible example of new materials and technologies utilisation, which typically acts a barometer to change. A typical modern motor vehicle is constructed from a mixture of many different materials from all classes of metals, plastics, rubbers and ceramics, produced in different forms by different processes, and combined by a similar variety of joining methods. Also in common with a lot of industries, the automotive industry undertakes extensive testing to determine how technical advantages can be gained while maintaining product quality and reliability irrespective of the material.

Anish Kelkar, Richard Roth and Joel Clark (2001) established why aluminium could be an economical alternative to steel when the use in cars has been increasing for the past years. Randall J. Urbance, Frank Field, Randy Kirchain, Richard Roth, and Joel P. Clark (2002) studied the impact of increased automotive interest in magnesium. Due to increasing energy and environmental concerns making automakers become more interested in lightweight alternatives to traditional component designs, light materials, such as aluminium and magnesium as lightest standard engineering metals, has often been cited as showing potential in the automotive world, but has been resisted by automakers due to high prices and limited availability. Natalia S. Ermolaeva, Maria B.G. Castro and Prabhu V. Kandachar (2003) also studied the materials selection techniques for an automotive structure by integrating structural optimization with environmental impact assessment, as the sustainable product development of an automotive structure requires a balanced approach towards technological, economical and ecological aspects. Adam Gesing (2004) presented the way to ensure a continued recycling of light metals in end-of-life vehicles during the 2004 TMS Annual Meeting in Charlotte, North Carolina, reviewing issues and technologies in recycling, both current and future, with a focus on end-of-life vehicles (ELVs) and their increasing light material content. J. Hilmann, M. Paas, A. Haenschke and T. Vietor (2005) studied a method of structural optimisation for the body in white structure by developing a model for optimisation and robust design of passenger.

In the conventional modern motor vehicle, nearly 15% of the vehicles weight, and 50% by volume, is the body shell and still increasing. By using aluminium instead of steel, the total mass could be reduced nearly 40%.

Motor vehicles manufacturers are being compelled to make vehicles lighter and more fuel-efficient at lower manufacturing costs with increased productivity, but also are striving to shorten the product development cycle to enable new models to be brought out more quickly, more often and with lower tooling costs.

Changes can and often do become altered or accelerated by the introduction of new legislation such as End-of-Life Vehicle recycling directives. As a consequence, every manufacturer is expected to comply with any new legislation, with a tendency to level out the competition. However, each manufacturer will where possible interpret the legislation differently for competitive advantage.

The constraints above to both a lesser and greater extent, depending on the product, have strong analogies with new product development in general. This paper analyses product development from a materials selection perspective by following the development of automotive components over the past decade.

1. MAJOR ISSUES FACED OVER THE LAST DECADE

Some of the major issues faced over the last decade that have influenced change in materials usage in motor vehicles can be summarised as follows.

1.1. Environmental constraints

One of the major strategies for reducing fuel consumption is weight reduction. In addition to the environmental benefits, reduced weight also contributes to improved vehicle dynamics, improved safety and the opportunity to add more features. This was recognised by Henry Ford in 1923 when he said that "saving even a few pounds of a vehicle's weight … could mean that they would go faster and consume less fuel".

One way of reducing exhaust emissions from motor vehicles is by reducing their fuel consumption. Fuel consumption can be improved by increasing the thermodynamic efficiency of the engine but significant gains can also be achieved by reducing the weight of the vehicle and its aerodynamic drag. To achieve a weight reduction, higher performance materials are required.

Materials with high specific stiffness and strength properties for example allow highly efficient lightweight load bearing structures to be produced. Similarly, materials with enhanced processing capabilities, such as near net moulding allow greater design freedom in producing complex shapes for improved aerodynamics, further reducing fuel consumption. Reducing weight involves reducing materials, which, in turn, means reducing cost as well." Since 1923 a greater range of materials have been developed and it is now possible to reduce weight by using lower density materials that result in better property to weight ratios.

One avenue is the use of composite and polymeric materials. The other is the use of light metals such as aluminium and magnesium alloys. The density of aluminium is about 35% that of steel while magnesium is about 23% that of steel and about 65% that of aluminium. Another light metal titanium has an extremely good strength to weight ratio but it is difficult to produce and form and therefore is comparatively expensive. It will be at least a decade before titanium will become a significant contender for automotive applications. The light metals aluminium and magnesium are attractive because they have good strength to weight ratios and are easy to form, durable, thermally resistant, energy absorbing when stressed, relatively low cost and readily recyclable. The last factor is also important with

European legislation requiring 85% of a vehicle to be recycled at the end of a vehicle's life in 2005 and 95% in 2015.

A whole aluminium car body will reduce the final mass a 50% versus a conventional steel body construction, ensuring a fuel saving from 2% to 10%.

Significant introduction of aluminium and its alloys into the construction of vehicles began about 20 years ago with the conversion of engine blocks and cylinder heads from cast iron to aluminium alloys.

This process of substitution is well advanced with aluminium alloys accounting for the production of a high proportion of engine components. Recent activity has focused on the body structure with Audi and Jaguar now marketing entirely aluminium car bodies (Figures 1 & 2).

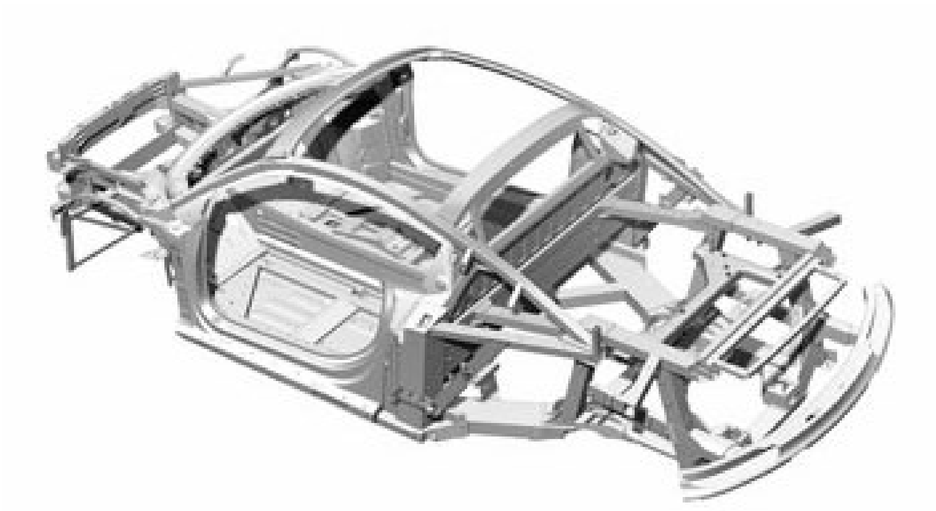

Figure 1: Aluminium Space Frame (ASF®) Audi R8 that is constructed of aluminium alloy extrusions and sheet pressings joined together by bolts, rivets and welding cords. (Picture courtesy of Audi)

The technology is now available to introduce aluminium into most components of a car. However, some of these technologies introduce extra cost. Over the coming decade the main focus will be to reduce manufacturing cost. For example, the first aluminium space frames introduced by Audi were relatively expensive. However, with each new model the cost has decreased due to the introduction of new manufacturing innovations. This has included new approaches to joining the individual components such as extrusions and castings.

Figure 2: An illustration of the aluminium body structure of the Jaguar XJ that is constructed of aluminium alloy extrusions, sheet pressings and castings joined together by self-piercing rivets and adhesives. (Picture courtesy of Jaguar)

Welding methodologies have improved with robotic application of laser welding. A further innovation has been to replace welds with self-piercing rivets. The rivets, in combination with adhesive, improve fatigue performance creating stiff durable structures. Such technology is also ideally suited to robotic manufacture.

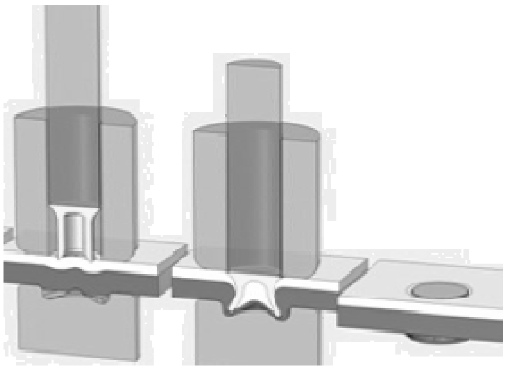

Figure 3: Self-piercing rivet process

Due to the time taken to test and then introduce new components into vehicles and the ongoing development still required to establish magnesium as a mature industry it is likely that it will take another 20 years to see magnesium as a major material of construction in vehicles.

However, the weight reduction advantages are substantial. Another factor that may encourage the application of magnesium alloys is their energy absorbing characteristics that CAST has recently found to be significantly better than aluminium and steel on an equal weight basis.

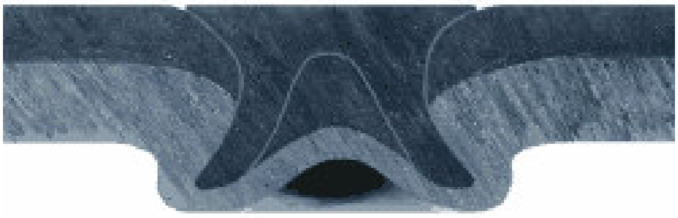

Figure 4: Self-piercing rivet sample (Picture courtesy of Jaguar)

Both aluminium and magnesium have advantages over heavier materials and are also readily recyclable. Aluminium is more corrosion resistant than magnesium and magnesium can be cast more readily into complex parts of very thin section compared to aluminium. This implies that new generation light weight vehicles will be largely constructed of both aluminium and magnesium components.

Although magnesium was introduced into cars such as the VW beetle after the Second World War it dropped out of favour because the cost of aluminium became significantly less than magnesium. However, over the last ten years the pressure for ongoing automotive weight reduction has led to a renewed interest in magnesium. Also, the cost of magnesium has significantly decreased over the last decade due to rapid growth in magnesium production in China. Many parts are already being cast in magnesium alloys with steering wheels and instrument panel (IP) beams becoming common.

While aluminium developments are well advanced there is still considerable development required to make magnesium useful in many parts of a vehicle’s construction. However, improvements are occurring every year and new applications are continually being introduced such as the one-piece fascia inner support on the 2002 Model year Jaguar S-Type X202 and the new Jaguar XF X250 (see Figure 6)

Other development is the hybrid body technique with whole areas constructed in aluminium joined by bolts to the steel body cell. This enables a balanced design for mass savings and cost of production.

There are some examples, mainly on the premium brands. Some current examples are: Land Rover Discovery L322, Range Rover Sport L320, Mercedes E & S class, BMW 5 & 7 series and Volvo V70 & S60 & S80.

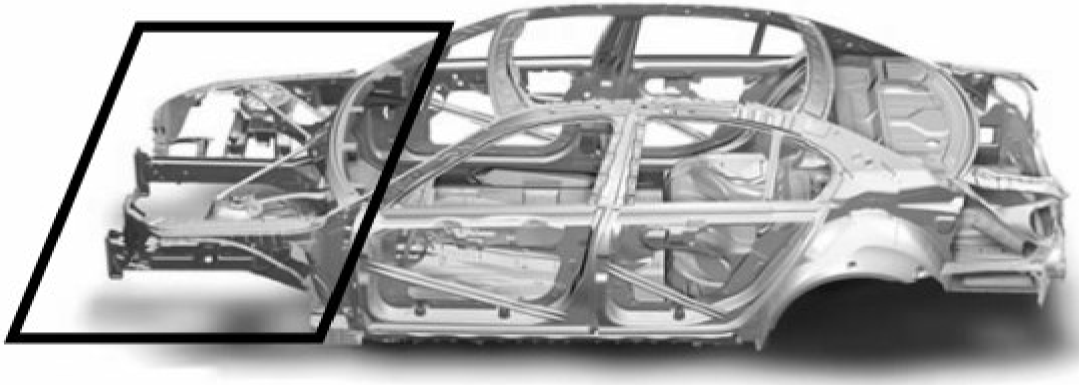

Figure 5: BMW Hybrid design with Aluminium front (Picture courtesy of BMW)

Automotive industry already possesses the skills, capabilities, manufacturing industries and technologies, and appropriate research and development infrastructure to support the introduction of light metals to automotive applications.

1.2. Economic demands

The cost of tooling for a new motor vehicle accounts for around 40% of the total investment necessary for its production. With the increasing demand for more frequent new motor vehicles, there is a trend towards reducing tooling costs, increased flexibility in production methods and shorter lead times. Implicit in this is the use of low investment cost materials for tooling and materials that can be processed faster and cheaper than conventional materials.

The increasing need to recycle or reuse materials has put additional constraints on motor vehicle manufacturers. The easy disassembly of motor vehicles places greater importance on the use of separate components that can be easily maintained and/or replaced. This puts up the initial cost of the motor vehicle but over the life cycle of the vehicle the cost of ownership goes down. The approach in the past has been on component consolidation, keeping production costs low but component replacement costs high.

Longer vehicle life and ownership is contrary to frequent new motor vehicle replacement and implies a balance needs be struck for the future.

1.3. Performance enhancements

Extended warranty periods for new motor vehicles have increased demands on component reliability and environmental resistance. To achieve these aims, materials have to possess predictable long-term performance retention. This has been achieved through improved quality of materials and materials processing.

2. A BRIEF REVIEW OF THE MAIN DEVELOPMENTS

The developments in materials for use in automotive vehicles have been rapid over the last decade. Some of the main developments, whilst not exhaustive, are described in terms of the major automotive product categories as follows:

2.1. Wheels

The use of pressed steel wheels still remains an economical solution for production motor vehicles, especially when combined with attractive clip-on injection moulded polymer wheel trims, creating an impression of cast wheels. Cast spun aluminium wheels have replaced normal cast aluminium wheels with lower levels of porosity.

Magnesium is catching on, but composite wheels have failed to get into production because of poor impact properties.

2.2. Seating

The modern motor vehicle seat forms an integral part of the suspension system, being designed to support the driver and passengers, while cushioning them against the continuous motion generated by irregular road surfaces.

The advances in foam technology to produce the required foam density and moulded shapes have enabled the desired comfort and ride expected today. The seat is designed to carry high abuse loads, and normally lasts the life of the vehicle with little or no maintenance. The seat frame in standard production motor vehicles is still predominantly a robust tubular metal welded space frame construction.

Today, the seat is a very important part of the vehicle's driver/passenger safety restraining system.

2.3. Vehicle interior

The use of polymers in vehicle interiors dominates, with just about every component which used to be metallic now plastic, apart from the fasteners.

Magnesium can be easily shaped by casting and makes a perfect solution inside the car as remains protected from corrosion and impacts. The dashboard has seen the most change and is now mostly a single moulding with inserts and soft touch features, eliminating hundreds of separate metal components. Figure 6 shows the raw casting for a magnesium alloy instrument panel. The first generation of these components had the advantage of replacing up to forty steel brackets, bolts, etc.

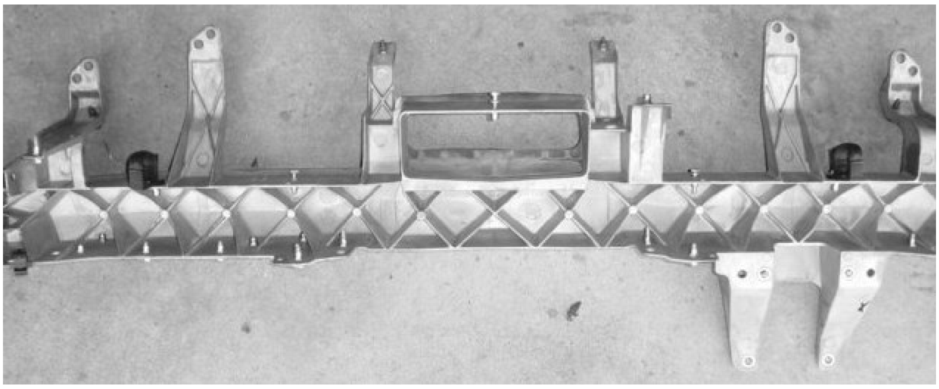

Figure 6: A cast magnesium alloy instrument panel (Inner dashboard beam)
The biggest advantage has been the reduction in manufacturing time and costs, and increased styling potential. The headline and door trim have seen similar developments, with sound dampening properties in the materials also important. All interior components have to meet strict fire and smoke regulations.

2.4. Cooling system

Cooling fans (moulded one-piece hub and blades) are now all polymeric, normally polypropylene, facilitating low cost high aerodynamic efficiency. As with heating and ventilation systems, the radiator is now an aluminium matrix with bonded polymer end tanks.

2.5. Engine applications

The intake manifold on modern fuel injection engines is relatively large and complex and made from cast aluminium but some use is being made of glass reinforced polymers for further weight savings. Engine blocks are now all cast aluminium with steel cylinder liners.

Stainless steel despite its cost is growing in use, especially for catalytic converters, exhausts and fuel lines.

Powder metallurgy has seen significant growth in production motor vehicles and used for components such as connecting rods, valve seats and guides, cam and crank sprockets. Its use will continue to grow as it realises considerable production benefits. Ceramics in the form of coatings have also grown in use, mostly in diesel engine applications on rubbing surfaces such as piston rings and valve facings to protect from wear and corrosion.

Most tanks, covers and ducting are now made from a variety of engineering polymers, although the engine oil sump is mostly pressed steel. All the applications above all add up to significant weight reduction compared to vehicles of a decade ago and importantly reduce the effect of the concentrated mass associated with the engine.

2.6. Drive train and suspension systems

Drive train and suspension systems comprise of highly stressed components and therefore put very high demands on the materials used. All components in these systems have been successfully replaced with composites in the last decade but are unable to satisfy the demands of high volume production, being used on niche vehicles only, if at all. Modern production methods and high quality conventional materials ensure high reliability and performance.

Most gearbox and differential cases are now all cast aluminium as standard for lightness.

2.7. Exterior body panels

High strength and strain alloy steel sheets with transformation-induced plasticity are now used for body panels. The properties of these alloy steels allow deep drawing, provide resistance to denting, and the opportunity to use lighter gauges to reduce vehicle weight.

There is still competition from aluminium and polymers but these tend to be reserved for high-end expensive and niche vehicle applications. Reinforced polymers, although offering high specific stiffness and strength with enhanced styling potential, have had limited success for production motor vehicle body panels, being unable to be made fast enough. As such reinforced polymers have only been used on niche vehicles.

2.8. Bumpers

Bumpers are now mostly incorporated within the front and rear valances of motor vehicles and so form a major part of the exterior styling. Polymer bumpers have become the norm and have been formulated for low/high temperature performance, toughness, and ultra-violet (UV) light stability and paint adhesion.

The latter property is required as most vehicles have colour co-ordinated bumpers matching the paint colour of the main body panels.

2.9. Heating and ventilation systems

Modern heating and ventilation systems in motor vehicles are very sophisticated, especially those that include air conditioning and climate control.

The predominant materials used are engineering polymers, polymer alloys and filled polymers in various combinations to achieve the desired mechanical and thermal stability properties.

High mould ability is expected of materials for a modern heating and ventilation system to produce the complex ducting required. The modern liquid filled heat exchanger has been standardised as an aluminium alloy matrix with bonded polymer end tanks.

2.10. Lighting

Headlamps have seen major changes with traditional glass reflector/lens assembly being replaced with polycarbonate and acrylic injection mouldings with high heat, optical and UV stability performance. This has realised considerably greater design freedom and vehicle styling capability. Modern headlamps, like rear light clusters, are multiple bulb and reflector configurations and therefore necessitate complex shaped mouldings.

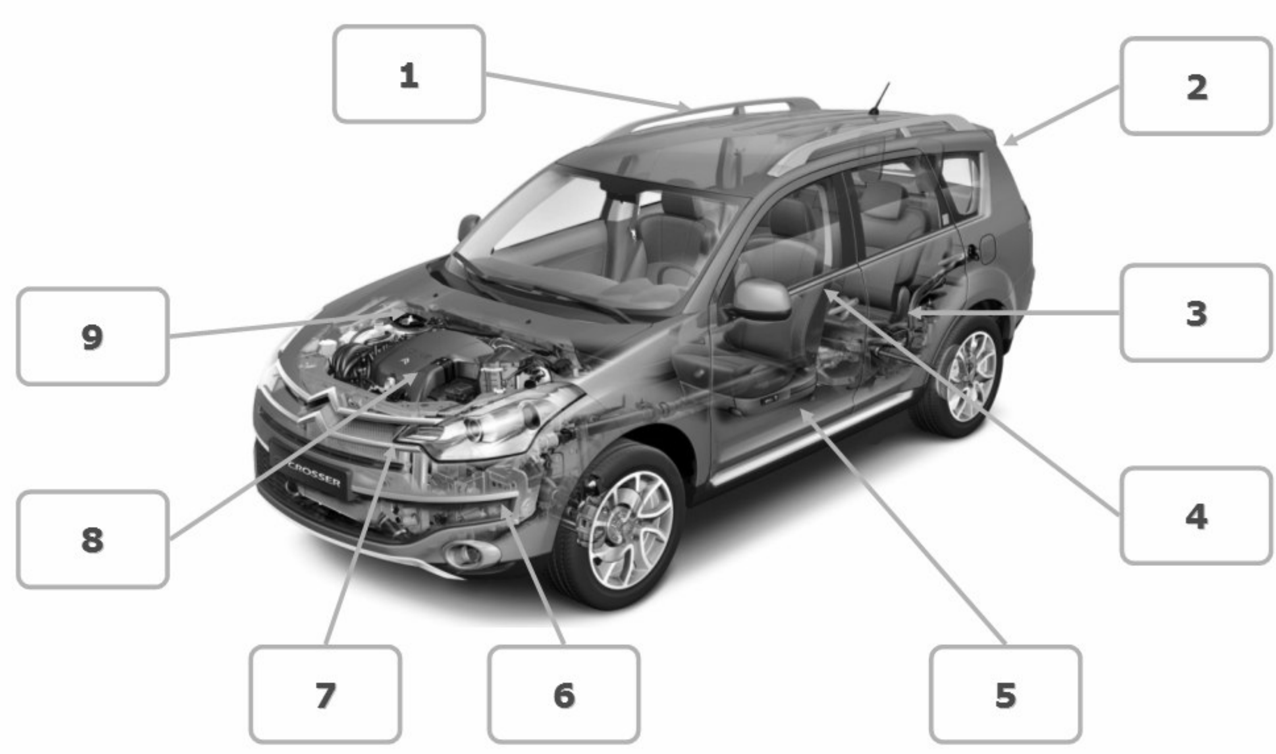

Figure 7: Hybrid technique application examples on a conventional stainless steel body shell

1. Cosmetics in aluminium

2. Aluminium rear hood

3. Aluminium chassis axels

4. Aluminium seat frame

5. Aluminium bonnet & door panels

6. Polymer bumpers

7. Magnesium inner reinforcement

8. Aluminium engine block

9.Suspension mountings & wishbones

3. Future developments

Competitor products have a direct influence on future design direction. Developments in technology for those that exploit them provide a step change in design direction. Legislation is noise in the overall process that either deflects or distorts design direction. The automotive example, although specific, serves to illustrate the development of the motor vehicle is typical of most product development in general.

Components tend to get developed in isolation of the rest of the product and at different rates, leading to sub-optimal solutions. Often the product as a whole does not realise its full potential for improvement because of the inability to improve every component simultaneously. This is also the case at inception, when it is normally cost effective for new products to make use of technology and materials available at the time. UV

Longer life span products, like a total motor vehicle, go through a series of technological developments, with individual components only exploiting technology developments. At some point the whole motor vehicle gets up-dated but even then a large proportion of the original vehicle is retained and carried over to save development time and production costs. Generally, the most of the engine and running gear last several so called face-lifts and even full body modifications before being fully changed.

Personal transportation is still a viable proposition but traffic congestion is becoming a major worldwide problem. The pressure on the need to control private vehicle usage has never been so high. Public transportation is receiving growing investment as a means of easing traffic congestion, but it will never attain the versatility of private motor vehicles. There is therefore a growing trend towards the use of private motor vehicles with higher fuel efficiency and lower pollution generation.

Materials development for the next decade is not easy to forecast, given the changes experienced over the last decade, but aluminium body techniques and technologies are now standard and there is no expectation of evolution. The up take of new materials and the technological opportunities realised as a consequence have been considerable in the automotive industry.

Reinforced polymers, whether particulate or fibre filled, carry on promising significant advantages over conventional materials. Reinforced polymers continue to develop in terms of production capability but have yet to make a major impact on the main body structure, only appearing as isolated components. A significant difficulty for future use is the ability to recycle highly integrated materials like fibre reinforced composites. Separating the constituents for recycling remains technically difficult and expensive however new techniques a way forward.

For high thermodynamic efficiency of an internal combustion engine, the operating temperatures need to be as high as possible. This has driven combustion chamber temperatures up over the last decade. The engines of the future will be operating at even higher temperatures than at present. There will therefore be an even greater role for coatings in engine components. To keep costs to a minimum, both metallic and ceramic coatings have and will continue to be applied to standard materials. Research progresses on metal and ceramic matrix composites for light weight high strength and stiffness engine components. These have been seen on racing engines but have not yet appeared on standard production engines.

The performance of adhesives has improved dramatically over the last decade and as a consequence their use has grown significantly in motor vehicles. This trend will continue, with adhesives being developed with even greater mechanical and environmental performance and as a consequence greater use being seen in more demanding applications like engine components and bodywork. A big advantage of adhesives over mechanical fasteners is the ability to distribute stress more evenly. A big hurdle has been their performance in crash test conditions, with adhesives having a tendency to peel quite easily as the substrate distorts.

The drive towards more automatic control of vehicle operating parameters is leading to greater demand for so-called smart materials. The incorporation of sensing elements within the structure of materials is being used to transmit/feedback information on such things as temperature and strains levels to onboard computers.

Legislation will continue to play an important part in the future direction of developments in materials and materials technologies. For the future, as now, environmental and safety legislation will impact motor vehicles design the most. This has a direct and indirect effect on the materials and processes used in the manufacture of vehicles. Considerations have been and will continue to be in the future placed on the total life cycle of the vehicle from conception to eventual destruction, rather than simply on its production. Amortising the cost of production and the cost of ownership over the total vehicle life is an important factor in new motor vehicle design and materials usage in the future.

4. Conclusions

The economical and environmental operating parameters placed on motor vehicles design and use will continue to remain highly restrictive with ever increasing legislation. The long-term use of internal combustion motor vehicles is uncertain, but for the short to medium-term because of the large support infrastructure its existence is assured. Developments in motor vehicles will obviously come from a variety of technological developments but as previously a major driver has been through developments in materials and manufacturing technologies.

Future developments will again be through a combination of existing materials development and the development of completely new materials, opening up new opportunities for motor vehicle performance and styling.

Functionally graded materials will see greater use in motor vehicles, allowing the properties of materials to be tailored to suit different applications. Although composites already possess this property, their use has tended to be structural, allowing optimum material utilisation. Other materials have this ability and if designed appropriately at the materials processing stage the resulting properties can produce say variable thermal conductivity, hence an ability to channel heat.

This paper has demonstrated the feasibility of intensive use of aluminium for car body development, mapped against forecasts, increases the quality of future design decision-making and the probability of successful new product introduction.

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