Use of magnesium alloys in optimizing the weight of automobile: Current trends and opportunities

Mutua James, J. M. Kihiu, G. O. Rading, and J. K. Kimotho

Abstract—Magnesium alloys are characterized by unique properties, which when fully exploited offer opportunities for structural applications in automobiles. This paper will identify the main features of magnesium alloys and highlight their uses in both structural and sub-structural applications. The current trends and opportunities in automobile materials substitution will also be presented. Further, the impact of weight optimization on automobile fuel consumption efficiency and pollutant gas emission will be highlighted. This paper will contribute positively towards research and development of magnesium intensive automobile meeting safety standards and passengers' comfort.

Keywords—Magnesium alloy, magnesium intensive vehicle, materials substitution, weight optimization

I. INTRODUCTION

The ever increasing fuel costs and automobile emissions have called for attention of the automotive fuel economy and the climatic changes evidenced nowadays. Technologies geared towards improving fuel economy and reduction of emissions including; fuel injection, improved engine aspiration, transmission technologies, four wheel drives, improved aerodynamics, tyres with lower rolling resistance and increased use of light weight materials have been used in production of vehicles [1]. Though many of the above measures have been used, the aspect of light weight has not been exhaustively addressed. The use of light weight materials for body and chassis components is an area that promises significant improvement in the fuel economy and gas emission in future. The use of alternative materials such as aluminium, magnesium and polymer matrix composites (PMCs) instead of steel in automobile structural members is sought to reduce the parts count and eventual weight of the vehicle. This is done without compromise to performance, safety and comfort of the passengers. Despite the superior mechanical properties demonstrated by polymer matrix composites, the carbon fiber structures face technical and economic hurdles which limit the possible elaborate advancements in such light weight materials. Magnesium is abundant and the eighth most common element. Seawater forms the main supply of 0.13% and its supply is virtually unlimited. Besides possessing very high specific energy absorption properties, structures designed for rigidity and meeting the safety requirements can be derived from it. Mechanical properties of this lightweight material depend on both chemical composition and microstructure. These mechanical properties define how a vehicle can be made lighter, how that affects the fuel consumption efficiency and also defines the strength and safety of the vehicle [2].

Mutua James, Department of Mechanical Engineering, JKUAT (phone: +2540720408251; fax: (067) 52164 ; e-mail: mutuajay@eng. jkuat.ac.ke).
J. M. Kihiu, Department of Mechanical Engineering, JKUAT (e-mail: kihiusan@yahoo.com).
G. O. Randing, Department of Mechanical Engineering, UoN
J. K. Kimotho Department of Mechanical Engineering, JKUAT

II. OVERVIEW

There is a notable increase in oil insecurity, geopolitical rivalry among vehicle manufacturers, price volatility in materials for fabricating most structural components of automobiles and climatic instability due to gas emissions. These factors coupled with the need to increase the vehicle fuel consumption efficiency stimulate the idea of weight reduction in both automobile and aerospace sectors. With less that 1% of the fuel energy injected into a vehicle being used to move the driver, which is the prime function of the car and 67-75% of the fuel use being weight related, the urge of making the vehicle much lighter has been the automakers driving force [3]. Advances have been made by automakers in achieving weight reduction by use of lightweight materials, plastics and integrated parts. The various mass reduction modes adopted include; downsizing, optimizing car design to minimize weight, replacing the materials used in its construction with lighter strength equivalent and by parts integration and holistic design approaches [1].

III. VEHICLE MASS DISTRIBUTION

Several studies have examined the distribution of mass within typical vehicles. The mass distribution in a passenger car according to component group puts the body as the single heaviest group at about 43% of the total vehicle mass. The powertrain and chassis follows in almost equal proportions at 27% and 26% of the total vehicle mass respectively. More recently, it has been established that within the body group, the unit-body, or body-in-white (b-i-w), is the single largest component, with about 28% of the total vehicle mass [4]. This mass distribution is shown in Fig. 1.

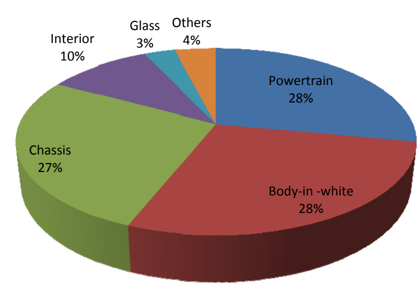

Fig. 1. Vehicle mass distribution by subsystem [4].

Further analysis showed that the engine is the single heaviest component within the powertrain group with about 14% of total vehicle mass, while the transmission represents about 5% of total vehicle mass. The chassis group is not dominated by any single component. However, the wheels and tyres are usually the single heaviest system representing only around 6% of the entire vehicle mass [1].

IV. DISCUSSION

A. Main features of magnesium alloy

Magnesium alloys possess higher specific strength than aluminium alloys and steels. For equivalent crush-loading capability, Mg extrusions exhibit higher potential than Al extrusions for weight reduction. Due to Mg's low density and high specific strength as shown in Fig. 2 [5], thicker rail can be made of Mg that possesses the same crush loading capacity as a steel rail, with less weight penalty than one made of Al extrusions. However, as with Al, Mg alloys exhibit lower energy-absorption capability than steel for the same geometry [6]. Two of the most important properties of a material to determine its strength are the modulus of elasticity and the tensile strength. Steel is known to be a very strong material which makes it suitable for most types of structural applications. Steel has a modulus of elasticity of around 200 GPa depending on the specific composition. Steel has a tensile strength in the range of 400 MPa to 3000 MPa [7]. Comparison of the physical properties can be summarized as shown in Table 1 [2].

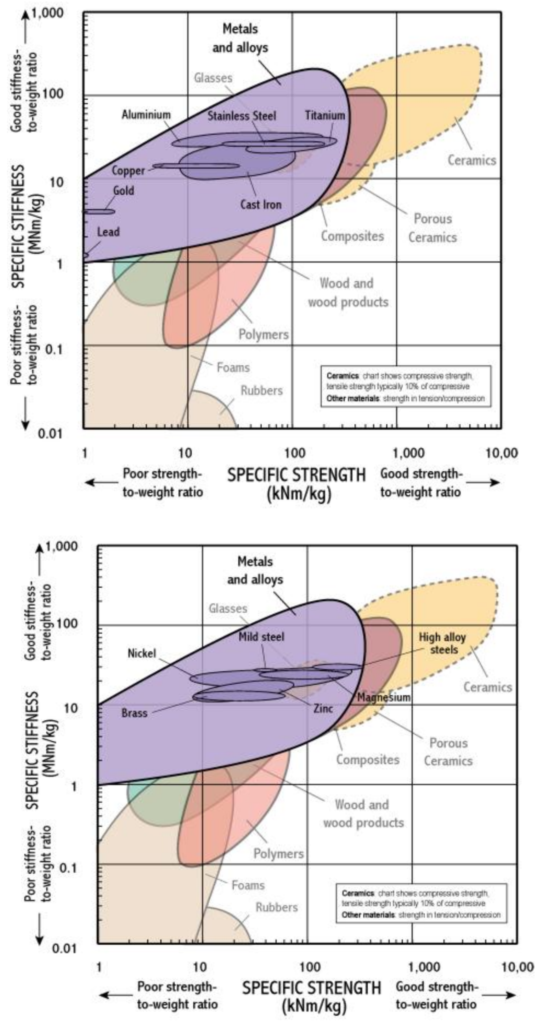

Fig. 2. Specific strength-specific stiffness of various materials [5].

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF STRUCTURAL AND SUB-STRUCTURAL MATERIALS [2].

Property	Magnesium	Aluminium	Iron
Atomic number	12	13	26
Atomic weight	24.32	26.98	58.7
Crystal structure	HCP	FCC	BCC
Density at 20°C (g/cm^3)	1.74	2.70	7.86
Elastic modulus (Gpa)	45	69	207
Melting point °C	650	660	1536
Boiling point °C	1105	2520	2862
Poisson's ratio	0.35	0.33	0.33
Specific strength(kNm/kg)	35-260	7-200	30-50
Specific stiffness(MNm/kg)	21-29	25-38	28-30

B. Current trends in material substitution

The average weight of a new car ranges between 1200 kg and 1400 kg while that of a light truck is approximately 2200 kg. Both cars and light trucks were at their lightest weight in 1987. This was facilitated by the use of aluminium intensive vehicles. However, the use of aluminium intensive vehicle was deemed unsatisfactory because of the increased roll-over and crash accidents attached to the lightweight. Since then, the weight has been generally increasing due to increased research and development. In 2006, the light trucks averaged 521 kg heavier than cars [8]. With this trend in mind, weight reduction took the center stage in order to curb the increase of accidents. The changes in the material composition are based on the following assumptions:

- replacement of 5% of conventional ferrous metals with high strength steel (the declining use of ferrous metals results from the application of less HSS to achieve the same resistance performances)
- replacement of 12% of ferrous materials with aluminium
- intensive replacement of 30% of ferrous materials with aluminium
- intensive substitution of 30% of ferrous materials with magnesium.

C. Recent developments in magnesium alloys and applications in automobiles

Magnesium, in its purest form, can be compared with aluminium. Because of its strength and lightness, it is used in several high volume part manufacturing applications, including automotive and truck components. Specialty, high-grade car wheels of magnesium alloy are called "mag wheels", although the term is often more broadly misapplied to include aluminum wheels. There are two forms of magnesium that are commonly used for most structural application, these are wrought and cast magnesium. Magnesium alloys, including cast and wrought alloys, can be broadly divided into two groups: Magnesium-aluminium alloys and zirconium containing alloys [9]. The common magnesium alloys that are in use in automobiles are as shown in Table 2 [10].

TABLE II
COMMON MAGNESIUM ALLOYS AND THE RECENT APPLICATIONS IN AUTOMOBILES [10].

Application	Form	Mg alloy
Bumper support beam	Extrusion	AZ31B
Steering column support	Extrusion	AZ31B
Air-bag channel and end caps	Extrusion	AZ31B and AM60
Two way seat adjust channel	Extrusion	AZ31B
Seat/channel guide	Extrusion	AZ61A
Electric-motor frame	Extrusion	AZ31B
Tubular bucket seat	Stamping /extrusion	AZ61A/ AZ31B
Two-piece mini-spare	Extruded rim section	AZ31B/ AZ61A
Valve cover	Deep drawn	AZ31B
Oil pan	Deep drawn	AZ31B
Battery tray	Stamping	AZ31B
Two-piece billet wheels	Spun rim	AZ61A
Forged wheel	forging	ZK60A
Rolled rim	Formed sheet	AZ61A

D. Current trends and opportunities in automobile materials substitution

Wrought magnesium and aluminium alloys could be used in auto bodies. The ability of both metals to be easily extruded gives them a clear advantage over steel. Unfortunately, there are few current automotive body applications for extrusions, but this is circular reasoning, because steel cannot be extruded. As the need to reduce body weight continues, extrusions could find increasing applications. Secondary structural parts, such as pillars, roof rails, window frames, and door sills, are obvious possibilities. Entire space frames, already made from aluminium alloy, could also be made from extruded magnesium components, or from a mixture of magnesium and aluminium. Considerable mass reduction especially in space frame led to a weight saving of 35% or more over the traditional steel unibody [2]. This leads to improved fuel economy and reduced emissions without downsizing the vehicle or compromising passenger comfort or safety. The best potential opportunities for wrought magnesium in body components lie in the use of extrusions on primary structures, such as space frames. There could also be some opportunities for seat frames, where magnesium castings are already being used and a combination of castings, extrusions, and possibly sheet could be competitive. The use of magnesium sheet in body panels would require development of an economical, high-volume, hot-forming process [11]. The possibilities for Mg in the powertrain component group entails magnesium castings replacing some of the iron and even Al castings in some housings and covers. Most new opportunities for Mg use in the chassis group require castings, but the opportunity clearly exists for Mg extrusions to replace fabricated steel components.

E. The impact of weight optimization on automobile fuel consumption efficiency and pollutant gas emission

Weight reduction is the most cost effective means to reduce fuel consumption and green house gases from the transportation sector. Generally, 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 a reduction of about 20 kg in carbon dioxide emission [12]. Based on vehicle simulations, it is assumed that fuel consumption reduces by 0.4 L/100 km for cars, and 0.5 L/100 km for light trucks for every 100 kg weight reduction. In other words, for every 10% weight reduction, fuel economy increases by 6% for cars, and 8% for light trucks [13].

V. CONCLUSION

In this paper, the current trends and opportunities associated with the use of magnesium alloys in optimizing the weight of automobile has been reviewed. Weight optimization in automobiles can be fully achieved by carrying out intensive substitution of ferrous materials with magnesium alloys of equivalent strength and stiffness for both structural and sub-structural applications. As noted, weight optimization offers the most cost effective means of managing fuel consumption efficiency and green house gases in the transportation sector. The finding of this paper is very useful in identifying the latest advances made towards attaining physically and economically feasible automobile.

REFERENCES

[1] Stodolsky F., Vyas A., Cuenca R., "Lightweight materials in the light-duty passenger vehicle, their market penetration potential and impacts," *International scientific journal*, pp. 3–9, 1995.

[2] Gaines L., Cuenca R., Stodolsky F., Wu S., "Potential Applications of Wrought Magnesium Alloys for Passenger Vehicles," *International Scientific Journal*, pp. 1–14, 1995.

[3] Amory B., Datta E. K., Nathan J. G., "Winning the Oil Endgame," *Rocky mountains institute snow mass*, 2005.

[4] Codd D., P. E., "Advanced, Lightweight Materials Development and Technology for Increasing Vehicle Efficiency," *KVA Incorporated*, December 9, 2008.

[5] Hgskolen N., "Material selection in product design," *4 klasse Ingenir design*, pp. 12–14, 2009.

[6] Greger M., Kocich R., Cizek L., "Possibilities of Mechanical Properties and microstructure improvement of magnesium alloys ," tech. rep., 2007.

[7] Schmidt J., "Building a Lightweight Future for American Transportation," *Digital commons@ university of Nebraska Lincoln*, pp. 3–7, 2008.

[8] *Vehicle Technologies Program-Light Vehicle Weight on the Rise*, 2007.

[9] Westengen H., "Magnesium alloys for structural applications; recent advances," *Journal de physique iv (Colloque C7, supplement au Journal de Physique 111)*, vol. Volume 3, 1993.

[10] Barnes, Fougner S., "Assessment of Availability of Magnesium for Automotive Applications," *Spectrulite Consortium*, 1994.

[11] Preez W., Damm O., Trollip N. G., John M., "Advanced materials for application in the aerospace and automotive industries," *CSIS Materials Science and Manufacturing*, pp. 4–7, 2009.

[12] Faresdick J., Stodolksy F., "Lightweight Materials for Automotive Applications," tech. rep., Global information inc., 2005.

[13] Cheah L., L. Heywood L., Kirchain R., "The Energy Impact of US Passenger vehicles Fuel economy Standards," *Cooperate average fuel economy (CAFE)*, 2009.