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ECONOMIC BENEFITS OF THE SUBSTITUTION OF TRADITIONAL CAST IRON AND STEEL BY ALUMINUM AND MAGNESIUM BASED MATERIALS IN AUTOMOTIVE SEGMENT

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ABSTRACT

The economic advantages of weight reduction of vehicles by substituting aluminum and magnesium alloys as well as Al MMCs and Mg MMCs for steel were considered. As demonstrated, each of proposed lightening route, either with Al and Mg alloys or Al and Mg MMCs combined with recycling at the end of product life, would result in significant economic benefits for the customer by complete returning of the investment in lightening, in most cases in the first part of the vehicle's lifetime plus environmental benefits in terms of reduced fuel consumption.

Key words: automotive, weight reduction, aluminum and magnesium alloys, Al MMCs, Mg MMCs

INTRODUCTION

The substitution of traditional cast iron and steel by aluminum, and in the last few years also by magnesium and advanced high strength steel (AHSS), is a major factor in the implementation of lightweight constructions in the automotive segment. The important reason for this is the automobile industry's voluntary commitment to support the Kyoto global warming agreements by achieving a 25% reduction in average fuel consumption for all new cars by the year 2005 compared to the level in 1990. Due to the well-known fact that a 10% reduction in vehicle weight yields approximately a 5.5% improvement in fuel economy, the 2005 model vehicles should be about 45% lighter than cars in 1990.

However, in opposition to weight reduction for improved fuel economy, there is also trend to interior weight increase of about 20-30 kg/year due to numerous improvements in comfort, safety and the implementation of many new electronic devices. This trend is not only apparent in large cars of the luxury class but also in small and medium size vehicles.

Table 1 presents a typical passenger car mass distribution. As evident, the chassis, body-in-white and power train comprise more than 80% of the total mass of the vehicle and hence are emerging segments for weight reduction. For achieving a 50% weight reduction, the application of advanced light materials such as aluminum, magnesium, AHSS and plastics should significantly reduce use of traditional ferrous materials in these three automotive groups.

Table 1 - Passenger car mass distribution [1]

Group	**Mass distribution (%)**
Chassis	27
Body-in-White	28
Powertrain	28
Interior	10
Glass	3
Other	4
Total	**100**

Although the use of aluminum in cars has been increasing for the past two decades exceeding 100 kg per vehicle in the material mix of a typical year 2000 model family sedan built in North America (Table 2), steel remained dominant (54%) with an aluminum content of about 8% and a magnesium content of only 0,2% [2].

In contrast with the situation on the market, numerous R&D studies recognized aluminum [3] and magnesium [4] as alternative automotive materials with a great technical and commercial future. So-called “alumobils”, “all-aluminum vehicles” and vehicles with a magnesium-intensive interior, body, chassis and powertrain are confidently predicted in the literature, and some prototypes, including the recent 3 liter Lupo, are known. In parallel, projects like the Ultralight Steel Auto Body-Advanced Vehicle Concept (ULSAB-AVC) [5] are the most recent additions to the global steel industry’s series of initiatives offering steel solutions to the challenges facing automakers around the world today. The ULSAB-AVC is a showcase for the latest high-tech steel grades for automotive applications-advanced high-strength steels (AHSS). Combined with innovative design and the latest manufacturing processes, these steels are key factors in its highly efficient structure and its capability to deliver exceptional fuel economy and safety at an affordable cost. To achieve the goals of high strength and light weight, a high percentage of advanced high-strength steel (AHSS) is applied in both body structures and other components.

In contrast to the significant progress made on prototypes, design and product engineers remain very conservative in the matter of substitution of advanced automotive materials for steel. In many cases only part-by-part substitution of aluminum and from case to case magnesium for steel or plastics occurs, mostly in the form of castings and forgings in the transmission, wheels, interior etc. Aluminum is well suited to the chassis and power train group. However, it is far from being a material of choice for mass production of auto bodies. Magnesium is mostly used in the form of castings [2] for interior applications. Recently, as part of a new trend, several magnesium power train, chassis and body projects dealing with development of high temperature, creep and corrosion-resistant alloys were launched in the USA and Europe [6, 7].

In order to achieve 50% lightening of vehicles compared to levels in 1990, the content of aluminum and magnesium-based materials in the automotive material mix must be increased significantly. Regarding the mass saving potential of aluminum, design engineers recognized that the requested mass reduction could not be achieved merely by displacing ferrous materials with aluminum. The solution lies in the higher implementation of magnesium as a structural material in vehicles. The target is a typical light vehicle in which about 600 kg of ferrous metal will be replaced by 150 kg aluminum and 100 kg magnesium. However, even in this target case the 50% mass reduction will not be gained. To achieve the goal of 50% weight reduction, an additional replacement of traditional cast iron and steel with advanced high-strength steel (AHSS) and more use of plastics will be necessary, as proposed in Table 2.

Table 2 - The current and predicted material mix for a typical family sedan in North America currently weighting 1200 kg

Material	**Material mix**			
	Current (in year 2000)		Predicted (in year 2009)	
	Mass (kg)	Portion (%)	Mass (kg)	Portion (%)
Steel	648	54	92	16
Iron	132	11	23	4
Plastics	96	8	132	23
Aluminum	96	8	138	24
Fluids/Lubricants	72	6	35	6
Rubber	48	4	23	4
Glass	36	3	29	5
Magnesium	2,4	0.2	87	15
Others	69.6	5.8	17	3
	1200 kg	**100**	**576 kg**	**100**

One of the most important obstacles in lightening by aluminum- and magnesium-based materials is the high cost. Although various legislative frameworks for environmental protection (such as the European CO_2 reduction program) will be an important driving force for further investments in lightening, for the automotive industry, cost of weight reduction represents a particularly important and sensitive issue. When light material cost issues are raised, most people tend to think of the material and manufacturing costs. However, there are additional, and usually quite large, costs associated with implementing any new material in the automotive segment. These costs include materials and process qualification and engineering design, near-net shape forming, machining, bonding, joining and recycling. Because advanced light metals as composites are significantly different from traditional ferrous counterparts, both the material and, in the case of composites, the processes used to manufacture them must be understood by the end-user, particularly when safety issues are considered. These qualification costs are incurred before any benefit of the light materials can be realized. In order to take full advantages of advanced light materials, components must be redesigned to exploit their advantages and also to minimize their limitations. Unfortunately, this re-engineering incurs additional costs. Hence, a cost/benefit analysis must be performed as early as possible when considering the insertion of new automotive materials.

In this study, the cost of substitution of aluminum- and magnesium-based materials (alloys as well as Al MMCs and Mg MMCs) for steel is studied in order to understand which particular technical and economical improvements should be achieved for final customer benefits.

REDESIGNING OF AUTOMOTIVE PARTS FOR ALUMINUM- AND MAGNESIUM-BASED MATERIALS

Automotive components and structures made in aluminum and magnesium are designed in a similar way to steel. When transposing a part from steel or cast iron to aluminum or magnesium alloy or composites, it is essential to establish a design for equivalent strength, stiffness and for strength and stiffness combined. In general, structures are subjected to multiple stresses, and the designer must ensure that the elastic stress calculated according to the Van Mises criterion stays below the minimum guaranteed proof stress.

Based on this, the thickness (t) ratios and mass (m) ratios of components made of the two materials for an equal stiffness design may be expressed as [2, 8]:

$$t/t_s = (E_s/E)^{1/3} \tag{1}$$

$$m/m_s = (d/d_s)\,(E_s/E)^{1/3} \tag{2}$$

where E and d are the elastic modulus and density of the materials, respectively. The properties of steel are designated with subscript S while Al, Mg, Al metal matrix composites (MMC) and Mg MMC properties are non-designated.

For a bending strength-limited design, such ratios become:

$$t/t_s = (YS_s/YS)^{1/2} \tag{3}$$

$$m/m_s = (d/d_s)\,(YS_s/YS)^{1/2} \quad (4)$$

where YS is the yield strength of the materials.

COST COMPARISON

For cost comparison, product engineers are most interested in the cost of a material relative to its mechanical and physical properties (Table 3), since this information reflects what the customer is paying for in terms of performance. Therefore, the performance cost index (PCI) of a lightweight material can be defined as its cost per unit volume times its thickness ratio relative to steel for equal stiffness or strength [2], as calculated in Table 4 using the most recent average prices in relative values of the steel price.

Table 3 - Comparison of Density and Mechanical Properties of Selected Materials [2, 9, 10]

Material	Steel	Wrought Mg	Mg MMC	Wrought Al	Al MMC	Plastics (PC/ABS)
Grade		AZ80-T6	AZ80/SiC/15p-T6	6061-T6	6061/SiC/15p-T6	Dow Pulse 2000
d (g/cm^3)	7.80	1.80	2.01	2.70	2.78	1.13
E (GPa)	210	45	73	69	91	2.3
YS (Mpa)	200	250	310	275	342	53
UTS (Mpa)	320	345	383	310	364	55
e (%)	40	11	1	12	3	5 at yield 125 at break

d-density; E-Elastic modulus, YS-Yield strength, UTS-Ultimate tensile strength, e-elongation
NA-Not Available

Table 4 - Cost Ratios Over Steel and Performance Cost Index (PCI) of Selected Materials

Material	Steel	Al 6061	Al MMC 6061/SiC/15p	Mg AZ80	Mg MMC AZ80/SiC/15p	Plastic PC/ABS
Cost ratio* per unit weight	1	3.36	4.8	7.5	10.6	6.14
Cost ratio per unit volume	1	1.17	1.7	1.67	2.73	0.83
PCI for equal stiffness	1	1.69	2.25	2.79	3.88	3.74
PCI for equal strength	1	1.00	1.30	1.49	2.19	1.61

*in relative values of the steel price

COST OF LIGHTENING

The cost of 1 kg weight reduction in a vehicle achieved by the use of aluminum and magnesium alloys and MMCs is reported in Table 5 as the cost (in relative values of the steel price) for both equal stiffness and equal strength. As evident, lightening is very expensive, which is the main reason why in the current generation of passenger cars there is only 8% of aluminum and 0.2% of magnesium. A vehicle weight reduction of 1 kg by substituting aluminum for steel costs 2.4 to 3.4 kg of steel, while the same lightening with magnesium alloys costs 2.6 to 4.8 kg of steel.

Lightening with Al MMCs is less expensive than weight reduction with Mg alloys. In contrast, lightening with Mg MMCs is definitely too expensive for automotive application. Lightening with plastic is also very expensive. Exceptions are parts in which the bending strength is the most valuable property.

Of course, these estimations are based on the current cost of raw materials.

In order to provide net economic benefits to the customer, the payback time for lightening should be shorter than the total vehicle lifetime. Let us propose first an automobile with 150 kg of aluminum (the prediction for European cars in the year 2009) in which 300 kg of steel is replaced. The cost of 150 kg lightening is calculated to be about 1275 USD. By adding the investment cost for entry into mass production and the cost of development and engineering, which are estimated to be about 125 USD per vehicle, the total cost of lightening becomes 1400 USD. Taking into consideration that such a weight reduction improves fuel economy byabout 6.6% and regarding the existing cost of fuel in the EU, the payback will complete after driving approximately 45 000 km. The payback interval will become significantly shorter (just about 8500 km) if complete recycling of automotive aluminum (saving at least 80% of its initial value) is practiced. Also in the case of the most expensive lightening considered in this analysis (by Mg MMC), one can calculate that the payback is complete after driving approximately 100 000 km (without recycling) or just 20 000 km with the recycled value included in the payback. Lightening by Mg MMC is about twice as expensive than with aluminum (Table 5). The investment cost of entry into the market and the cost of development and engineering are estimated to be also about twice as much.

Consider further an automobile with 150 kg of aluminum and 100 kg of magnesium in which 600 kg of steel is replaced by these non-ferrous materials. A 350 kg lightening would cost about 3500 USD. By adding the investment cost for entry into mass production and the cost of development and engineering, which for this case are estimated to be about 300 USD per vehicle, the total cost of lightening becomes 3800 USD. Taking into consideration that such a weight reduction improves fuel economy by about 16% and regarding the existing cost of fuel in the EU, the payback would be complete after driving approximately 165 000 km. However, if complete rècycling of aluminum and magnesium were practiced, the payback would be complete after driving approximately only 33 000 km. Here, the economic benefit of implementation of magnesium as a structural material depends, beside the cost of virgin metal, on cost-effective high-yield recycling of magnesium automotive scrap [11]. Without saving its initial value through multiple recycling loops magnesium cannot become a material of choice for automotive application.

Table 5 - Mass saving over steel and cost of lightening

Material	Steel	Al 6061	Al MMC 6061/SiC/15p	Mg AZ80	Mg MMC AZ80/SiC/15p	Plastic PC/ABS
Cost * per unit weight	1	3.36	4.8	7.5	10.6	6.14
Mass for equal stiffness (kg)	1	0.50	0.47	0.39	0.37	0.65
Cost* for equal stiffness	1	1.68	2.26	2.93	3.92	3.99
Mass for equal strength (kg)	1	0.30	0.27	0.21	0.21	0.28
Cost* for equal strength	1	1.00	1.30	1.58	2.23	1.72
Mass saving over steel for equal stiffness (kg)	0	0.50	0.53	0.61	0.63	0.35
Mass saving over steel for equal strength (kg)	0	0.70	0.73	0.79	0.79	0.72
Cost* for 1 kg mass saving under equal stiffness	1	3.36	4.26	4.80	6.22	11.4
Cost* for 1 kg mass saving under equal strength	1	1.42	1.78	2.28	2.82	2.39

*in relative values of the steel price

CONCLUSION

The economic advantages of weight reduction of vehicles by substituting aluminum and magnesium alloys as well as Al MMCs and Mg MMCs for steel were considered. As demonstrated, each of proposed lightening route, either with Al and Mg alloys or Al and Mg MMCs combined with recycling at the end of product life, would result in significant economic benefits for the customer by complete returning of the investment in lightening, in most cases in the first part of the vehicle's lifetime plus environmental benefits in terms of reduced fuel consumption. Due to well-documented benefits for customers, current problems in the market acceptance of alternative automotive materials will depend in future more on technical than economical issues, although the cost of lightening will remain one of the key issues.

The collected results indicate that after achieving their technical and design maturity as well as efficient recycling practice, not just aluminum but also magnesium as well as Al-MMCs and Mg MMCs will all become automotive materials of choice.

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