Yugoslav Association of Metallurgical Engineers *UDC:669.721.5:621.73.046=20*
YAME

AZ80 AND ZC71/SiC/12P CLOSED DIE FORGINGS FOR AUTOMOTIVE APPLICATIONS-TECHNICAL AND ECONOMIC ASSESSMENT OF POSSIBLE MASS PRODUCTION

TOPLO KALUPNO KOVANJE PROTOTIPNIH AUTOMOBILSKIH DELOVA IZ MAGNEZIJUMOVE LEGURE AZ80 I KOMPOZITA ZC71/SiC/12P

VARUZAN KEVORKIJAN [1], TOMAŽ SMOLAR[2],
VUKAŠIN DRAGOJEVIČ[2] and DAVORIN LENARČIČ[3]

[1]ZRVK p.l.c., Maribor, Slovenia, [2]IMPOL d.d., 2310 Slovenska Bistrica, Slovenia, [3]LP MYCRON d.o.o., Ptuj, Slovenia

Primljeno: 17. 9. 2002.

IZVOD

U radu opisujemo dimenzioniranje i izradu prototipne automobilske klipnjače iz magnezijumove legure AZ80 i kompozita ZC71/SiC/12p. Da bi sačuvali iste funkcionalne osobine klipnjače, koju serijski izradjujemo iz aluminijeve legure 6061, smo klipnjaču dimenzionirali na osnovu mehaničkih osobina legure AZ80 i kompozita ZC71/SiC/12p. Klipnjaču smo izradili pomoću klasičnog toplog kalupnog kovanja. Ispitivanja mikrostrukture SiC čestica u kompozitu posle toplog kovanja so pokazala, da pri tom ne dolazi do oštećenja keramičke faze. Ivršili smo probe kidanja odkovanih materijala, na epruvetama dobijenim mašinskom obradom kovanih delova i utvrdili nezantno poboljšanje njhovih mehaničkih osobina.

Na osnovu izradjenih delova smo odredili smanjivanje mase klipnjače u odnosu na klipnjaču iz aluminijeve legure 6061 i čelika i ocenili ekonomske učinke takve zamene.

Ključne reči: Toplo kovanje u kalupu, magnezijumova legura AZ80, magnezijumov kompozit ZC71/SiC/12p, klipnjača, mikrostruktura, mehaničke osobine, smanjivanje mase prouzrokovano zamenom materijala

ABSTRACT

In this study, redesigning for equal functional properties and rapid prototyping of hot forged automotive parts based on commercially available wrought magnesium alloys (AZ80) and composites (AZ80/SiC/12p were performed.

To achieve the same functional properties in a forged automotive component irrespective of the structural material selected, an automotive connecting rod, currently mass-produced in aluminium alloy 6061, was redesigned for usage of wrought magnesium alloy (AZ80A) and particle-reinforced magnesium alloy matrix composite (ZC71/SiC/12p). By applying conventional hot forging technology, prototype connecting rods were forged, trimmed and heat-treated on a semi- industrial scale.

The microstructure of both as-extruded and hot forged species was examined and the tensile properties of AZ80, ZC71/SiC/12p, 6061 and 6061/SiC/15p testing bars machined from hot forged connecting rods were measured. Weight reduction in the redesigned connecting rods was determined and the substitution of magnesium and aluminium-based materials for steel was compared in terms of cost in order to demonstrate the main economic advantages.

Key words: Hot forging, AZ80 magnesium alloy, ZC71/SiC/12p magnesium composite, connecting rod, microstructure, tensile properties, weight reduction

INTRODUCTION

Wrought magnesium alloys have mechanical properties basically similar to those of aluminum and can be used for similar tasks, that is for structural applications with light to moderate loading conditions. The important reason for the steadily increasing usage of magnesium in the voluntary commitment by some leaders of the automotive industry to supporting 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 an approximately 5.5% improvement in fuel economy, 2005 model vehicles should be about 45% lighter than cars in 1990.

In order to achieve a 45% 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 necessary 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 would be replaced by 150 kg aluminum and 100 kg magnesium, resulting in about a 30% weight reduction. However, to achieve the goal of 45% 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 1.

Although the use of aluminum and magnesium in cars has been increasing for the past two decades and now exceeds 100 kg per vehicle in the material mix of a typical year 2000 model family sedan built in North America (Table 2), steel remains dominant (54%), with an aluminum content of about 8% and a magnesium content of only 0.2% [1].

In contrast to the actual situation on the market, numerous R&D studies recognized aluminum [2] and magnesium [3] as alternative automotive materials with a great technical and commercial potential. So-called "alumobiles", "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.

Table 1 - The current and predicted material mix for a typical family sedan in North America currently weighing 1200 kg

Tabela 1 - Posotojeći i predvidjen trend potrošnje pojedinih automobilskih materijala u američkim putničkim automobilima mase 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

In contrast to the actual situation on the market, numerous R&D studies recognized aluminum [2] and magnesium [3] as alternative automotive materials with a great technical and commercial potential. So-called "alumobiles", "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) [4] 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.

One of the most important obstacles in lightening by aluminum- and magnesium-based materials is their high absolute cost in comparison with steel and cast iron. The 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, so that for the automotive industry, the 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 from the light materials can be realized. In order to take full advantage 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.

Whereas wrought aluminum in the form of forged, extruded and rolled semi and finished products is extensively used in the automotive industry, wrought magnesium is only applied in very low percentage, mostly in prototypes. This is due to higher specific manufacturing costs, so that the use of magnesium wrought alloys is currently limited to special (non-automotive) applications.

The aim of several currently launched industrial projects is to improve wrought magnesium manufacturing technology for structural components by development of forming procedures and tailoring alloys and billet pre-treatment to improve formability and meet functional requirements for lightweight automotive, aerospace, railway and bicycle applications, thus enabling a breakthrough for wrought magnesium in transport applications. The main topics are hot extrusion and rolling, including continuous casting. Wrought Mg-alloy forging processes, as near net-shape forming technologies, have the potential for stimulating the production of lightweight applications. Especially aerospace and automotive components, with their high requirements on security and weight aspects, offer a wide range of applications for the use of forging processes.

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 with aluminum and from case-to-case with 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 [1] for interior applications. Recently, as part of a new trend, several magnesium power train, chassis and body research activities dealing with development of high temperature, creep and corrosion-resistant alloys were initiated in the USA and Europe [5, 6].

However, the material characteristics of wrought Mg-alloys and especially composites with a Mg matrix discontinuously reinforced with ceramic particles (Mg MMCs) require specific process know-how, which as yet is not sufficiently available. Therefore, attractive wrought Mg alloys and Mg MMCs forging processes are still reserved to a small group of forging companies. In order to establish the process parameters and develop our own in-house wrought Mg alloys and Mg MMCs forging practice, a semi-industrial forging trial was performed.

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 of 0.2%.

Based on this general principle, the thickness (t) ratios and mass (m) ratios of components made of the two materials for an equal stiffness design may be expressed as [1, 7]:

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

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

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:

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

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

where YS is the yield strength of the materials.

Practical rules and examples of component designs with alternative materials are summarized in [1, 7-10].

EXPERIMENTAL PROCEDURE

The wrought magnesium alloy AZ 80 (supplier Elektron) and the particle-reinforced magnesium alloy matrix composite (Mg MMC) (ZC71/SiC/12p; supplier Elektron) were used in the present work. As received cast billets (diameter 246 mm; length 600 mm) in the standard form with a machined finish were first hot extruded into 35 mm diameter rods in order to obtain a fine grain structure. The direct extrusion process was employed. The temperature for extruding AZ80 magnesium alloy was 350±25 °C, while the temperature for extruding ZC71/SiC/15p was selected to be slightly higher (420±25 °C). The pressure required for extrusion of AZ80 was 440±30 MPa, while in the case of ZC71/SiC/15p composite the applied pressure was 460±30 MPa.

A connecting rod (Fig.1) for an automotive application was selected for hot forging. A similar cedure and the same production line extensively used for industrial forging of aluminum alloys were selected for manufacturing the Mg and Mg MMC components, in this way providing the semi-industrial scale of work.

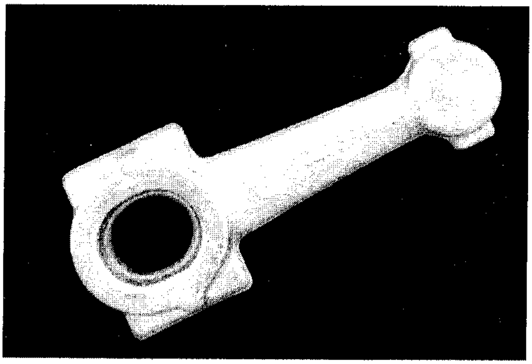


Figure 1 - Connecting rod made in forged ZC71/SiC/12p

Slika 1 - Klipnjača iz magnezijumovog kompozita ZC71/SiC/12p izradjena toplim kovanjem u kalupu

Each pre-extruded rod in AZ80 having a diameter of 35 mm and a length of 1 m was cut on conventional saws using blades with carbide-tipped teeth (speeds <70m/min combined with medium-heavy pressures) to obtain bars with length 300 ± 1 mm.

A 550 mm diameter saw blade, tipped with 48 PCD teeth, sectioned the extruded rods in ZC71/SiC/12p. The PCD tool, requiring no lubricant, cut through the billet in one pass. At a cut loading of 0.4 mm/tooth, the cut was completed in less than 10 seconds with an acceptable sawn surface produced on the cut faces of the billet.

A closed die with two cavities prepared by convenient HSM (High Speed Milling) technology was used for the forging trial, Fig. 2a.

After cutting and prior to forging, the bars were preheated to the required working temperature in a fuel-fired furnace operated without a protective atmosphere. The preheating parameters for AZ80 and ZC71/SiC/12p were 415±10 °C and 450±10 °C, respectively. Holding time in both cases was 1 hour. The average temperatures of the forging die for AZ80 and ZC71/SiC/12p were about 300±10°C and 400±10°C, respectively; these values were continuously monitored throughout the trials by embedded thermocouples. The optimum lubrication conditions both for AZ80 and ZC71/SiC/12p were found to be a dispersion of fine graphite in a light carrier oil or kerosene sprayed between each operation, and animal grease mixed with lead oxide "painted" onto the dies every third or fourth forging. This lubricant is swabbed or sprayed onto the hot dies, so that the carrier burns off and leaves a light film of graphite.

The process of forging was performed in one step by closed-die forging under a strain rate of $0.11 s^{-1}$. The forgings were obtained on the hydraulic press with a capacity of 1000 t (minimum pressure on hydraulic press was 200 MPa).

Forgings were hot trimmed using blades made of high-alloy steel hardened to 58 to 60 HRC. Hot trimming was accomplished in conjunction with the hot-forging process at a flash temperature of 205±10 °C for AZ80 and 260±10 °C for AZ80/SiC/12p.

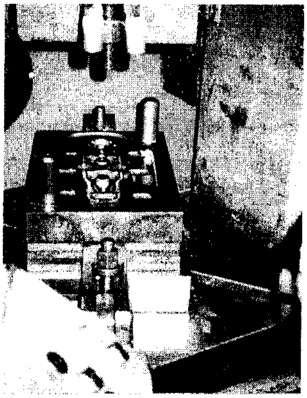
Forgings made in AZ80 were artificially aged at 177±5 °C for 24 hours to the final temper T5 and then cooled in still air. In contrast to this, forgings made in ZC71/SiC/12p were first solution treated at 430±30 °C for 8 hours and quenched in water at 65 °C. Then, the forgings were artificially aged at 180±10 °C for 16 hours to the final temper T6.

Cleaning of forged products was performed in two steps. First, the work pieces were blast cleaned to remove lubricant residue. After that, forgings were dipped in a solution of 8% nitric acid and 2% sulphuric acid and rinsed in warm water. The clean forgings were also dipped in a dichromate solution to inhibit corrosion.

The tensile properties of as-received as well as forged AZ80 magnesium alloy and ZC71/SiC/12p composite material were determined by constant velocity room temperature tension tests carried out in accordance with ASTM B557. 24 parallel tensile tests for each specimen were performed. Samples were first rough cut parallel to the direction of extrusion, directly from forging bars or forgings, and then machined on a lathe to tensile test specimens. Tensile tests were carried out in an Instron 8562 frame at a constant displacement rate (0.017mm/s).

Optical microscopy and SEM were also used to determine any potential sources of failure in the forgings, especially some possibly cracked particles of ceramic reinforcement. The final forgings were subjected to dimensional inspection on a coordinate-measuring machine.

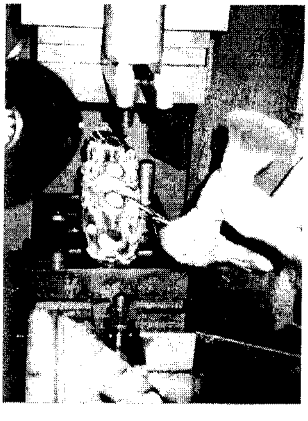
a)



b)

c)

d)



e)

Figure 2 - Various stages of hot forging: a) opening of forging die with two cavities, b) lubricating a hot die, c) insertion of forged bar, d) removing the forged part, e) forged connecting rods ready for trimming

Slika 2 - Pojedinačne faze toplog kovanja: a) otvaranje kovačkog kalupa, b) podmazivanje kovačkog gnezda, c) postavljanje kovačke palice na kalup, d) odstranjivanje odkovanog dela iz kalupa, e) odkovana klipnjača u paru, spremna za obrezivanje

RESULTS AND DISCUSSION

In the forging trial performed, samples of connecting rods were routinely prepared by closed die hot forging of both AZ80 and ZC71/SiC/12p on a semi-industrial scale.

The measured loss of material during cutting of the extruded rods was 1.5%. The quality of the cut surface was appropriate.

Non-trimmed forgings typically had a flash consisting of 25-35 % of the forged bar material.

All forged parts were dimensionally inspected; the findings confirmed that the tolerances specified in DIN 1749 could be achieved with absolute certainty.

The tensile properties of as-received and forged composite materials are summarized in Table 1. As evident, in both AZ80 and ZC71/SiC/12p, a slight improvement in the tensile properties of forgings in comparison with the as-received extruded bars was observed. In the case of ZC71/SiC/12p, the improvement of tensile properties proved that the forging trial performed did not introduce substantial damage to the ceramic reinforcement.

In most cases, the mechanical properties developed in magnesium forgings depend on the strain hardening induced during forging. This is particularly important for alloy AZ80, which is subject to rapid grain growth at forging temperatures. Strain hardening is accomplished by keeping the forging temperature as low as practical; however, if temperatures are too low, cracking will occur.

No failures in the microstructure of the forged AZ80 were observed under a strain rate of $0.11 s^{-1}$.

In the case of ZC71/SiC/12p, forged under the same strain rate, no breaking of ceramic particles was observed, Fig. 3.

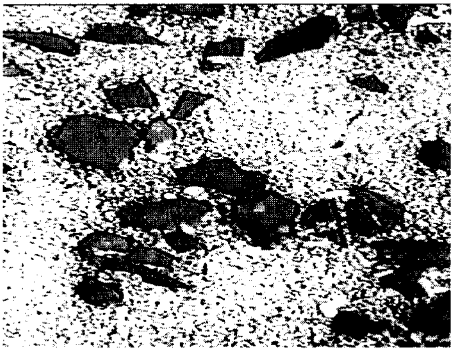


Figure 3 - Optical micrograph of SiC ceramic particles in ZC71 matrix showing no cracking after forging of connecting rod.

Slika 3 - Mikrostruktura nepoškodovanih SiC čestica u matrici iz legure ZC71 posle toplog kovanja u kalupu

However, in these samples some ***individual*** cracks were occasionally detected in the matrix, Fig.4. As evident in Fig. 4, the cracks found tend to grow through the matrix, by-passing individual ceramic particles. Regarding the high forming temperature (450±10 °C) applied and the non-appearance of cracks in non-reinforced AZ80 alloy, a possible explanation for individual cracks formed in ZC71/SiC/12p could be based on reduced ***local*** workability caused by a non-homogeneous distribution of ceramic reinforcement in the matrix, as illustrated in Fig. 5b. Usually, SiC particles in ZC71 matrix are distributed uniformly (Fig. 5a), reinforcing the composite material. In addition to this, regions with no ceramic particles were also observed, Fig. 5b. Because in these regions the matrix is not reinforced, one can expect that initial crack formation is favoured.

The experimentally measured tensile properties of as-received and forged composite material are summarized in **Table 2**, proving a slight improvement in the tensile properties of forgings in comparison with the as-received extruded bars.

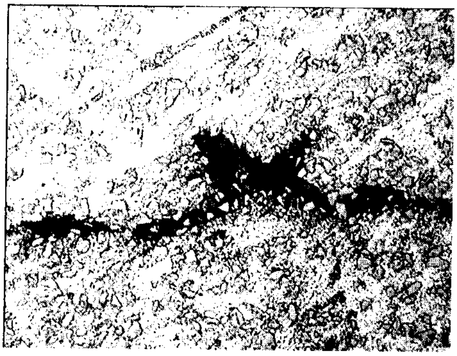


Figure 4 - Individual cracks observed in the matrix of hot forged ZC71/SiC/12p.

Slika 4 - Pojedinačne pukotine opažene u matric iz ZC71/SiC/12p.

Table 2 - Room temperature tensile properties of as-received (extruded) and forged AZ80 and ZC71/SiC/12p

Tabela 2 - Mehaničke osobine ekstrudirane i toplo kovane legure AZ80 i kompozita ZC71/SiC/12p izmerene pri sobnoj temperaturi

	YS (MPa)	UTS (MPa)	Elongation (%)
Material: AZ80-T5			
Sample:			
Extruded bar	262	379	8
Forged part	274	389	8
Material: ZC71/SiC/12p-T6			
Sample:			
Extruded bar	386	441	1
Forged part	397	453	1

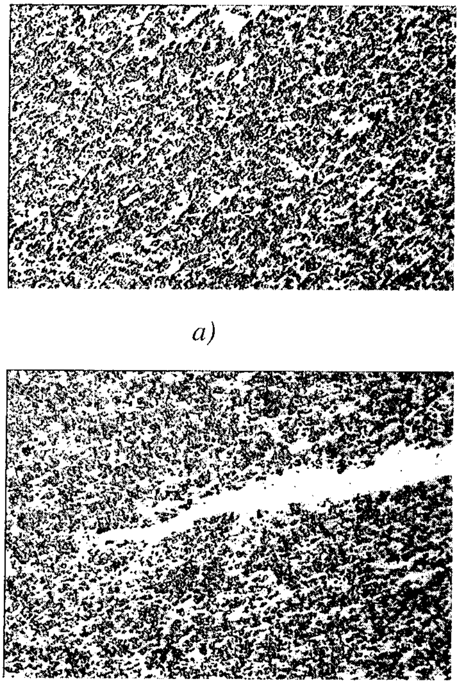


Figure. 5 - Optical micrograph of regions in as-extruded ZC71/SiC/12 sample with: a) completely homogeneous and b) irregular distribution of ceramic particles.

Slika 5 - Mikrostruktura ekstrudiranih uzoraka kompozita ZC71/SiC/12p a) područje sa homogenom raspodelom SiC čestica, b) karakteristična područja u ZC71 matrici bez SiC čestica.

Forging and trimming die-life could not be verified due to the limited number of forged pieces.

The experiments performed demonstrated that the same forging technique applied for non-reinforced magnesium alloys could also be used for forging of ZC71/SiC/12p.

Regarding cost competitiveness in comparison with both traditional ferrous and aluminum-based materials, product engineers are most interested in the cost of a material relative to its mechanical and physical properties, since this information reflects what the customer is paying for in terms of performance.

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 3 as the cost (in relative values of the steel price) for both equal stiffness and equal strength.

Table 3 - Mass saving over steel and cost of lightening

Tabela 3 - Smanjivanje mase klipnjače u odnosu na čeličnu i cena uštede na masi

Material	Steel	6061	6061/SiC/15p	AZ80	ZC71/SiC/12p
Cost * per unit weight	1	3.4	4.8	7.5	10.6
Mass for equal stiffness (kg)	1	0.5	0.5	0.4	0.4
Cost* for equal stiffness	1	1.7	2.3	2.9	3.9
Mass for equal strength (kg)	1	0.3	0.3	0.2	0.2
Cost* for equal strength	1	1.0	1.3	1.6	2.2
Mass saving over steel for equal stiffness (kg)	0	0.5	0.5	0.6	0.6
Mass saving over steel for equal strength (kg)	0	0.7	0.7	0.8	0.8
Cost* for 1 kg mass saving under equal stiffness	1	3.4	4.3	4.8	6.2
Cost* for 1 kg mass saving under equal strength	1	1.4	1.8	2.3	2.8

*in relative values of the steel price

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 150kg of aluminum (the estimate for European cars in the year 2010) in which 300 kg of steel is replaced. The cost of 150kg lightening is calculated to be about 1275USD. By adding the investment cost for entry into mass production and the cost of development and engineering, which are estimated to be about 125USD per vehicle, the total cost of lightening becomes 1400USD. Taking into consideration that such a weight reduction improves fuel economy by about 7% and regarding the existing cost of fuel in the EU, the payback will complete after driving approximately 45000km. The payback interval will become significantly shorter (just about 8500km) 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 100000km (without recycling) or just 20000km with the recycled value included in the payback. Lightening with Mg MMC is about 65% more expensive with aluminum (Table 3). The investment cost of entry into the market and the cost of development and engineering are estimated to be about twice as much.

Further consider an automobile with 150kg of aluminum and 100kg of magnesium in which 600kg of steel is replaced by these non-ferrous materials. A 350kg lightening would cost about 3500USD. 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 300USD per vehicle, the total cost of lightening becomes 3800USD. 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 165000km. However, if complete recycling of aluminum and magnesium were practiced, the payback would be complete after driving approximately only 33000km.

CONCLUSION

Industrial production of Mg and Mg MMc forgings was successfully performed by closed-die hot forging as practised for aluminium alloys, introducing some minor adaptations.

These forging trials demonstrated that ZC71/SiC/12p could be forged under a strain rate of $0{,}11\mathrm{s}^{-1}$ without visible damage to the ceramic phase and only occasionally appearance of individual cracks in the matrix. Tensile tests performed on 24 parallel samples machined from connecting rods produced in ZC71/SiC/12p proved slightly better structural properties in comparison with the as-received extruded bars.

Dimensional inspection of the forgings confirmed that the tolerances specified in DIN 1749 could be achieved with absolute certainty.

The economic advantages of weight reduction of automotive components by substituting aluminium and magnesium alloys as well as Al MMCs and Mg MMCs for steel were also considered. As demonstrated, each proposed lightening route, either with Al and Mg wrought alloys or Al and Mg MMCs combined with recycling at the end of the product life, would result in significant economic benefits for the customer by complete return of the investment in lightening, in most cases in the first part of the vehicle's lifetime.

The economic analysis projected on the example studied in this work (a lightweight connecting rod made in magnesium alloy AZ80 and ZC71/SiC/12p) verified that the magnesium-based components are in competition with their functional equivalents produced from both aluminium and steel.

REFERENCES

[1] Luo, A. A. Magnesium: Current and Potential Automotive Applications. JOM. **2002,** *54* (2), 42-48.

[2] Vinarcik, J. E. Automotive Light Metal Advances, Part I: Innovative Designs and Emerging Technology. Light Metal Age, **2002**, *60* (5,6), 38-41.

[3] Stalmann, A.; Sebastian, W; Friedrich, H; Schumann, S; Droeder, K. Properties and Processing of Magnesium Wrought Products for Automotive Applications. Adv. Eng. Mater. **2001**, *3* (12), 969-974.

[4] Steel Industry Report, Ultralight Steel Auto Body, Advanced Vehicle Concepts. Adv. Mater. Proc. **2002**, *160* (3), 78-79.

[5] Powell, R. B. The USAMP Magnesium Powertrain Cast Components Project. JOM. **2002**, *54* (2), 49-50.

[6] Schumann, S.; Friedrich, F. The Usage of Magnesium in Cars-Today and in Future. In *Magnesium Alloys and their Applications*; Kainer, K. E., Ed.; Wiley-VCH, 1998; 3-13.

[7] ASM Handbook. Materials Selection and Design. Ed. Dieter, E. G. ASM, Materials Park, OH, 1998, Vol. 20.

[8] Ashby, F. M.; Brechet, Y.; Cebon, D. Selection Strategies for Materials and Processes. Adv. Eng. Mater. **2002**, *4* (6), 327-334.

[9] Ashby, M.; Brechet, Y. Materials Selection for a Finite Life Time. Adv. Eng. Mater. **2002**, *4* (6), 335-341.

[10] Aluminium in Cars. Pechiney Automotive, Rhenaly, 1998, pp.52-61.