DEVELOPMENT OF MAGNESIUM-MATRIX COMPOSITES FOR POWER TRAIN APPLICATIONS

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SUMMARY: As a result of the demands made in transport technology, particularly in automobile, to use more light materials it is also necessary to fully utilise the potential of light metal alloys. This can imply substituting aluminium alloys by magnesium alloys, for example aluminium casting alloys in power train parts which have only become established in that few years. Experience has shown that there are limits to such substitutions as the high temperature properties required may not be realised. In particular, the creep resistance and fatigue properties at elevated temperatures and the high coefficient of thermal expansion may be the limiting factors. Reinforcement by short fibre or hybrid material can produce composites which fulfil the technical requirements. In this paper a survey is presented of interesting material systems together with their production route. The influence of the matrix alloys and the reinforcements on the microstructure and properties of the composite materials are discussed. The potential for substitution with magnesium composites is demonstrated by examples of an aluminium piston alloy and a crankcase alloy.

KEYWORDS: Magnesium-matrix composites, short fibre reinforcement, hybrid reinforcement, squeeze casting, creep, automotive application, mechanical properties.

INTRODUCTION

Over the last twenty years it has proved possible to continuously reduce the fuel consumption of every generation of cars [1]. Further reduction is limited by the steady increase in their weight. Despite the demand over the years for a reduction in weight each class of car has shown in fact an increase. The reason for this results from the requirements for increased safety, e.g. side-impact protection and airbags, and increased comfort. In order to compensate for this increase in weight it is necessary to establish a different concept for weight reduction. The aim is therefore in many areas to adopt the structural light construction approach or to use increasingly light constructional materials. During the last three years magnesium alloys have become candidates as a result of the low density and the numerous economical production methods. Magnesium is an ideal material where components are produced by automatic casting methods, e.g. housings and instrument panels. Its use in power train units is also a strong possibility. In the 1940s [2, 3] and 60-70s [4] magnesium materials were being used in engine blocks of air cooled engines and gear box housings. With the introduction of water cooled engines and increasing performance of the drive units and hence increased operating temperatures it was necessary to discontinue to employ magnesium alloys as they were unable to provide sufficient hot strength, creep resistance and thermal cycling stability. The terms of reference have changed and the pressure to increase the use of light metal constructions has resulted in magnesium materials becoming increasingly important.

Materials for use in power train components must exhibit a complex property profile, which depends on the operating conditions. Components can be subjected to oscillating movement, e.g. pistons, piston pins or valve components which must exhibit high strength and fatigue resistance at elevated temperatures as well as temperature cycling resistance. In addition the tribological properties must be acceptable. A similar property profile must be realised in crankcases and cylinder heads where in the latter case the tribolocical properties are of secondary importance. Sufficient elevated temperature strength and long term stiffness is of primary importance for the application of main bearing covers in crank cases. A further interesting application is the gear box housing where the main requirements are hot strength and creep resistance. Traditional magnesium materials can only fulfil these requirements to a limited degree because magnesium materials are in general characterised by low strength at elevated temperatures, low Young's modulus and a high coefficient of thermal expansion which leads to very poor resistance to thermal fatigue [5]. In addition magnesium alloys have a low hardness and consequently poor tribological properties for many applications. An improvement of the whole range of desired properties is not possible using standard alloying procedures. Improvements of individual selected properties is, however, possible. Young's modulus and coefficient of thermal expansion cannot significantly be improved by alloying. The solution is to develop magnesium matrix composites. The scope for variation and flexibility of this technology enables the development of tailor made composite materials. The use of various matrix alloys and reinforcements such as ceramic fibres and/or particles leads to characteristic property profiles which depend on the nature, volume fraction and distribution of reinforcement as well as method of production. In some applications a partial reinforcement suffices which results in a reduction in cost for this advanced technology.

PRODUCTION OF MAGNESIUM-MATRIX COMPOSITES

Economical considerations are of prime importance when deciding on a manufacturing process. Consequently the use of continuous high performance fibres is ruled. The property profile required, as described above, can only be achieved in a few cases with particle reinforced materials as insufficient creep resistance can be achieved [6]. Appropriate reinforcements are short fibres or short fibre/particle mixtures (hybrid reinforcement). Table 1 lists the short fibres and particles which have been used for magnesium alloy composites. The materials used are alumina-short fibres, shopped carbon fibres or a hybrid of SiC- or Si-particles and short fibres. The reinforcement material must first be brought into an appropriate shape. This is usually accomplished by producing preforms, which is binding the fibres and/or particles using an inorganic binder into the required shape with a high open pore fraction capable of infiltration. The short fibres in hybrid preforms are necessary to produce a skeleton between which the fine particles are arranged. As a general rule the optimum volume fraction of reinforcement should lie between 15 and 25vol%.

Infiltration of the preforms is best carried out by squeeze casting. Other processes such as gas pressure infiltration in autoclaves is only suitable for batch production with low production rates. In addition the contact time of the molten matrix phase with the ceramic reinforcement is

Table 1: Properties of reinforcements used magnesium-matrix composites

	Alumina fibre Saffil®	Carbon fibre Sigrafil®	SiC-particles	Si-Particles
Producer	ICI Ltd	Sigri	various	various
Density [g/cm³]	3.3	1.76	3.2	2.34
E-Modulus [GPa]	300	239	400-420	113
Strength [MPa]	2000	3000	----	----
CTE [10^{-6} K^{-1}]	4.7	-1	4-5	7.6
Diameter [µm]	2-3	7	variable	variable
Length [µm]	30-150	variable	----	----
Price [Eu/kg]	55	40	5-20	5-20
Physically harmful	+	-	-	-
Availability	-	+	++	++

very long, which can lead to undesirable reaction between magnesium and fibres or particles. Such a reaction can have benefits if the reaction leads to additional reinforcement phases, e. g. in the system $Mg + Si \leftrightarrow Mg_2Si$. In squeeze casting the preheated preform is placed in the form. In direct squeeze casting the melt is poured into the form, the form closed and the pressure applied by the upper die [7]. The melt solidified in about 90sec including infiltration. In indirect squeeze casting the form is closed after insertion of the preform and the matrix is introduced through a feeder system an application of pressure to the casting piston. Indirect squeeze casting is particularly suitable for near net shape production of completely or partially reinforced components. It is also possible to cast in pre-infiltrated preforms local reinforcement of critical, highly loaded areas of components [8]. Matrix alloys can be primarily economical conventional magnesium alloys. It must be born in mind that the properties of the matrix exert a profound influence in many cases on the properties of the composites, e. g. an improvement of the mechanical properties at high temperatures of a non creep resistant alloy provides in some cases results, no better than those of non reinforced very creep resistant alloys. Consequently for such applications it is not appropriate to use composite materials because creep resistance can be achieved economically by conventional alloys. But in cases in which creep resistance is required combined with improved properties, e.g. CTE or thermal fatigue properties, the use of the advanced technology becomes important. The possibility of using systems with a wide range of properties enables the properties of a material with specific tailor made property-profile. Table 2 provides a list of the systems investigated potential.

STRUCTURE OF MAGNESIUM COMPOSITE MATERIALS INVESTIGATED

The microstructure of a composite depends on the choice of reinforcement, i. e. the type, shape and distribution of the fibres or particles. Since all materials produced in this work involved squeeze casting, preforms were used which contained a minimum of fibres. The preforms for hybrid materials contained at least about 7vol%. This implies, for the microstructure, that the fibres as a result of the preform manufacture as distributed planar isotropically. This orientation becomes more pronounced at higher fibre contents. The fibre orientation influences naturally the orientation dependence of the properties [9,10]. Figure 1 shows the various microstructures of magnesium composites for different alloy/fibre/particle combinations.

Table 2: Material systems investigated

Alloy	Composition	Saffil®	Sigrafil®	Saffil-SiC hybrid	Sigrafil-Si hybrid
Mg99,5	Mg99,5	**X**	**-**	**X**	**-**
AM20	MgAl2Mn0,4	**-**	**-**	**-**	**X**
AZ31	MgAl3Zn1	**-**	**-**	**-**	**X**
AS41	MgAl4Si1	**-**	**X**	**-**	**-**
AZ91	MgAl9Zn1	**X**	**X**	**X**	**X**
AZ91Ca	MgAl9Zn1Ca1	**-**	**X**	**-**	**-**
ZE41	MgZn4RE1	**X**	**-**	**-**	**-**
QE22	MgAg2RE2	**X**	**-**	**X**	**-**

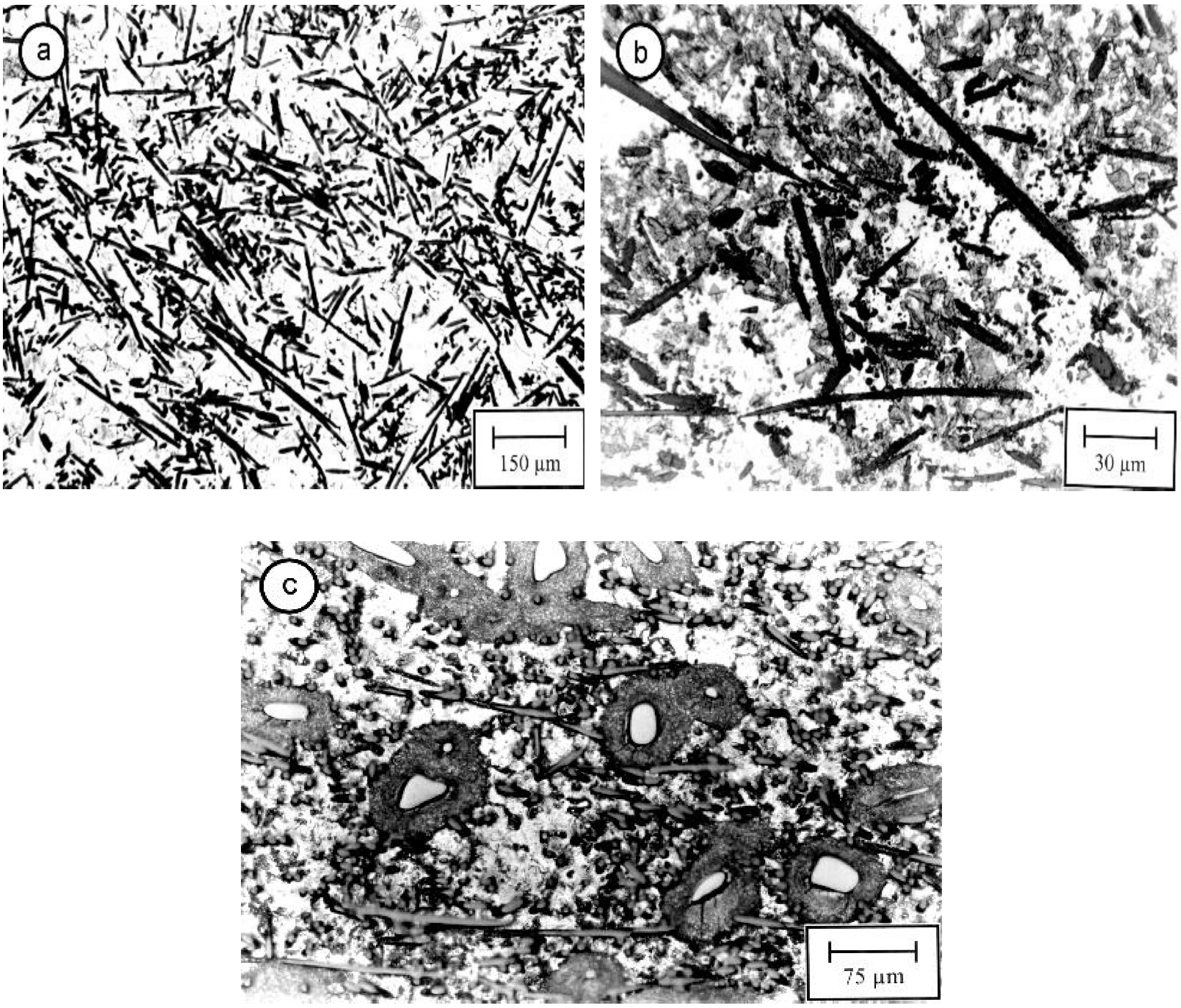

Figure 1: Microstructures of different magnesium composite materials:
a: AS41+20vol% C-fibres, b: QE22+22.vol% hybrid (7.5vol% Saffil+15vol%SiC),
c: AZ91+7.5vol% C-fibre+4vol% Si-particles)

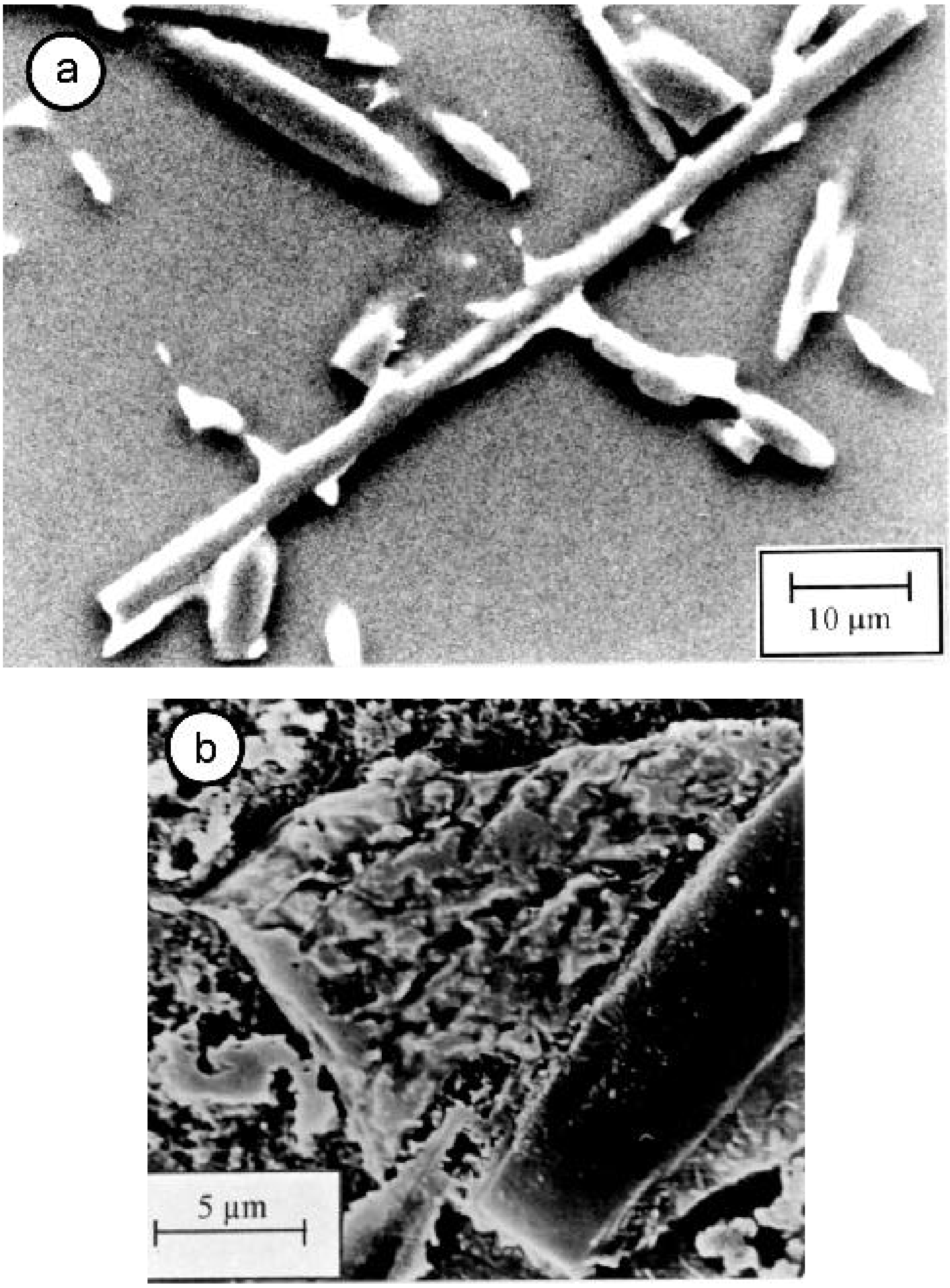

Figure 2: Scanning electron micrographs of interface regions in different composites:
a: QE22+20vol% Saffil ($Mg(Ag)_{12}Nd$-precipitates) at the interface,
b: Reaction formed Mg_2Si build from the SiO_2-binder (AS41+20vol% C-fibre)

All composite materials were produced by squeeze casting. They show only limited evidence of a reaction at the fibre or particle/matrix interface. Stronger reactions take place if the inorganic binder is present (max. content ~3-4vol%), which remains after production of a preform in form of porous Al_2O_3 or SiO_2. In some cases the reinforcement can completely be consumed e. g. in case of Al_2O_3 aluminium devolves as alloying element in the matrix or forms a intermetallic phase together with other alloying elements, e. g. rare earths. If a SiO_2 binder is used Mg_2Si is formed. In both cases the released oxygen forms MgO. The reaction products are generally discontinuous and located in the vicinity of the fibre or particle surface. Figure 2 shows, as example, the structure of the interface in the C-fibre/AS41 where Mg_2Si, Figure 2b, discontinuous precipitates were identified. In the system QE22+ Al_2O_3, Al_2Nd and MgO, Figure 2a, were observed and in AZ91/Al_2O_3-materials $Mg_{17}Al_{12}$ and MgO. These precipitates influence the strength at the interface i. e. the matrix/particle or fibre adhesion and thus the properties of the composite. Since, in general, for economic reasons heat treatments are avoided the cast structure determines the properties and particular the creep properties. The precipitates which influence the creep behaviour of the matrix must be optimally distributed. An ageing treatment would produce precipitate free zones in the neighbourhood of the interface, because precipitation e.g. of reaction products or precipitates typically for the alloy takes place preferentially on the reinforcement (Figure 3).

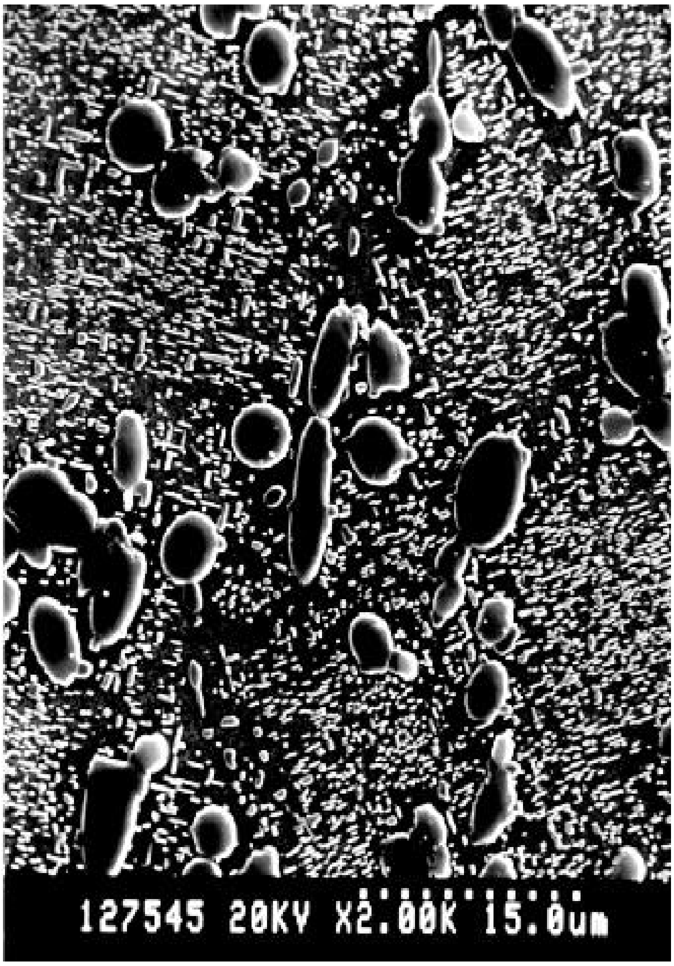

Figure 3: Scanning electron micrograph of a AZ91+20vol% Saffil-composites aged during creep tests at 250°C showing precipitate free zones near the fibres.

PROPERTIES OF THE COMPOSITE MATERIALS

As already stated the properties of the composite materials are determined by the type, shape and distribution of the reinforcements as well as the matrix properties, which in term depends on the thermomechanical history. Table 3 lists selected properties of various magnesium-matrix composites. It is apparent that the room temperature strength is scarcely improved if at all. The reason for this lies in the fact that only about 30vol% of the fibres lie in the direction of loading [9]. This applies also at higher temperatures but in this case softening of the matrix depending on the alloy composition takes place. Alloy AS41 and to a greater degree QE22 are more stable than AZ91 at higher temperatures and thus more creep resistant. This influences the hot strength and creep properties of the composites (Tables 3 and 4).Other critical properties in the use of magnesium at elevated temperatures are the high coefficient of thermal expansion,

Table 3: Properties of selected magnesium-matrix composites compared with non reinforced alloys. Materials were in as squeeze cast condition, only QE22 materials were in T6 condition. (YS: yield strength, UTS: ultimate tensile strength, CTE: coefficient of thermal expansion, RT: room temperature, n.d: not determined).

Material	YS [MPa]	UTS [MPa]		Elongation [%]	E-modulus [GPa]	CTE [$10^{-6}K^{-1}$]	Creep rate [1/s]	
		RT	250°C				150°C/ 70MPa	200°C/ 60MPa
AZ91	180	238	110	2.7	45	27.0	$8.5x10^{-6}$	$6.3x10^{-7}$
AZ91+20% Saffil	230	290	157	2.0	69	20.5	$7.0x10^{-9}$	$9.8x10^{-9}$
AZ91+22,5% SiC-hybrid							n.d.	n.d.
AZ91+20% C-fibre	220	242	117	0.5	66	19.5	$1.3x10^{-8}$	$2.6x10^{-9}$
QE22 (T6)	185	262	210	5.2	48	26.0	$4.6x10^{-9}$	$4.6x10^{-9}$
QE22+20% Saffil (T6)	270	290		1.2	70	20.0	$1.1x10^{-9}$	$4.6x10^{-9}$
QE22+20% SiC-hybrid (T6)	265	285		2.4	74	19.5	n.d.	n.d.
AS41					46	26	$5.8x10^{-9}$	$2.7x10^{-7}$
AS41+20% C-fibre	155	186	100	0.5	78	19.5	$1.2x10^{-9}$	$2.2x10^{-8}$

Table 4: Comparison of Mg-composite properties with those required for use as materials for pistons (AlSi12CuMgNi-T6) and crankcases (AlSi17Cu4Mg) [12,131]. (NDG: low pressure chill casting).

Property	Unit	AlSi12-CuMgNi (T6)	AlSi17-Cu4Mg NDG	AZ91Ca1+ 20vol%C-fibres	AS41+ 20vol%C-fibres	QE22+ 20vol% Saffil (T6)
Density	kg/cm³	2.7	2.73	1.9	1.8	2.1
YS (RT)	MPa	275-335??	210-240	200-240	150-160	250-275
UTS (RT)	MPa	295-360??	220-300	225-260	175-196	270-300
YS (200°C)	MPa	190-220??	160-180	152	110	215
UTS (200°C)	MPa	240-250??	200-250	160	120	245
Elongation	%	1-3	0.2-0.8	~0.5	~0.5	1.5~
Bending fatigue (RT)	MPa	120	100-110	90-125	90-100	100-130
Bending fatigue (200°C)	MPa	85	75-85	60	75	85-100
Creep rate 200°C/60MPa	10^{-9} 1/s	~0.6	n.d.	180.0	20.0	1.25
E-modulus	GPa	79.5	83-87	60-66	74	78
CTE (20-200°C)	10^{-6} 1/K	20	18	19-20	19.3-19.7	20
Thermal conductivity	W/mK	155	110-150	~140	n.d.	n.d.

which has a direct influence of the stability to thermal fatigue [9], are also improved Values can be achieved which lie in the range of those obtained for eutectic Al-Si piston alloys and below those for hyper eutectic crank case alloys (Table 4).

The creep properties of magnesium alloys can be improved correspondingly by short fibre reinforcement. Figure 4 shows a comparison of creep results of various reinforced and non reinforced magnesium alloys. The creep specimen were tested under constant stress condition. Creep strain versus exposure time was recorded for 200°C and different stresses. From the creep curves the steady state creep rate for unreinforced alloys or the minimum creep rate for composite materials were calculated. This creep rates depending on stress applied are plotted in Figure 4. Such a presentation can be problematic because the temperature range chosen is critical to high for some magnesium alloys. In this range creep behaviour changes directly from primary to tertiary creep with rapid failure. In the short fibre reinforced composites the creep rate decreases with increasing time. Only small strains are achieved. The diagram in Figure 4 also shows the influence of the creep properties of the matrix alloys on the creep properties of the composites based on the same alloys, i.e. the high creep resistant alloy QE22 forms also the best creep resistant composite.

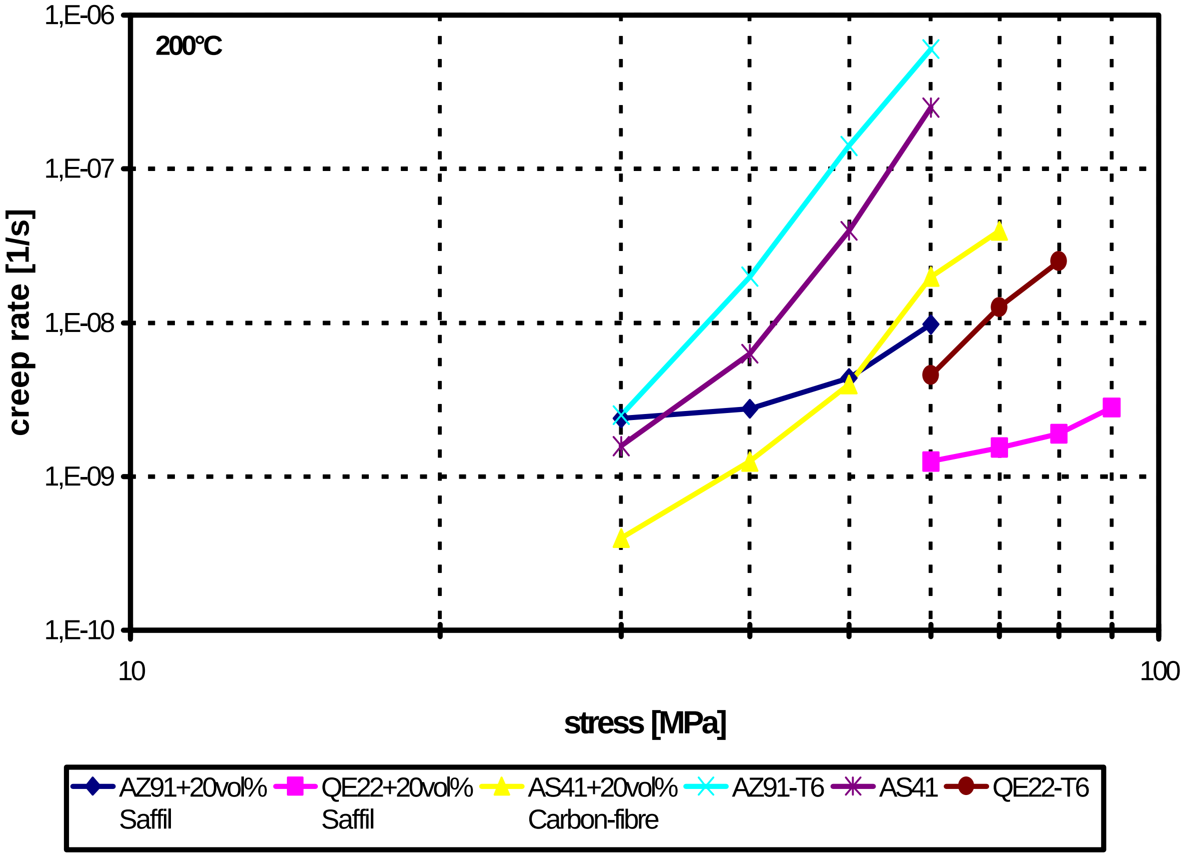

Figure 4: Dependence of the creep rate on stress for selected squeeze cast magnesium alloys and composites

CONCLUSIONS

It could be shown that squeeze casting is a suitable technique for producing magnesium-matrix composites reinforced by short fibres or hybrids. This technique results in improved elevated temperature strength and creep resistance compared to unreinforced material. Values of Young's modulus and coefficient of thermal expansion can be achieved which are of the same order as those for aluminium alloys. Since magnesium-matrix composites are relatively new there is a requirement to optimise them. The materials must also demonstrate their reliability. First tests, e.g. of piston alloys have shown, however, the potential of these materials. A straight forward 1:1 substitution of an aluminium piston by a carbon fibre reinforced magnesium piston for an internal combustion engine results in a weight saving of 30%. Motor and bench tests were carried out. The first long time test in a 4 cylinder engine was successful [14].

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