# Magnesium Pistons in Engines: Fiction or Fact?

N. Hort, H. Dieringa, and Karl Ulrich Kainer

**Abstract**

Magnesium alloys are already widely used in numerous applications in transportation and consumer products. Ways have been found to improve corrosion and creep resistance, formability in general, and processing routes have been optimized. But would Mg alloys also be suitable for use in an environment where friction, corrosion, thermal fatigue and creep resistance at elevated temperatures are issues? Due to lightweighting benefits, pistons would be an ideal application for Mg based materials. It is much more efficient to accelerate and to decelerate a lightweight material compared to a heavier one. Al alloy pistons are already fairly well established. But Mg could provide further benefits compared with Al due to its specific strength and mass. We will report the state of the art in Mg pistons, with our own and others approaches to improve properties and the challenges that Mg pistons have to face.

**Keywords**

Magnesium alloy • Piston • Corrosion • Creep

## Introduction

The question in the title is if Mg pistons are fiction or fact. Both can actually be answered with yes. The fact is that there are Mg pistons in service. But their application is limited to racing. In today's real life applications Mg pistons in internal combustion engines are still fiction regardless of its history. And this story leads back to the early days of Mg alloy development and its use in several applications [1–4].

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D. Orlov et al. (eds.), *Magnesium Technology 2018*, The Minerals, Metals & Materials Series, https://doi.org/10.1007/978-3-319-72332-7_53

After the synthesis of metallic Mg by Sir Humphrey Davy in 1808 it took a long time to establish production processes, to produce Mg in larger amounts (in the range of tons) and to find proper applications. Due to its affinity to oxygen and the bright flame of burning Mg, it was proposed as a possible flashlight during the early days of photography. This offered completely new possibilities and Mg was used in this area until the 1980s when Mg flashlights were replaced by electronic flashes.

However, flashlights are not a lightweight application where Mg is utilizing one of its advantages, its good specific strength. Also if there are other challenges like poor corrosion behavior especially in contact with other metals (and an electrolyte), its relatively poor creep performance and poor deformation behavior, Mg still has advantages.

The benefits of Mg as a lightweight material was already shown in the early 20th century [3]. Chemische Fabrik Griesheim used their patented Elektron alloy (Mg–Al) for an aircraft engine (1. Internationale Luftfahrtausstellung 1909, Frankfurt, Germany). However, after World War I, in Germany Mg got an increased attraction and alloy and process development for several industrial applications started successfully. The reason why Germany especially focused on Mg alloys and process development is not completely clear but resources, experiences and available processing opportunities were developed and magnesium was widely applied.

1921 seemed to be the year of Mg pistons. There are reports that DOW produced Mg pistons [4]. But more importantly, the German Ministry of Transportation (Reichsverkehrsministerium) issued a competition to develop a lightweight piston. Two Mg pistons and two Al pistons were awarded. The first two places went to:

1. Chemische Fabrik Griesheim (later bought by W. Mahle), Mg piston
2. K. Schmidt (became later Kolbenschmidt), Al piston.

In the years after the competition, the Chemische Fabrik Griesheim sold around half a million of Mg pistons mostly for internal combustion engines for cars.

It seemed that Mg pistons would be a superior or even equal alternative to Al pistons. Racing motor cycles had internal combustion engines with Mg piston. Mg pistons also were applied in different engines for automobiles at this time. Even in engines for airplanes Mg piston were widely used (Fig. 1). At this time, the regular use of Mg pistons in common internal combustion engines was a fact and companies used the achieved world records etc. for advertisements. But things changed and now Al pistons are most common in high performance internal combustion engines. What are the reasons that Mg pistons are now rarely used when they were widely used in the 1920s to the 1940s?

On reason could be that molten Mg cannot be handled as easy as molten Al. Molten Al always has a protective surface layer in the solid and in the molten state (Pilling-Bedworth ratio > 1). For molten Mg the Pilling-Bedworth ratio is in the range of 0.8. This means that the surface layer of MgO always cracks and allows further oxidation. Additionally the MgO film does not stick to either molten or solid Mg. The result is an ongoing oxidation that could lead to the ignition of molten Mg. Therefore, melt protection is necessary and increases the efforts during melt handling compared to Al alloys [5].


**Fig. 1** Advertisement for Elektron piston from Mahle for airplane engines, Germany, 1940

The obvious sensitivity of Mg and its alloys regarding oxygen is also one obstacle to its use in piston applications. Internal combustion engines combust fuel in a reaction that repeats several times per second. This also could lead to improved oxidation of a Mg piston in service. This especially important for the piston head. However, as the fuel is even more prone to oxidation (the reason why fuel is used in internal combustion engines) normally oxygen should be consumed by the combustion and is in general not available for the reaction with Mg.

The piston head is frequently heated up by the combustion, followed by rapid cooling immediately afterwards. This continued expansion and contraction is also known as thermal fatigue. The more heat resistant the piston material is, the better the performance of a piston in service. To overcome this problem metal matrix composites were already considered for piston applications.

In general, it also has to be stated that properties of standard Mg alloys at elevated temperatures often cannot compete with Al alloys. Creep resistance is here of importance. To improve creep resistance several methods are possible. Alloying is the first method. A combination of alloying elements that form intermetallic phases on grain boundaries and within grains have been state of the art for decades. WE series alloys work like this. According to the ASTM designation system [6] for Mg alloys, W represents Yttrium. E stands for rare earth elements and in this case mostly for Ce and Nd or a mixture of both (mischmetal).

Y forms intermetallics that are dissolved and re-precipitated during heat treatments. Mg–Y intermetallics can therefore be regarded as a useful measure to improve creep resistance. They form in the grains and can act as obstacles for dislocation movement. In WE additionally Zr is added to achieve a homogeneous grain size. Ce/Nd form intermetallic particles mainly on grain boundaries during solidification. Due to their low solid solubility these particles remain stable even at elevated temperatures and can pin grain boundaries, preventing grain boundary sliding.

Figure 2 shows tomographic image of a WE43 cross section. Here an enrichment of Y towards the grain boundary can be observed as well as the fact that Nd is mainly observed at grain boundaries. Moreover, the Zr particles are in the center of the grains.

Nevertheless, due to the use of rare earth elements (RE) it is relatively expensive. Moreover, WE series alloys have been designed as sand cast alloys and are not really suitable for high pressure die casting (HPDC). Due to the nature of the casting processes production of pistons from WE by sand casting does not fit industry requirements regarding mass

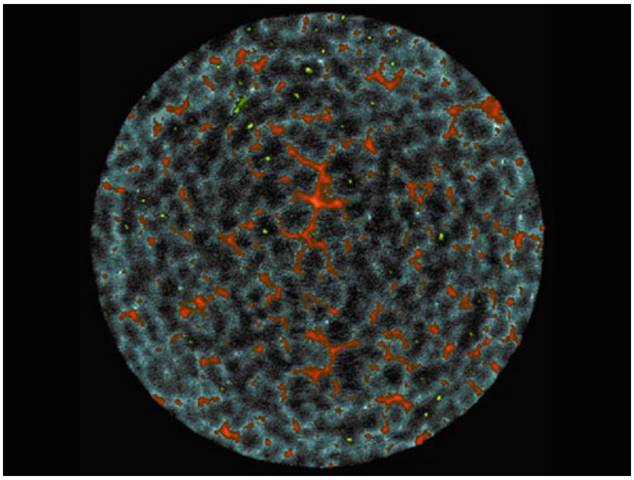

**Fig. 2** Microtomography of a WE43 alloy: blue is Y, red is Nd, yellow is Zr, the diameter of the structure is 1 mm [7]

production, dimensional accuracy, and cost efficiency. HPDC fits these requirements but the WE alloy system (like other creep resistant Mg alloy systems) have a relatively short freezing interval. This leads to difficulties regarding castability and mold filling and prevents its use in HPDC.

The mechanisms of alloying to improve creep performance can be easily transferred to other alloys to improve creep resistance. For instance, Ca or Sr can be added to Al containing Mg alloys, reducing the amount of $Mg_{17}Al_{12}$ by forming Al containing, producing high temperature stable intermetallics within grains and on grain boundaries. However, REs are expensive and any intermetallic forming during solidification has an impact on castability.

Using reinforcements is another possibility to improve creep resistance. Options available include long or short fibers, whiskers, micron or nano-sized particles or a mixture of fibers/whiskers and particles. Long fibers have been used in a project funded by the German Ministry of Research and Education (Long-fiber reinforced magnesium alloys, 03M0361, 1994–1997) [8]. Preforms made from long carbon fibers have been manufactured and were infiltrated by squeeze casting. It could be shown that this process is suitable to produce pistons. The pistons showed acceptable creep resistance and thermal fatigue was also not an issue.

However, the reinforced pistons suffered from other problems. The carbon fibers ended in the surface of the piston head and the piston shaft. Therefore, they could react with the environment. In the head, the fibers burned off during combustion. This resulted in a loss of properties and affected the function of the piston. Moreover, corrosion occurred at the body of the piston.

Another approach was undertaken in the project "Matalend—Materials and Process Engineering of new creep resistant Mg alloys for Thixomolding", also funded by the German Ministry of Research and Education (03N3085, 2000–2004) [9]. Thixomolding (TM) was the chosen production process and carbon short fibers reinforcements with a length of 250 μm as well as micron sized Si particles (100 mesh) have been used in combination with AZ91 and creep resistant MRI alloys. It could be shown that addition of Ca to Mg–Al alloys in combination with thixomolding is suitable to improve creep resistance by two orders of magnitude compared to materials produced by HPDC (Table 1) [10]. Moreover, corrosion resistance is also improved [11].

The carbon fibers align parallel to injection direction during thixomolding. Unfortunately, the process broke the short carbon fibers into smaller pieces (Fig. 3a) due to the screw movement in the thixomolding device. Therefore, the fibers lost their effectiveness and did not contribute to an improvement in strength at elevated temperatures.

The addition of Si particles also could be regarded as successful. They partially reacted with Mg from the matrix alloy. An interface consisting of $Mg_2Si$ formed and further reactions were avoided. Figure 3b shows Si particles in a matrix of MRI 230D. The Si particles appear in grey color, while the $Mg_2Si$ at the interface between matrix and particles appears in a blueish color. However, the Si particle were also broken during thixomolding and had final sizes in the range of 20–50 μm and therefore the efficiency of reinforcement was not as high as expected.

The project "Nano-MMC—Ultra-lightweight materials based on spray-formed Al alloys with high volume fraction of $Mg_2Si$ and nano-particle reinforcement", again funded by German Ministry of Education and Research (03X3007, 2005–09), applied spray forming in combination with forging to produce pistons [12]. To further improve properties, micron and nano sized particles were introduced. Even if in this project Al was the matrix, the new processing chain could be of interest for Mg as well. Again, feasibility was shown. But in this project the consortium failed to

**Table 1** Secondary creep rates ($s^{-1}$) of AZ91-D and MRI153 [10]

| Appl. stress (MPa) | AZ91-D | | MRI153 | |
|---|---|---|---|---|
| | HPDC | TM | HPDC | TM |
| 50 | $6.3 \times 10^{-8}$ | $4.3 \times 10^{-8}$ | $2.7 \times 10^{-9}$ | $4.2 \times 10^{-9}$ |
| 60 | $6.6 \times 10^{-8}$ | $6.2 \times 10^{-8}$ | $4.01 \times 10^{-8}$ | $1.3 \times 10^{-8}$ |
| 70 | $1.2 \times 10^{-6}$ | $8.9 \times 10^{-7}$ | $9.80 \times 10^{-8}$ | $5.0 \times 10^{-8}$ |
| 85 | $1.2 \times 10^{-6}$ | $1.2 \times 10^{-6}$ | $4.96 \times 10^{-7}$ | $3.3 \times 10^{-7}$ |

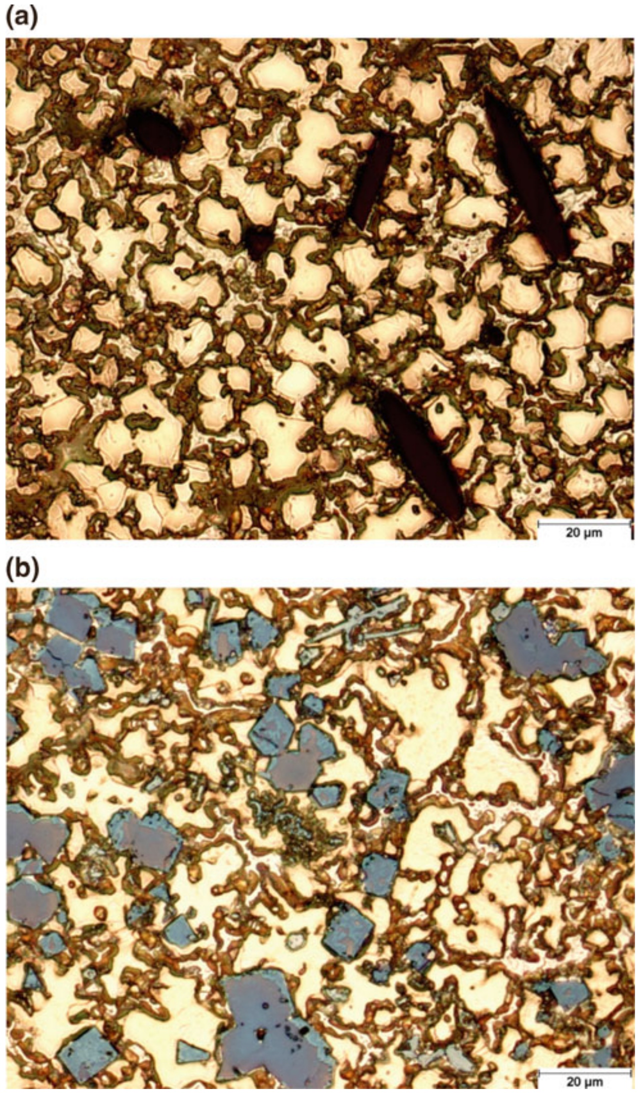


**Fig. 3** MRI 230 D with (**a**) carbon fibers and (**b**) Si particles

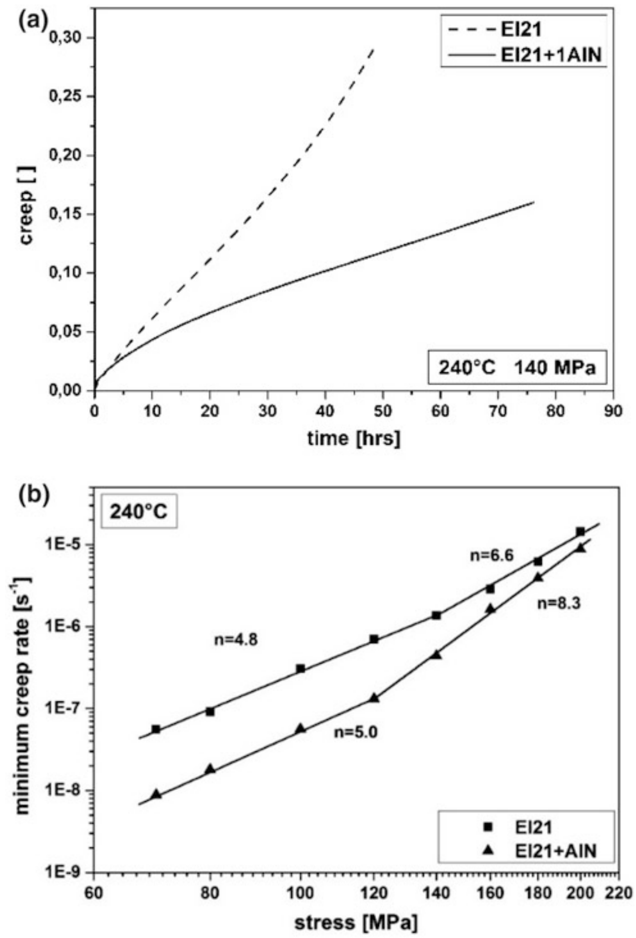


**Fig. 4** (**a**) Creep curves of Elektron21 and Elektron21+1 wt% AlN (**b**) and double logarithmic plot of minimum creep rate versus applied stress from tests performed at 240 °C [14]

incorporate the nano-particles into the matrix during spray forming. Around 80% of the nano-particles were lost.

The problem of incorporating nano-particles into a melt was solved within the EU project "Exomet—Physical processing of molten light alloys under the influence of external fields" (EU Grant Agreement 280421) [13]. This project dealt with the improvement of properties of Al and Mg alloys. External fields (electromagnetic, ultrasound) were successfully used to incorporate nano-particles in the lightweight metal matrix. The nano-particles could be homogeneously distributed. Their use in combination with the already creep resistant alloy also improved creep resistance further in the case of Elektron 21 (Fig. 4). Additionally the application of ultrasound did not only distribute the nano-particles homogeneously in the melt. It also led to a substantial grain refinement (Fig. 5).

Besides improved properties at elevated temperatures, wear has to considered. Obviously the body of the piston has to avoid direct contact with the cylinder liner. Therefore piston rings were established, to mitigate the effects of wear. However, these rings are also in contact with the piston itself and a can cause wear.

Last but not least there is the issue of corrosion. During combustion water is created. And Mg easily reacts with water and corrodes. While this is not a problem for the piston head, corrosive attacks can occur on cold parts of the piston e.g. the piston body.

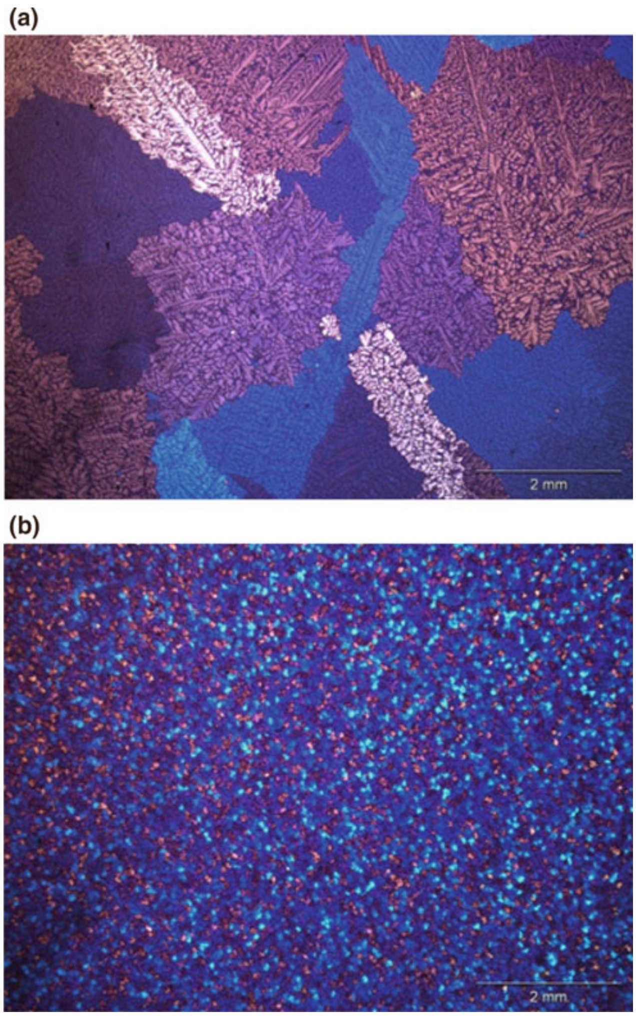


**Fig. 5** Microstructure of (**a**) AM60, and (**b**) AM60+AlN [15]

## Conclusions

What needs to be done to successfully introduce Mg pistons to modern internal combustion engines?

- Use a creep resistant alloy
- Prevent corrosion
- Select appropriate materials that withstand thermal fatigue
- Install a suitable production process.

A number of creep resistant alloys exist and can be processed without too many difficulties. Feedstock material can also be produced. Nano-particles can be effectively incorporated into the melt for further improvement of properties. And like Al pistons, Mg pistons should be forged to obtain an improved microstructure with an optimal property profile. Where necessary a coating should be applied to locally improve wear resistance and corrosion behaviour.

Even if e-mobility will be important in the future, internal combustion engines will not completely disappear in the near future. And due to this fact, Mg pistons can definitely contribute to a more efficient use of fuel. It is time for it!

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