A Die-Cast Magnesium Alloy for Applications at Elevated Temperatures

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Abstract

The application of magnesium alloys in internal combustion engines has advantages of lightweight, better damping and noise reduction and less vibration during operation. However, the applications of magnesium pistons in internal combustion engines are still difficult due to the demanding work environment and the rigorous requirements of the increased mechanical performance, thermal conductivity, and corrosion resistance at elevated temperatures. The development of high temperature die-cast magnesium alloys for piston applications is therefore challenging, as the high temperature mechanical performance, the die casting capability, and the thermal conductivity usually conflict with each other. Here we report a die-cast magnesium alloy for the piston applications at elevated temperatures, and the alloy development and the piston manufacturing process are introduced.

Keywords

Magnesium alloy • High pressure die casting • High temperature application

Introduction

Magnesium alloys have a great potential for structural applications in industries due to their significant weight savings, thus improving fuel economy and lessening environmental impact. The most significant magnesium applications are in castings, such as instrument panel, transfer cases, valve covers, various housings and brackets, and steering components in automobiles [1]. High pressure die casting is a high efficiency process for the massive casting of the magnesium alloys [2]. Commercial die-cast magnesium alloys of AZ91, AM50, and AM60 are widely used in industry, and these alloys offer excellent combination of cast-ability, corrosion resistance and room temperature mechanical properties [3, 4]. However, it is hard for these widely applied die-cast magnesium alloys to use at elevated temperatures.

The limitation of the industrially widely used die-cast AZ91, AM50 and AM60 magnesium alloys in high temperature applications is due to the poor creep resistance of these Mg–Al based alloys at the elevated temperatures, as the low melting point β–$Mg_{17}Al_{12}$ phase is not stable when the temperature increases to the level of ~175 °C [5]. Improvements of creep resistance at elevated temperatures have been made by the introduction of alloying elements such as Si, Ca, Sr, and rare earth (RE) elements to the magnesium alloys [6–9], and RE elements is well accepted helpful for the improvement of mechanical performance at elevated temperatures [10, 11]. There have been a number of successful Mg–RE based alloys developed for semi-solid processing [12], sand-casting and permanent-mould casting, including WE54/43 [13] and AM-SC1 [14], but it has proven very challenging to make these alloys cast-able in high pressure die casting, as high pressure die casting is demanding for the low solid-liquid solidification temperature range, hot-tearing resistance, die soldering resistance, and excellent fluidity of the alloy, while the heavy addition of the RE in these Mg–RE based alloys deteriorate the features that required for high pressure die casting.

For die-cast magnesium alloys focusing on applications at elevated temperatures, in the earlier time, modifications and improvements have been focused on the Mg–Al based alloy system by the addition of the alkaline earth and RE elements [6–11]. Nissan patent [15] on a Mg–Al–Ca–RE alloy and later a Honda alloy ACM522 (Mg–5Al–2Ca–2RE) [16]. Two separate alloy systems with combined additions of Sr and Ca but no rare-earths have been developed by Noranda

[17] and General Motors [18]. The Noranda alloy is a Mg–Al–Sr–Ca alloy with small amounts of Sr and Ca (AJX Alloy). The GM version is a Mg–Al–Ca–Sr alloy with substantial Ca and a small amount of Sr (AXJ Alloy) [19]. A major development was the AE42 alloy including 4 wt% Al and 2 wt%RE, and the addition of the RE can suppress the formation of the β–$Mg_{17}Al_{12}$ through the priority formation of the more thermal stable Al–RE containing intermetallics [20]. The AE42 alloy was further improved to the AE44 alloy with the increased addition of the RE of up to 4 wt% [5, 21]. Recently, a new Mg–RE based high temperature die-cast magnesium alloy HP_2^+ has been developed, which demonstrates better mechanical performance especially creep resistance at elevated temperatures than the previous reported high temperature die-cast magnesium alloys [22]. The HP_2^+ alloy includes (in wt%) 2.0–2.8La/Ce, 1.0Nd, 0.3Mn, up to 0.5Zn, less than 0.2Al and minor addition of Y or Be, and RE elements La/Ce acts as the cast base in the alloy rather than Al.

The application of magnesium alloys in internal combustion engines has advantages of lightweight, better damping and noise reduction and less vibration during operation. However, the applications of magnesium pistons in internal combustion engines are still difficult due to the demanding work environment and the rigorous requirements of the increased mechanical performance, thermal conductivity and corrosion resistance at the elevated temperature of at least 250 °C. The AE44 and HP_2^+ alloys might be the two promising high temperature die-cast magnesium alloys for applications at the elevated temperatures of ~200–250 °C, and it is hard for these alloys to be pistons alloys working at the elevated temperatures of at least 250 °C in engines. The development of high temperature die-cast magnesium alloys for piston applications is necessary but challenging [23], as the high temperature mechanical performance, the die cast-ability and the thermal conductivity usually conflict with each other.

In this work, the Mg–RE based Mg2.0La1.0Ce alloy was focused, and the effects of the RE element Y on the die-cast-ability and high temperature mechanical performance of the alloy were investigated. The optimized alloy with appropriate Y content was selected for the high pressure die casting trial of the magnesium piston.

Experimental

Material Preparation

The designed die-cast magnesium alloys, with the actual compositions (in wt%) of Mg2.0La1.0Ce0.3Mn0.3ZnxY (x = 0.5, 1.0, 2.0), were melted in the steel crucible using the electric resistance furnace. The covering gas of N_2 and SF_6 with a volume ratio of 240:1 was used for the protection of the melts. The commercial purity ingot of pure Mg was first melted in the crucible, then the pure ingot of Zn and the master alloys of Al–30 wt% La, Al–30 wt% Ce, and Al–5 wt% Mn were added into the molten Mg to make the desired composition. During melting, the temperature of the furnace was controlled at 710 °C, and the melts were stirred at least three times for homogenisation. Afterwards, the melts were held for 30 min, and then the melts were ready for high pressure die casting.

High Pressure Die Casting

The high pressure die casting was conducted on a 4500 kN cold chamber high pressure die casting machine. Two kinds of dies were applied for the high pressure die casting. The die shown in Fig. 1a was used for the high pressure die casting of the ASTM B557 standard round tensile test bars with the gauge dimension of ϕ6.35 mm × 50 mm, for the tests of the room temperature and high temperature tensile properties of the developed die-cast magnesium alloys. The die shown in Fig. 1b was applied for the high pressure die casting of the magnesium piston using the developed die-cast magnesium alloy. The casting dies were heated by the circulation of the mineral oil, and the shot sleeve was heated by the circulation of the compressed hot water. The prepared magnesium alloy melts were loaded into the shot sleeve for high pressure die casting, and the pouring temperature of the melts was controlled at 690 °C by the K–type thermocouple.

Tensile Tests at Room and Elevated Temperatures

The tensile tests of the die-cast ASTM B557 standard round tensile test bars were performed on an Instron 5500 Universal Electromechanical Testing Systems equipped with Bluehill software and a 50 kN load cell, at room temperature and the elevated temperature of 250 °C. Room temperature tensile test was conducted according to ASTM E8/E8 M [24]. During room temperature tensile test, the extensometer with a gauge length of 50 mm was applied for the monitoring of the strain, and the ramp rate for extension was set as 1 mm/min. High temperature tensile test was carried out according to the ASTM E21 [25] in which specimens were exposed to 250 °C for at least 40 min in an electrically heated air-circulating chamber before performing the tensile test. During high temperature tensile test, the straining rate for extension was set as 0.0002/s.

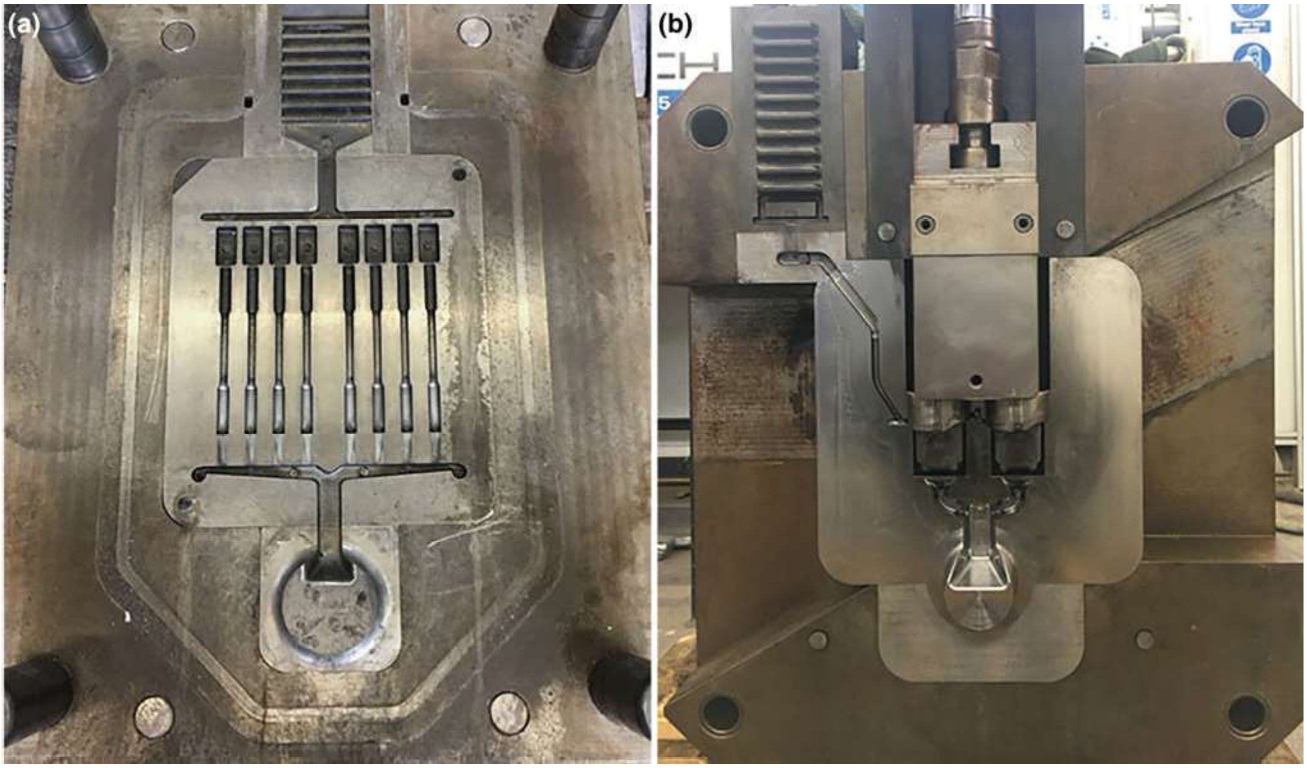

Fig. 1 **a** Die-set for the high pressure die casting of the ASTM B557 standard round magnesium tensile test bars, **b** die-set for the high pressure die casting of the magnesium piston

Results and Discussion

Die-Cast-Ability

Figure 2a, b, and c present the ASTM B557 standard castings made under high pressure die casting using the 0.5 wt% Y, 1.0 wt% Y, and 2.0 wt% Y die-cast magnesium alloys, respectively. Complete castings were obtained under the conditions of the 0.5 wt% Y and 1.0 wt% Y die-cast magnesium alloys, as shown in Fig. 2a and b, also no hot-tearing was observed in the castings, indicating the good die-cast capability of the 0.5 wt% Y and 1.0 wt% Y die-cast magnesium alloys. Incomplete casting was obtained under the condition of the 2.0 wt% Y die-cast magnesium alloy, as shown in Fig. 2c, indicating that the die-cast capability of the 2.0 wt% Y die-cast magnesium alloy was not good. Therefore, the die-cast capability of the designed die-cast magnesium alloy is acceptable within the Y content of 1.0 wt%, and the designed die-cast magnesium alloy became hard for die casting with the increase of the Y content of up to 2.0 wt%.

Tensile Properties at Elevated Temperatures

Figure 3 presents the tensile properties of the die-cast magnesium alloys at the elevated temperature of 250 °C, basing on the ASTM B557 standard round tensile test bars with the gauge dimension of ϕ6.35 mm × 50 mm that were cast under cold chamber high pressure die casting. Figure 3a shows the typical tensile stress-strain curves of the die-cast magnesium alloys in as-cast state with different Y contents. With the increase of the Y content, the strength of the die-cast magnesium alloys at 250 °C increased, while the ductility of the die-cast magnesium alloys at 250 °C first increased and then decreased. Figure 3b presents the average tensile properties of the as-cast die-cast magnesium alloys at 250 °C with different Y contents. The yield strength, UTS, and elongation of the 0.5 wt% Y die-cast magnesium alloy at 250 °C were 105 ± 2 MPa, 119 ± 2 MPa, and 10.7 ± 0.9%, respectively. The 1.0 wt% Y die-cast magnesium alloy provided the yield strength of 121 ± 3 MPa and UTS of 134 ± 3 MPa in conjunction with the ductility of 12.3 ± 1.0% at 250 °C, while the 2.0 wt% Y die-cast magnesium alloy delivered the yield strength of

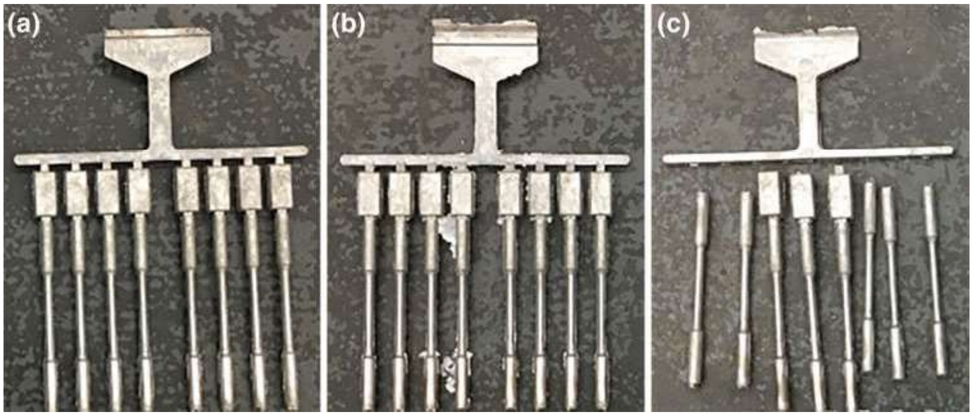

Fig. 2 ASTM B557 standard castings made under high pressure die casting. **a** 0.5 wt% Y magnesium alloy, **b** 1.0 wt% Y magnesium alloy, **c** 2.0 wt% Y magnesium alloy

136 ± 3 MPa and UTS of 155 ± 3 MPa in association with the ductility of 8.6 ± 0.7% at 250 °C. It should be mentioned that the mechanical properties of the high pressure die castings depend on the wall thickness of the castings, and the mechanical properties of the die castings usually decrease with the increase of wall thickness. For high pressure die castings, the wall thickness ranges generally between 2 and 7 mm. Here the wall thickness of the ASTM B557 standard round tensile test bars was in the high level of 6.35 mm, which was significantly higher than the 2–3 mm wall thickness applied in some reports, and the difference of the wall thickness should be considered when compare the mechanical properties between different reports.

Die-Cast Magnesium Piston

According to Sect. "Die-Cast-Ability", the 1.0 wt% Y die-cast magnesium alloy has good die-cast capability, while the die-cast capability of the 2.0 wt% Y die-cast magnesium alloy was insufficient. According to Sect. "Tensile Properties at Elevated Temperatures", the high temperature strength of the investigated die-cast magnesium alloys increases with increasing content of Y, and the 1.0 wt% Y die-cast magnesium alloy has good strength and ductility at the elevated temperature of 250 °C. Therefore, the 1.0 wt% Y die-cast magnesium alloy was chosen for the high pressure die casting trial of the magnesium piston using the piston die shown in Fig. 1b. Figure 4 shows the magnesium piston made under high pressure die casting using the 1.0 wt% Y die-cast magnesium alloy. Complete casting of the magnesium piston was well obtained, as shown in Fig. 4a. Figure 4b presents the top view showing the inner side of the cast piston, and the piston had good surface quality. Also no hot-tearing was found in the die-cast piston. Thus, the designed 1.0 wt% Y die-cast magnesium alloy demonstrated good die-cast capability for the manufacturing of the magnesium piston through the high efficiency high pressure die casting process.

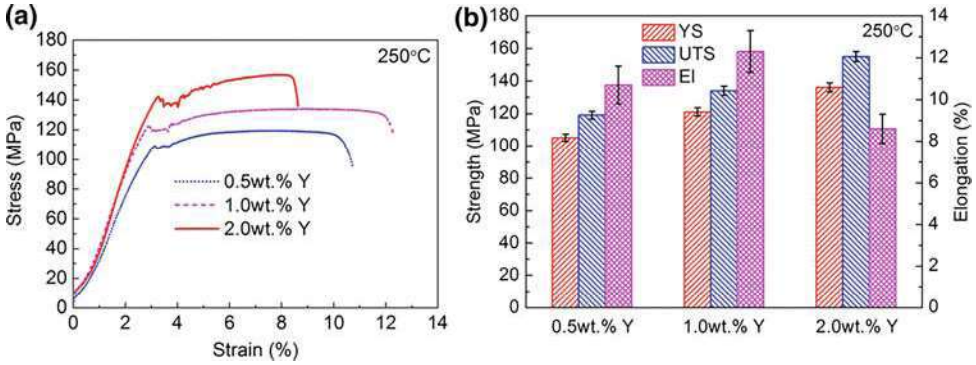

Fig. 3 Tensile properties of the die-cast magnesium alloys at the elevated temperature of 250 °C. **a** Typical tensile stress-strain curves, **b** average tensile properties

Fig. 4 Magnesium piston made under high pressure die casting using the 1.0 wt% Y die-cast magnesium alloy. **a** Complete casting of the magnesium piston, **b** top view of the magnesium piston

Conclusions

(1) The addition of the rare earth element Y decreases the die-cast capability of the Mg2.0La1.0Ce0.3Mn0.3ZnxY (in wt%) alloy, and the die-cast capability of the alloy is good within the addition of 1 wt% Y, while the die-cast capability of the alloy is not acceptable with the addition of the Y of up to 2 wt% Y.

(2) The high temperature strength of the Mg2.0La1.0Ce0.3Mn0.3ZnxY alloy increases with the increase of Y content. The yield strength, UTS, and elongation of the 0.5 wt% Y alloy at 250 °C are 105 ± 2 MPa, 119 ± 2 MPa, and 10.7 ± 0.9%, respectively. The 1.0 wt% Y alloy provides the yield strength of 121 ± 3 MPa and UTS of 134 ± 3 MPa in association with the ductility of 12.3 ± 1.0%, while the 2.0 wt% Y alloy delivers the yield strength of 136 ± 3 MPa and UTS of 155 ± 3 MPa in conjunction with the ductility of 8.6 ± 0.7%, at 250 °C.

(3) The Mg2.0La1.0Ce0.3Mn0.3Zn1.0Y die-cast magnesium alloy demonstrates good die-cast capability for the manufacturing of the magnesium piston through the high efficiency high pressure die casting process.

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