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An Analysis of the Development and Applications of Current and New Mg-Al Based Elevated Temperature Magnesium Alloys

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Abstract. The current status of research and application in the AZ(Mg-Al-Zn), AS(Mg-Al-Si), AE(Mg-Al-RE), AX(Mg-Al-Ca), ACM or MRI（Mg-Al-Ca-RE）and AJ（Mg-Al-Sr）series elevated temperature magnesium alloys are reviewed, will special attention paid to the effects of alloying elements and the control of second phases. The existing problems on the development of elevated temperature magnesium alloys are discussed.

Introduction

Since the 1990s, the use of magnesium alloys in the automative industry has been expanding at an impressive rate. The number of available Mg-based alloys, however, is very limited. At present, the widely used magnesium alloys are Mg-Al based alloys, but they are unsuitable for manufacturing drive-train parts operating at temperatures higher than 120℃ because of their poor creep resistance. Therefore, in order to expand the application of magnesium alloys, many research projects about the Mg-Al based elevated temperature magnesium alloys have been put forward, and much data have been obtained. Up to now, the Mg-Al based elevated temperature magnesium alloys which have been developed focus mainly on the following alloy series, such as AS(Mg-Al-Si), AE(Mg-Al-RE), AX(Mg-Al-Ca), ACM(Mg-Al-Ce-Mn) or MRI（Mg-Al-Ca-RE）and AJ(Mg-Al-Sr), etc [1-4]. The current status of research and application on Mg-Al based elevated temperature magnesium alloys are reviewed, and existing problems on the development of elevated temperature magnesium alloys are discussed.

Materials system of Mg-Al based elevated temperature magnesium alloys

In the past decade, the research on the Mg-Al based elevated temperature magnesium alloys has focused mainly on two aspects, the improvement of high temperature performance for AZ(Mg-Al-Zn) series and the development of new types of elevated temperature magnesium alloys. The research on Mg-Al based elevated temperature magnesium alloys were carried out based on the Mg-Al based binary alloys with the additions of alloying elements, such as Si, RE, Ca, Sr and others, then new types of alloys series, such as AE(Mg-Al-RE), AX(Mg-Al-Ca), AS(Mg-Al-Si), ACM or MRI(Mg-Al-Ca-RE), AJ(Mg-Al-Sr) and others, were developed.

Development and application of AS (Mg-Al-Si) series magnesium alloys

The early investigation on AS series alloys was carried out in the 1970s. At present, the AS series of alloys has been applied to gearbox and other components. The strengthening of AS series alloys is mainly achieved by fine Mg_2Si phase particles formed on grain boundaries. Since the Mg_2Si phase has a high melting temperature, low density, high elastic modulus and low thermal expansion coefficient, it is a very effective strengthening particle. However, some investigation results indicated that the creep resistant properties of AS series alloys can be improved greatly only when the Si-content is high [5]. Representative AS series alloys include AS41, AS21 and AS21X. The creep strength of AS41 alloy at temperature of 175℃ is slightly higher than AZ91 and AM60 alloy. Although the creep strength of AS21 alloy is higher than that of AS41 alloy because of its low Al-content, its room temperature strength and castability are poor. Compared with AS21 alloy, AS21X has improved corrosion resistance due to small additions of RE combined with reduced level of Mn.

At present, the application of AS series alloys is restricted by following disadvantages [1]: ① Mg_2Si phase is prone to forming coarse Chinese script, which will result in decreasing room temperature mechanical properties, especially ductility; ②The increasing of Si-content will result in an increasing of the liquid temperature, then castability will become poor; ③The corrosion resistance is poor because of the low Al-content. In order to avoid the disadvantages of AS series, research has been carried out by small additions of alloying elements. The results showed that Mg_2Si particles could be modified and refined through alloying additions of Ca, Sr, P, Sb or others [1,6], then the mechanical properties and castability of AS series were improved greatly.

Development and application of AE (Mg-Al-RE) series magnesium alloys

In the 1970s, the investigation results that the high temperature properties of magnesium alloys might be improved by the addition of 1%Ce-rich mixture of RE elements had been reported. Rcent results also indicated that the high temperature properties of Mg-Al series might be improved effectively by the addition of RE elements, especially when the Al-content was below 4% [1,7]. The main AE series alloys which had been developed were AE21, AE41 and AE42: the high temperature properties of AE42 alloy was found to be most suitable for manufacturing parts used at temperatures lower than 150℃. The strengthening of AE series was thought to be related to the decreasing of $Mg_{17}Al_{12}$ phase amount and the forming of Al-RE intermetallic compounds such as $Al_{11}RE_3$ phase which is very stable at elevated temperature. Some results indicated that alloy phases in AE series probably had $Mg_{17}Al_{12}$, $Al_{11}RE_3$, Al_2RE, $Mg_{12}RE$, $Al_{10}RE_2Mn_7$ and $MgCe_2$, but the forming mechanism of these containing RE alloy phases and their effects on the creep properties of AE series alloys have not been investigated systematically. Generally, the increase of RE-content will produce more $Al_{11}RE_3$ phase at the grain boundaries and reduce the amount of aluminum available for $Mg_{17}Al_{12}$ phase. When the RE/Al ratio (by weight) is above 1.4, all Al will be bound to $Al_{11}RE_3$, and new phases such as another RE-richer Al-RE phase or the $Mg_{12}RE$ phase may be formed [1-2]. Main problems of restricting broad application of AE series alloys are poor castability and high material costs.

Development and application of AX (Mg-Al-Ca) series magnesium alloys

In the 1960s, investigations showed that high temperature performance was improved through the addition of 0.5~3%Ca to Mg-Al alloys. In the 1970s, Volkswagen(VW) attempted to develop Mg-Al-Ca die casting alloys based on the Mg-Al alloy with the additions of 1%Ca, but the hot cracking tendency of the alloy was very serious, and its application was restricted. Subsequently the AX series alloys were studied in Israel, and the AX51 alloy was reported [2]. Although the creep strength and corrosion resistance of AX51 alloy is similar to that of AE42 or AZ91D alloy respectively, but its diecastability and application range still needed to be estimated. In the past two decades, these AX series alloys such as AX51, AX52, AX53, AX506, AX508 and AX51J have been reported, but none of these AX series alloys was applied to manufacturing successful die casting components successfully. Some results [7] indicated that the strengthening of AX series was related to the forming of Mg_2Ca, Al_2Ca or $(Mg,Al)_2Ca$ on grain boundaries, and the casting defects such as die-sticking and hot cracking were very serious when the Ca-content was > 0.3%, especially about 1%. It was interesting that the casting defects decreased when the Ca-content was above 2% [8]. Furthermore, when the addition of 0.1%Sr was applied to Mg-Al-Ca alloys, not only the creep strength was improved greatly, but also the corrosion resistance property, castability and cost were restored to the level of AZ91D alloy.

Development and application of ACM or MRI(Mg-Al-Ca-RE) series magnesium alloys

Presently, ACM series alloys reported are ACM522 alloy, which is developed by Honda based on AM50 alloy with additions of 2.5%Ce-based mish metal and 2%Ca. The strengthening of ACM522 alloy is mainly realized by Al-Ce, Mg-Ca, Al-Ca and other intermetallic compounds distributed on grain boundaries. The ACM522 alloy is already in small scale industrial use, and exhibits good creep strength in the range of 150~200ºC similar to that of A384 alloy. However, ACM522 alloy, in addition to rather high cost, has very low ductility and impact strength that can limit its potential application. Furthermore, the presence of 2%Ca in this alloy can lead to hot cracking problems in components with variable wall thickness and complicated shape.

MRI series alloys were developed by Dead Sea Magnesium Ltd.(DSM) and Volkswagen(VW), and the representative alloy is MRI153 [2]. Some results [2] indicated that the high temperature strength and creep resistance of MRI153 alloy at 130~150ºC under stresses of 50~85 MPa are substantially superior to these of commercial die casting magnesium alloys. This can make MRI153 alloy a superior choice for automotive applications such as transmission housings, oil pans, valve covers and intake manifolds.

Development and application of AJ (Mg-Al-Sr) series magnesium alloys

To avoid the problems which AS, AE, AX and other Mg-Al series alloys suffer from, Noranda Magnesium Inc developed AJ series magnesium alloys based on the AM50 alloy with the additions of 1.7~2%Sr [3]. Presently, representative AJ series alloys have AJ50X, AJ51X, AJ52X, AJ62X and AJ62LX [4]. AJ52X alloy had been applied to oil pan, cylinder cover and other thin thickness components, and some results indicated that AJ52X alloy had good creep resistance in the temperature range of 150~175℃. The high temperature tensile strength and creep strength of AJ52X alloy were found to be also superior to these of conventional die casting magnesium alloys, but compared with AE42 alloy, the ductility of AJ52X alloy was found to be relatively poor. Some results indicated that alloy phases in AJ series alloys probably have $Mg_{17}Al_{12}$, Al_4Sr and $Al_3Mg_{13}Sr$. The forming mechanism of these alloy phases containing Sr and their effects on the creep properties of AJ series alloys have not been studied systematically.

In general, in order to be die castable, the AJ series alloys require very specific casting conditions such as casting temperature of 720ºC and die surface temperature of 300-350ºC that makes very difficult to die cast AJ52X alloy using existing equipment. In addition, the price of Sr containing master alloys is high. This fact also could be certain obstacle for mass production of alloys containing high Sr concentrations.

Development of other Mg-Al based elevated temperature magnesium alloys

Preview research[9] has shown that Sb addition to AZ series alloys was beneficial to improve the high temperature properties. In general, Sb in AZ series alloys exists in two forms, the first is the solution inβ-$Mg_{17}Al_{12}$ phase, the second is the precipitation in form of Mg_3Sb_2 particle with hexagonal structure($D5_2$ type). Since Mg_3Sb_2 is very stable at elevated temperature, the primary α-Mg could nucleate on Mg_3Sb_2 particle surface, so that the microstructure of Mg-Al based alloys can be effectively refined by the Sb addition. Thus the properties at both room temperature and high temperature may be improved.

Bi is also a beneficial element to improve the high temperature properties of AZ series alloy, Small amount of Bi additions to AZ series alloys will result in the refinement of as-cast structure and the formation of Mg_3Bi_2 phase with hexagonal structure($D5_2$ type) which strengthens both matrix and grain boundaries effectively. The Mg_3Bi_2 phase is very stable at elevated temperature and may suppress the discontinuous precipitation of $Mg_{17}Al_{12}$ phase, so that the creep resistance of AZ series alloys containing Bi may be improved greatly. Furthermore, if small amounts of Bi and Sb are added to AZ series alloys simultaneously, the discontinuous precipitation of $Mg_{17}Al_{12}$ phase may be suppressed more effectively and the thermal stability of the alloy is higher [9].

Small amount of Sn additions to AZ series alloys were found to result in the formation of Mg_2Sn phase with C1 cubic structure and high melting temperature [10], when the grain boundary sliding suppressed effectively, that the creep resistance of the containing Sn alloys are greatly improved.

Summary

The research work on Mg-Al based elevated temperature magnesium alloys had made great progress all over the world in the past decade. However, there are still many problems needed to be solved. For example, the number of available Mg-Al based elevated temperature magnesium alloys is very limited, and these alloys developed suffer from inferior diecastability or have disadvantages in terms of marginal performance improvement and high materials costs. In order to develop Mg-Al based elevated temperature magnesium alloys more quickly and more successfully, we should consider earnestly the existing problems on the development and industrialization of magnesium alloys and the research on some aspects such as the addition of alloying elements, controlling of alloy phase and optimization of casting process must be carried out emphatically.

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