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Review

Recent developments in high-strength Mg-RE-based alloys: Focusing on Mg-Gd and Mg-Y systems

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Abstract

Higher strength is always the goal pursued by researchers for the structural materials, especially for the lightweight magnesium (Mg) alloys which generally have relatively low strength at present. From this aspect, the present paper reviews the recent reports of a kind of Mg alloys, i.e. Mg-RE (RE: rare earths, mainly Gd or Y) casting and wrought alloys, which have been able to achieve high strength compared with common or commercial Mg alloys, from the viewpoint and content of the alloy system, alloying constitution, preparation process, tensile strength and each of the main strengthening mechanisms. This review of recent research and developments in high-strength Mg-RE alloys is beneficial for the further design of Mg alloys with higher strength as well as excellent comprehensive performance.

Keyword: Mg alloys; High strength; Rare earths (RE); Strengthening mechanism.

1. Introduction

Magnesium (Mg) is the lightest among all commonly used structural metals, with a density about two thirds that of aluminum and one quarter that of steels. Furthermore, Mg is an abundant element in the world compared with other commonly used metals. As the lightweight structural metallic materials, Mg alloys are of great interest for many potential applications including automotive, aircraft, aerospace, and 3C (computer, communication and consumer electronic product) industries and so on. Therefore, Mg alloys have received considerable research over nearly past two decades [1,2]. Despite the considerable efforts made so far, the engineering applications of Mg alloys remains limited compared with that of aluminum (Al) alloys. Just considering the reason from performance, there are roughly four aspects of performance, i.e. strength (absolute or specific strength), corrosion resistance, formability and creep resistance, are usually inadequate for the common Mg alloys. Accordingly, in recent years the most of reports about research of Mg alloys are around these four topics [3–12].

Fortunately, the Mg alloys with high strength at room temperature have been reported especially in more recent years. Researchers made full use of the precipitation hardening, grain refinement strengthening and also some new strengthening mechanisms to improve their strengths. In order to compare the strength of various Mg alloys more easily and uniformly and show a clear development level to readers, the present paper reviews the research development of high-strength Mg alloys according to tensile properties at room temperature. Due to the increasing requirements for military and civilian applications, here we define that the "high-strength Mg casting alloys" are the alloys with ultimate tensile

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strength (UTS) of above 350 MPa and the "high-strength Mg wrought alloys" are the alloys with UTS of above 400 MPa and/or yield strength (YS) of above 350 MPa. According to this standard, it can be found that almost all the high-strength Mg alloys are the new designed alloys rather than the commercial alloys, and most of them are Mg alloys with rare earths (RE). In other words, so far at least the researchers are obliged to admit the fact that Mg-RE-based alloys are the most promising high-strength Mg alloys despite the rapid development of RE-free Mg alloys with relatively high strength [13–16].

The high-strength Mg-RE alloys recently developed from the viewpoint of novel alloying designs can be roughly divided into Zn-free Mg-RE alloys, Mg-RE-Zn alloys, Mg-Zn-RE alloys. Since the properties of Mg alloys are determined not only by compositions but also by processing technologies, this article provides a concise review of new high-strength Mg-RE alloys roughly according to the alloying designs in the similar process technologies.

2. High-strength Mg-RE casting alloys

At present the casting technologies of reported high-strength casting Mg alloys are mainly related to the permanent mold gravity casting (PM). Thus in the paper, all the mentioned Mg casting alloys are prepared by PM but no high pressure die casting (HPDC), low pressure casting (LPC) and sand casting (SC) and so on.

Mg casting alloys usually have the microstructure with relatively large grains. Mg-RE casting alloys achieve their high strength mainly via age hardening, which involves (a) solid-solution treatment at a relatively high temperature, (b) water quenching to obtain a supersaturated solid-solution of α-Mg single-phase, and (c) subsequent ageing at a relatively low temperature to finally obtain the metastable or equilibrium precipitates in the Mg matrix. The age hardening effect is depended on the quality of precipitation, i.e. the size, number density, morphology, orientation as well as structure of precipitates. Both the internal and external factors, i.e. alloy constitutions and process technologies, control the microstructure and finally determine the mechanical properties of Mg alloys. Based on a large amount of literature investigations, it can be found that generally the strength of the earlier Mg-RE alloys developed is lower than that of the latest ones even if they have the similar alloy constitutions, revealing that the control of preparation processes (casting process, heat treatment process as well as deformation process) is also very important and becomes more and more perfect. The new Mg-RE casting alloys mainly include Mg-Gd, Mg-Y, Mg-Nd based alloys[3,17–22]. From the relevant references, it can be found that the Mg casting alloys with UTS > 350 MPa are only the Mg-RE alloys in which the RE is mainly Gd and RE content is at a relatively high level. For the Mg-Gd based alloys, they can further be divided into Mg-Gd-Y, Mg-Gd-Nd, Mg-Gd-Y-Nd, Mg-Gd-Sm, Mg-Gd-Dy, Mg-Gd-Er, Mg-Gd-Ho, Mg-Gd-(-Y)-Ag and Mg-Gd-Y/Dy-Zn series [3,16,17,23–29].

Table 1
Mechanical properties of the high-strength Zn-free Mg-RE (or rather Mg-Gd) casting alloys with UTS > 350 MPa (EL: Elongation).

Alloys (wt.%)	Testing conditions	Tensile properties			Refs.
		UTS (MPa)	YS (MPa)	EL (%)	
Mg-8Gd-3Y-0.4Zr	500 °C × 8 h + 200 °C × 80 h	362	222	7.6	[17]
Mg-9Gd-4Y-0.5Zr	525 °C × 6 h + 225 °C × 24 h	370	277	4.5	[30]
Mg-10Gd-2Y-0.4Zr	490 °C × 8 h + 225 °C × 16 h	362	239	4.7	[31]
Mg-10Gd-3Y-0.4Zr	500 °C × 8 h + 225 °C × 16 h	370	241	4.1	[17]
Mg-11Gd-2Nd-Zr	525 °C × 4 h + 250 °C × 2 h	353	224	3.7	[17]
Mg-8.3Gd-1.1Dy-0.4Zr	530 °C × 10 h + 230 °C × 65 h	355	261	3.8	[29]
Mg-8Gd-2Dy-0.2Zr	520 °C × 8 h + 200 °C × 72 h	360	215	7	[32]
Mg-8.5Gd-2.3Y-1.8Ag-0.4Zr	500 °C × 10 h + 200 °C × 32 h	403	268	4.9	[33]
Mg-18Gd-2Ag-0.3Zr	490 °C × 10 h + 200 °C × 36 h	414	293	2.2	[34]
Mg-15.6Gd-1.8Ag-0.4Zr	480 °C × 18 h + 500 °C × 8 h + 200 °C × 32 h	423	328	2.6	[35]

2.1. Zn-free Mg-RE casting alloys

Table 1 lists most of, if not all, the high-strength Zn-free Mg-RE (or rather Mg-Gd) casting alloys with UTS > 350 MPa, which have been reported up to now. These Zn-free Mg-Gd alloys can be further divided into Mg-Gd-RE (RE = Y, Nd, Dy) and Mg-Gd(-Y)-Ag series.

The precipitation sequence in Mg-Gd-RE (or Mg-Gd binary) alloys during ageing process has been well recognized: SSSS (super-saturated solid solution) → β'' (Mg_3Gd, hcp, $D0_{19}$) → β' (Mg_7Gd, cbco) → β_1 (Mg_3Gd, fcc) → β (Mg_5Gd, fcc) [3,36–44]. More recently, based on the HAADF-STEM observations, Zheng et al. [45] report a more detailed precipitation sequence in Mg-Gd-Y-Zr alloys: SSSS → clusters → nucleation β' (major)/β_H (minor) → precipitate β' (major)/β_M,$\beta_T{}'$ (minor) → β_1 → β (equilibrium), and under peak-age condition, the strengthening structure is independent defect-free β' with little interaction among each other, as shown in Fig. 1. Among these precipitate phases, the β' precipitates with nanoscale and dense distribution are well known as the key strengthening phase in peak-aged Mg-Gd-RE samples[28–31,37,39,42–46], and a few reports also suggest that some times $\beta'+\beta''$ or $\beta'+\beta_1$ coexist for the peak ageing hardening [21,42,47,48]. β' phase has a base-centered orthorhombic structure (a = 0.65 nm, b = 2.27 nm, c = 0.52 nm) and an orientation relationship with respect to the Mg matrix: $(100)_{\beta'}//\{1\text{-}210\}_\alpha$ and $[001]_{\beta'}//[0001]_\alpha$ [3].

The β' precipitates, which form on {11-20} prismatic planes of α-Mg phase in a dense triangular arrangement and are vertical to basal plane of α-Mg, provide the most effective

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