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Journal of Magnesium and Alloys ■■ (2017) ■■–■■
www.elsevier.com/journals/journal-of-magnesium-and-alloys/2213-9567

Review

Recent research and developments on wrought magnesium alloys

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Received 22 August 2017; accepted 4 September 2017

Available online

Abstract

Wrought magnesium alloys attract special interests as lightweight structural material due to their homogeneous microstructure and enhanced mechanical properties compared to as-cast alloys. In this contribution, recent research and developments on wrought magnesium alloys are reviewed from the viewpoint of the alloy design, focusing on Mg-Al, Mg-Zn and Mg-rare earth (RE) systems. The effects of different alloying elements on the microstructure and mechanical properties are described considering their strengthening mechanisms, e.g. grain refinement, precipitation and texture hardening effect. Finally, the new alloy design and also the future research of wrought magnesium alloys to improve their mechanical properties are discussed.

Keywords: Wrought magnesium alloys; Alloy design; Mechanical properties

1. Introduction

Magnesium alloy is one of the most promising lightweight metals for structural applications owing to its high specific strength, low density and high damping capacity. Owing to its hexagonal crystal structure with insufficient slip systems, its low temperature formality is not so satisfied. Additionally, its strength is also low because of easy activation of basal slip. Its present applications are still limited. Currently, most of commercial components were fabricated with die casting, while the use of wrought magnesium alloys is very few with less than 10%. How to improve the low temperature ductility and strength plays a very important role in extending the applications of magnesium alloys, especially the applications of wrought magnesium alloys [1].

There has been a large amount of works on enhancing the mechanical properties of Mg alloys, in order to further extend their industrial applications in automobile and aerospace industries. In the past decades, many commercial wrought Mg alloy systems have been developed, such as AZ system, ZK system, WE system and so on [2,3], the first large scale industrial line for magnesium sheet in the world has been put into mass production in China. Based on the previous investigations, researchers have developed new Mg alloys with high strength by the modification of the existing commercial alloy systems [4,5]or the designation of new alloy systems [6], making full use of grain refinement strengthening, precipitation strengthening and texture strengthening effect. For example, a high strength Mg-Y-Zn alloy which was produced by rapidly solidified powder metallurgy exhibits remarkable mechanical properties with a tensile yield stress (TYS) of 610 MPa and an elongation of 5% [7]. In addition, advanced processing, such as hot extrusion, rolling, forging and equal-channel angular processing (ECAP), is an effective technique to refine the microstructure and to improve the mechanical properties of Mg alloys. A Mg-10Gd-5.7Y-1.6Zn-0.7Zr alloy with a TYS of 473 MPa and an elongation of 8% had been successfully fabricated by hot extrusion and subsequent ageing [8]. Yu et al [9] developed a high strength Mg-11Gd-4.5Y-1Nd-1.5Zn-0.5Zr (wt.%) alloy with a TYS of 482 MPa, an ultimate tensile strength (UTS) of 517 MPa and an elongation to failure of 2% at room temperature via the combinative processing of hot extrusion, cold rolling and ageing treatment.

In this review, recent development of wrought Mg alloys in the past decade will be reviewed from the viewpoint of alloy designs, including Mg-Al system, Mg-Zn and Mg-RE system. Furthermore, the new alloy design and the future researches for wrought Mg alloys will be proposed.

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https://doi.org/10.1016/j.jma.2017.09.001

2. Mg-Al system

Mg-Al based alloys are the most widely used wrought Mg alloys as structural materials, as the addition of Al improves the strength, ductility and castability of Mg alloys at room temperature [10]. However, the $Mg_{17}Al_{12}$ (β) phase formed along the grain boundaries has a relatively low melting temperature (710 K), which leads to the microstructure instability over 400 K. This results in the grain boundary sliding and, thus, the degradation of mechanical properties of the Mg-Al alloys at elevated temperatures [11]. Additionally, the edge-cracking during rolling, the strong basal texture, and the non-homogeneous grain sizes limit the formability of Mg-Al alloys at room temperature. In this regard, several elements were used to optimize the microstructure of Mg-Al alloys. Series like Mg-Al-Zn (AZ), Mg-Al-Mn (AM) and Mg-Al-Si (AS) have been widely used, as Zn improves the ambient temperature mechanical properties and Mn, Si improve the creep resistance of Mg-Al alloys [3,12]. In addition, the modifications of commercial Mg-Al system alloys through adding Ca, Li, Sr, Sn, RE (rare earth) and so on were deeply investigated in the last decade.

2.1. *Modified AZ series*

The addition of calcium to Mg-Al alloys can result in the formation of thermally stable Al_2Ca phase with higher melting temperature of 1352 K [13], the presence of which can markedly increase the strength and creep properties of Mg-Al alloys. Jiang et al. improved the UTS, YS and elongation of extruded Mg-2.32Al alloy to 324 MPa, 275 MPa and 10.2%, respectively, by the addition of 1.7 wt.% Ca. It was found that the addition of Ca to the extruded Mg-Al alloy resulted in a remarkable grain refinement, a sharply broken of Al_2Ca phases (Fig. 1), and a formation of 30~50 nm plate-like Al_2Ca particles precipitated inside grains (Fig. 2), thus, a good mechanical property [14]. Similar results were found in a Ca containing AZ31 alloy which exhibited finer grains and performed a higher ductility compared with the Ca free AZ31 alloy after thermomechanical processing, however, the distribution of grain boundaries and crystallographic texture are similar (Fig. 3) [15]. Furthermore, Kwak et al [4] investigated the hot compressive behavior of the extruded 0.5 wt.% Ca-AZ31 alloy, and it was found that the addition of Ca led to a noticeable grain refinement and a more homogeneous microstructure. Also, compared to the extruded Ca free AZ31 alloy, the extruded 0.5 wt.% Ca-AZ31 alloy had a better formability at high temperatures (573–673 K) but a poorer formability at lower temperatures. This is because Al_2Ca phase would disperse in the matrix at high temperatures which can promote the dynamic recrystallization and retard the grain coarsening. In addition, Shang et al [16] investigated the microstructure and the elevated temperature deformation behavior of hot-rolled AZ31 microalloyed with Ca, Sr and Ce. It was found that the addition of Ca, Sr and Ce did not change the deformation mechanism under different temperatures and strain rates, but has an obvious effect on the ductility of AZ31 alloy under the high temperatures and low strain rate condition (e.g. 723 K and 0.0003 s^{-1}), under which the elongation to failure increased from 347% (AZ31) to 406% (AZ31 containing Ca only), 437% (AZ31 containing Ca and Ce), and 552% (AZ31 containing Ca, Sr and Ce), respectively. The results showed that the addition of Ca, Sr and Ce restricted the grain coarsening during hot deformation, and thus increased the ductility.

Li is another potential element to optimize the microstructure of Mg-Al alloys, since Li possesses low density and promotes cross-slip and non-basal slip in Mg alloys [17,18]. Pan's research

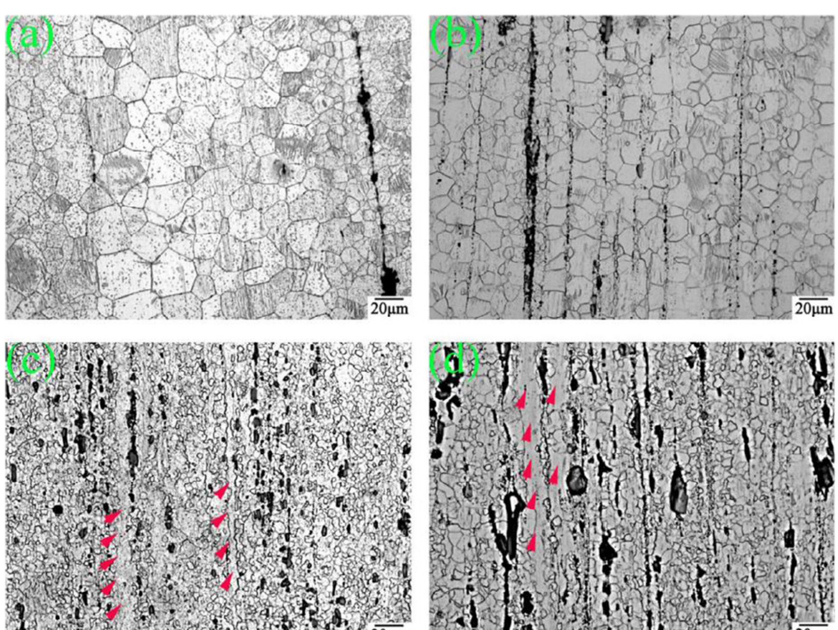

Fig. 1. Optical images of the as-extruded alloys: (a) Mg-0.61Al-0.46Ca; (b) Mg-1.34Al-1.03Ca; (c) Mg-2.32Al-1.70Ca; (d) Mg-3.74Al-2.52Ca [14].

Please cite this article in press as: Sihang You, Yuanding Huang, Karl Ulrich Kainer, Norbert Hort, Recent research and developments on wrought magnesium alloys, Journal of Magnesium and Alloys (2017), doi: 10.1016/j.jma.2017.09.001