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Research Progress in Alloyed Mg-Sn System Alloys

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Abstract: Mg-Sn alloys, as a classical precipitation-strengthened system, exhibit enhanced tensile strength and creep resistance at elevated temperatures due to the thermally stable Mg_2Sn phase. Compared with expensive Mg-RE-based alloys, Mg-Sn alloys are promising low-cost alternatives for high-strength heat-resistant wrought magnesium applications. Recent advancements in thermomechanical processing and alloying element additions have significantly optimized their mechanical properties, expanding their engineering potential. This review systematically summarizes the research progress of Mg-Sn-based alloys, focusing on the mechanisms by which alloying elements (e.g., Ca, Zn, Al, RE) modify microstructures and enhance mechanical performance. Future research directions are proposed to guide the design and development of high-performance Mg-Sn alloys.

Keywords: *Magnesium alloy; Alloying element; Precipitation strengthening; Creep resistance; Microstructure*

I. INTRODUCTION

Magnesium alloy, as the lightest metallic structural material (density 1.738 g/cm^3), is hailed as the "21st century green engineering material" due to its exceptional specific strength, specific stiffness, and damping properties[1]. However, the hexagonal close-packed (HCP) crystal structure of magnesium results in limited room-temperature slip systems (primarily basal slip) and poor plastic processing capability. Additionally, the activation of grain boundary sliding and dislocation climb at elevated temperatures significantly deteriorates their creep resistance[2]. Currently, commercial heat-resistant magnesium alloys mainly consist of Mg-rare earth (RE) systems, but their high costs restrict large-scale applications. In contrast, tin (Sn) offers cost-effectiveness, and Mg-Sn alloys demonstrate remarkable precipitation strengthening effects through the formation of Mg_2Sn phases, making them a research hotspot for low-cost heat-resistant magnesium alloys[3].

In recent years, researchers have significantly enhanced the comprehensive performance of Mg-Sn alloys through synergistic strategies combining alloying and deformation processing. For instance, the addition of elements such as Ca, Zn, and Al can refine grains and regulate precipitate phase morphology, while thermomechanical processing techniques like extrusion and rolling further optimize the distribution of secondary phases[4]. However, multi-element additions may lead to complex phase compositions, increasing material recycling challenges. Consequently, how to strike a balance between mechanical performance and cost remains the core research challenge for Mg-Sn alloys.

This article focuses on the influence of elemental additions on the microstructure and properties of Mg-Sn alloys, systematically reviewing recent research advancements and exploring future development directions, with the aim of providing theoretical support for the engineering application of high-performance Mg-Sn alloys.

II. EFFECT OF ELEMENT ADDITION ON MICROSTRUCTURE AND PROPERTIES OF MG-SN ALLOY

1.1 Precipitation behavior of Mg-Sn binary alloy

The typical microstructure of as-cast Mg-Sn alloys consists of an α-Mg matrix and Mg_2Sn phases. The size and distribution of Mg_2Sn phases significantly influence mechanical properties: coarse and continuous phases tend to act as crack initiation sites, while fine and dispersed phases can effectively hinder dislocation motion and enhance strength[5]. Studies have shown that increasing Sn content (e.g., 7 wt.%) promotes the precipitation of Mg_2Sn phases, enabling extruded Mg-7Sn alloys to achieve a tensile strength of up to 205 MPa[6]. Furthermore, the solid solubility of Sn decreases sharply with decreasing temperature, which provides a driving force for aging treatment. By optimizing aging processes, the morphology of precipitates can be further refined[7].

1.2 Ca

The addition of calcium (Ca) leads to the formation of a high-temperature stable phase, CaMgSn (melting point 1184℃), whose precipitation kinetics is governed by the Sn/Ca molar ratio. When Sn/Ca > 2.5, the CaMgSn phase preferentially forms over the Mg_2Ca phase, with its volume fraction significantly increasing as Sn content rises [8]. The CaMgSn phase inhibits grain coarsening during dynamic recrystallization by pinning grain boundaries and subgrain boundaries (Figure 1), while simultaneously inducing dislocation entanglement strengthening[9]. For example, in extruded Mg-2Sn-2Ca alloy, nanoscale CaMgSn phases uniformly distributed near grain boundaries enable the alloy to maintain high strength within the 20–175℃ range. However, beyond 175°C, grain boundary sliding dominates deformation, causing the strengthening effect to diminish[10].

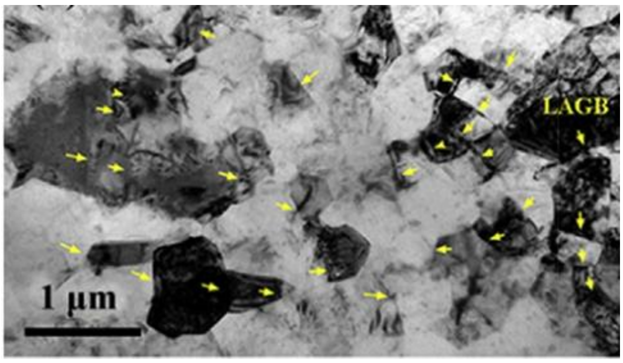

Fig 1TEM micrograph of CaMgSn phase pinning grain boundaries

It is noteworthy that excessive Ca addition may lead to continuous distribution of Mg_2Ca phases along grain boundaries, weakening grain boundary cohesion. Therefore, composition optimization (e.g., Sn/Ca = 3:1) is required to achieve a balanced distribution of CaMgSn and Mg_2Ca phases[11].

1.3 Zn

The solidification temperature of Zn (419.73℃) is significantly higher than that of Sn (232.06℃)[12]. Its preferential precipitation induces a component undercooling effect, providing heterogeneous nucleation sites for the Mg_2Sn phase[13]. Simultaneously, Zn's high growth restriction factor (GRF=5.31) further refines grains and inhibits dendritic growth . Transmission electron microscopy (TEM) analysis reveals that Zn element segregates at the Mg_2Sn/α-Mg interface (Fig. 2), forming nanoscale Mg_2Zn phases. This interfacial segregation behavior not only impedes dislocation motion but also suppresses coarsening of precipitates at elevated temperatures, thereby significantly enhancing creep resistance[14, 15].

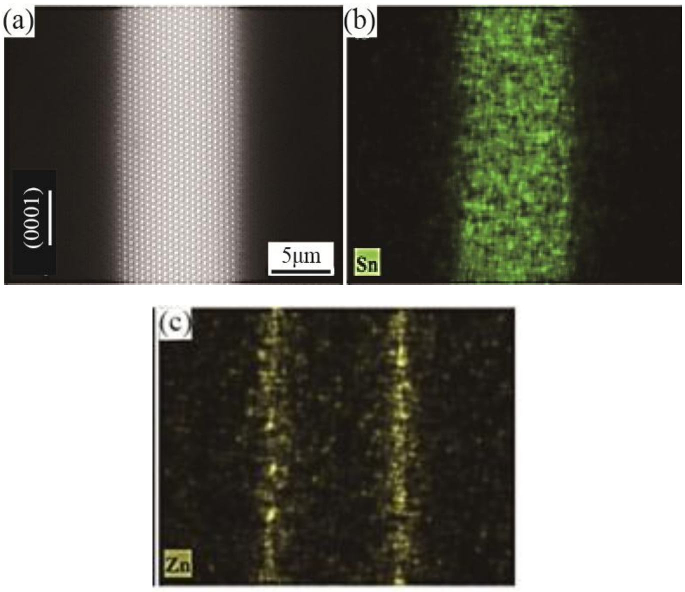

Fig.2(a) HRTEM image of Mg_2 Sn; (b) Sn elemental distribution; (c) Zn elemental distribution

Furthermore, the addition of Zn regulates the orientation distribution of Mg_2Sn phases. In the peak-aged Mg-9.8Sn-1.2Zn alloy, Mg_2Sn phases preferentially precipitate along the basal planes, interacting with dislocations to generate a pronounced precipitation strengthening effect, which elevates the alloy's yield strength to 280 MPa[16].

1.4 Al

The solid solution of Al significantly reduces the lattice parameters of α-Mg (c/a ratio decreases from 1.624 to 1.618) while diminishing the solid solubility of Sn, thereby enhancing the precipitation driving force for Mg_2 Sn phases[17]. For instance, in Mg-4Sn-4Al alloy, Al promotes the formation of Mg_2 Sn/$Mg_{17}Al_{12}$ eutectic structures. Acting as heterogeneous nucleation substrates, $Mg_{17}Al_{12}$ phases induce the precipitation of Mg_2Sn phases in nanoscale lamellar morphology, achieving dual strengthening effects[18].

However, excessive Al content (>5 wt.%) may lead to coarsening of $Mg_{17}Al_{12}$ phases, compromising grain boundary strength. Therefore, heat treatment processes such as T6 aging are required to regulate the distribution of eutectic structures[19, 20].

1.5 RE

The addition of rare earth elements (e.g., Yb, La, Ce) significantly refines grains and forms thermally stable phases (e.g., Mg_2 (Sn,Yb), $LaMg_3$)[21, 22]. In Mg-5Sn-4La alloy, La addition reduces the grain size from 50 μm to 10 μm while generating $LaMg_3$ and La_5Sn_3 phases[22]。. These dispersed phases enhance the alloy's tensile strength to 205 MPa through impeding dislocation motion and grain boundary migration, representing nearly double the strength of binary alloys[22].

Notably, Ce addition exhibits unique mechanisms. When 1% Ce is introduced into Mg-7Sn-1Al-1Zn alloy, plate-like Ce_3Sn_5phases form. Although these phases consume Sn atoms to reduce Mg_2Sn precipitation, their high thermal stability (decomposition temperature >400℃) still effectively enhances the alloy's high-temperature strength[23].

CONCLUSION

1. Ca, Zn, and Al enhance alloy strength by forming secondary phases (CaMgSn, Mg_2Zn, $Mg_{17}Al_{12}$) or inducing constitutional undercooling, which refines grains and promotes dispersed precipitation of Mg_2Sn phases.
2. Mg-Sn-Ca/Al/Zn-based alloys achieve an optimal balance between mechanical properties and cost. However, multielement additions may increase recycling complexity, necessitating the development of lean-alloy designs with fewer elements while maintaining high performance.
3. Synergistic application of thermomechanical processing (e.g., extrusion, rolling) and aging treatments enables precise control over precipitate distribution. For example, dynamic recrystallization during deformation can produce ultrafine-grained structures (grain size <1 μm), significantly enhancing comprehensive mechanical properties.

FUTURE RESEARCH DIRECTION

1. Investigate the effects of low-cost element additions (e.g., Na, Mn) and elucidate their interaction mechanisms with Mg_2Sn phases to guide the design of cost-effective alloy compositions.
2. Systematically study the coarsening behavior of Mg_2Sn phases during prolonged high-temperature service. Develop surface coating technologies or nano structuring modifications to improve phase stability under extreme thermal conditions.
3. Design advanced separation and regeneration processes tailored for multielement composite alloys. Establish closed-loop recycling frameworks to advance the sustainable development of Mg-Sn alloy systems.

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