Two-Stage Precipitation Strategy for Enhancing Thermal Conductivity in Mg-2Zn-2Cu Alloy

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Abstract： Magnesium alloys, recognized as the lightest structural materials, exhibit considerable potential for applications demanding both lightweight characteristics and superior thermal transport properties. This study focuses on optimizing the Mg-2Zn-2Cu (wt.%) system through compositional design and thermomechanical processingto achieve an optimal balance between thermal conductivity and mechanical performance. Microstructural characterization reveals that the as-cast alloy predominantly contains rod-shaped and intergranular MgZnCu phases. Subsequent hot extrusion induces significant grain refinement and phase redistribution, transforming the continuous network structure into discrete particles aligned along the extrusion direction, accompanied by nanoscale MgZnCu precipitates within the α-Mg matrix. The thermophysical and mechanical evaluations demonstrate substantial improvements: Thermal conductivity increases from 139.7±2.1 W/(m·K) in the as-cast state to 153.5±1.8 W/(m·K) post-extrusion, representing a 9.9% enhancement. Correspondingly, mechanical properties show remarkable progress with ultimate tensile strength rising from 104.8±3.5 MPa to 277.8±5.2 MPa, yield strength reaching 162.9±4.1 MPa, and elongation increasing from 8.0±0.5% to 37.7±1.2%. This synergistic improvement originates from two complementary mechanisms: Reduced lattice distortion through controlled alloying, and Through homogenization treatment combined with hot extrusion process, which generates bimodal-distributed strengthening phases while minimizing phonon scattering.

Keywords: Mg-Zn-Cu alloy; Hot extrusion; Precipitation strengthening; Thermal conductivity

1 Introduction

With the relentless advancement of electronic device miniaturization and power intensification, thermal management has emerged as a critical bottleneck constraining system reliability and operational efficiency [1, 2]. Beyond holistic thermal management solutions, the development of high-performance thermally conductive structural materials presents a strategic pathway for next-generation thermal engineering. Magnesium alloys, occupying the unique niche of being the lightest metallic structural materials, demonstrate exceptional promise in this regard. The inherent thermal conductivity of pure magnesium reaches 156 W/(m·K) at 25°C [3], surpassed only by copper and aluminum among common metals. This intrinsic thermal transport capability, combined with mass-saving advantages, positions magnesium alloys as dual-functional materials capable of simultaneous structural support and heat dissipation in thermal-critical applications.

Although pure magnesium has a high thermal conductivity, its insufficient mechanical properties limit its application. Introducing solute atoms through alloying can enhance its mechanical properties (such as increasing the tensile strength to over 200 MPa), but at the same time, it will reduce the thermal conductivity. This is due to the scattering effect of solute atoms on electrons. Precipitation strengthening offers a solution by forming a second phase to reduce solute atoms in the matrix, increase thermal conductivity, and simultaneously impede dislocation movement to enhance mechanical properties . The research by Li et al. [4] shows that the introduction of Al in the Mg-4Sm-2.6Al alloy enables Sm and Al to form micron-sized AlSm phases, thereby enhancing the thermal conductivity. However, such micron-sized particles may limit the comprehensive performance due to size and distribution issues. To break through these limitations, Qiao et al. [5] studied the dynamic precipitate α -Mn phase formed in the Mg-2Mn-2.5La alloy by forming a nanoscale second phase, which increased the thermal conductivity to 135 W/(m·K). Based on this, this study proposes to adopt a low alloy content and two-stage precipitation strengthening at the micron and nanometer scales to balance the thermal conductivity and mechanical properties of the material. Nanoscale precipitated phases can be achieved through rapid solidification and the preparation of metal matrix composites. For instance, Li et al. [6] successfully prepared the nanoscale metastable phase in WE43 magnesium alloy through laser powder bed melting and subsequent aging treatment. Another method is to prepare metal composites using immiscibility metals. For example, the Cu-W alloy prepared by Wu et al. [7] using discharge plasma sintering technology enables extremely fine W nanoparticles to be uniformly distributed in the Cu matrix, enhancing the strength, ductility and thermal conductivity of the alloy. Compared with these methods, this study adopted homogenization treatment combined with plastic deformation to form nanoscale precipitated phases. The supersaturated solid solution is formed through homogenization, and then high-density dislocations and grain boundaries are introduced through hot extrusion, providing nucleation positions for the precipitation of nanoscale phases, thereby forming nanoscale precipitated phases. Compared with the other two methods, this method has a simple process. At the same time, compared with the laser powder bed melting method and metal matrix composite materials, the microstructure after hot extrusion molding is dense, the porosity is low, and the surface roughness after extrusion molding is low. There are many alloy systems to choose from, and the equipment cost is low.

In alloy design, in order to maintain excellent thermal conductivity while enhancing mechanical properties, Zn and Cu were selected as additive elements [8]. Zn can enhance the tensile strength of Mg alloys, but it will reduce the elongation and increase the tendency of hot cracking and shrinkage porosity. Therefore, Cu element is added to the Mg-Zn basic alloy. Due to its grain refinement effect, it can also transform the MgZn phase into a continuous network of MgZnCu phase [9], increase the eutectic temperature of the alloy, and make high-temperature homogenization treatment possible. This not only increases the solid solubility of Zn and Cu, but also forms a supersaturated solid solution, laying the foundation for the subsequent realization of two-stage precipitation intensification at the micrometer and nanometer scales [10]. Combined with plastic deformation, by increasing the defect density, nucleation points are provided for the nanoscale precipitated phase, and the micrometer-scale precipitated phase is precipitated during the extrusion process.

2 Experimental section

2.1 Material compositions

The original ingot was prepared by melting high-purity Mg, Zn, and Cu at 750°C in a resistance furnace under an argon atmosphere, and the nominal composition of the ingot was Mg-2Zn-Cu. Then, the molten temperature was reduced to 730°C, and it was poured into the mold preheated to 200°C.

Before undergoing hot extrusion, the cast alloy was homogenized at 430°C for 60 hours. During the hot extrusion experiment, the sample was preheated at 240°C for 1 hour to achieve uniform temperature. Following this, it was extruded at 240°C with an extrusion speed of 0.4mm/s and an extrusion angle of 30°, utilizing a die with an extrusion ratio (Re) of 25.

2.2 Microstructure characterization

The microstructure of the Mg-2Zn-2Cu alloy in the as-cast and extruded states was observed by optical microscope and scanning electron microscope respectively, and the nanoscale precipitate phase in the matrix was observed by transmission electron microscope for phase identification. The samples used for OM and SEM observations were corroded with picric acid after mechanical polishing.

2.3 Thermal conductivity testing

The thermal diffusivity (α) of the sample was measured by an LFA-500 laser thermal conductivity instrument at room temperature (25 °C). The diameter of the sample was 12.7 mm, and the thickness was 2.5 mm ensuring a one-dimensional heat transfer state. The specific heat (C_p) was determined using a Q2000 differential scanning calorimeter (DSC). The density (ρ) was determined by Archimedes method. The thermal conductivity (λ) was calculated using Eq. (1):

$$\lambda = \alpha \rho C_p \quad (1)$$

Where λ is the thermal conductivity, α is the thermal diffusivity, ρ is the density, and C_p is the specific heat capacity.

2.4 Mechanical property testing

Tensile specimens with a gauge dimension of 18×4×2.5 mm^3 were cut from the casting bars. The tensile test was carried out on a universal stretching machine at room temperature under a tensile speed of 0.35 mm/min.The tensile test results were obtained by calculating the average values from three repeated tests conducted in this work.

3 Results and discussion

3.1 Mg-2Zn-2Cu alloy microstructures

As shown in Fig. 1(a), the as-cast alloy microstructure contains two distinct secondary phase morphologies, island-like precipitates and semi-continuous network structures. EDS mapping analysis (Fig. 1(b-e)) confirms both morphological types as ternary Mg-Zn-Cu phases. Quantitative EDS point analysis (Table 1) reveals near-equiatomic Zn:Cu ratios (≈1:1), conclusively identifying these secondary phases as the MgZnCu intermetallic compound. The calculated volume fraction of these MgZnCu phases reaches 6.61%, as determined through systematic microstructural characterization.

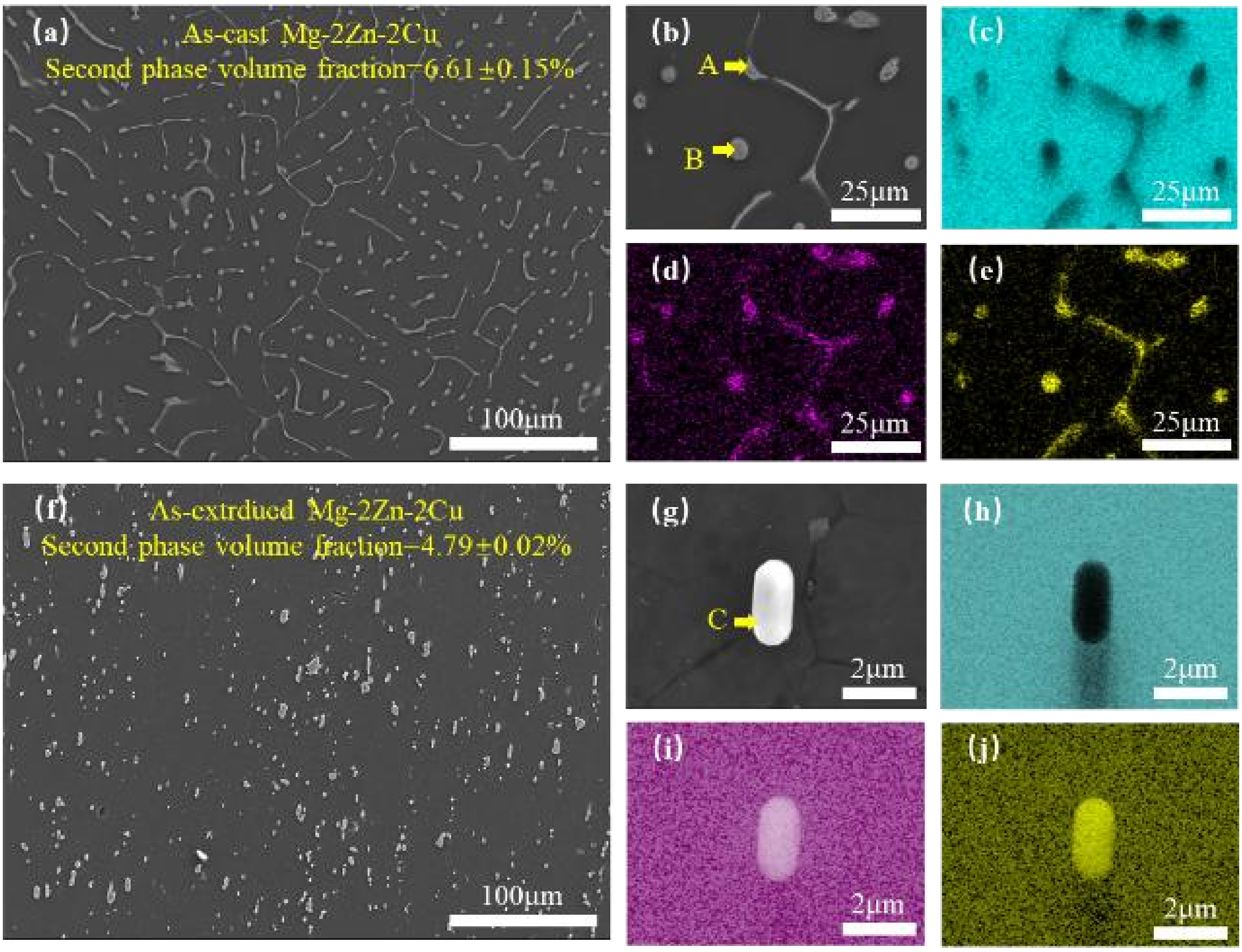

Fig. 1 SEM images of as-cast Mg-2Zn-2Cu alloy and as-extruded Mg-2Zn-2Cu alloy: (a-e) as-cast, (f-j) as-extruded

Table 1. EDS point results.

Location	Atomic concentration		
	Mg(at%)	Zn(at%)	Cu(at%)
A	89.7	4.6	5.7
B	84.2	6.5	9.3
C	78.7	7.6	13.8
D	88.68	4.71	6.61
E	81.04	7.96	11.0

As shown in Fig. 1(f), the extruded Mg-2Zn-2Cu alloy primarily consists of granular secondary phases distributed along the extrusion direction. Combined with EDS analysis results, it can be concluded that these granular secondary phases also correspond to the Mg-Zn-Cu phase, with a calculated volume fraction of 4.79%. This morphological transformation between the as-cast and extruded states can be attributed to two main factors, first, the homogenization treatment partially dissolves the secondary phases and diminishes their network-like structure. Second, the remaining secondary phases undergo mechanical fragmentation during hot extrusion, resulting in their particulate morphology and alignment along the extrusion direction. Concurrently, the elevated temperatures during extrusion facilitate elemental diffusion and recrystallization processes [11]. Ultimately, these combined effects lead to the formation of finely dispersed particles oriented parallel to the extrusion direction.

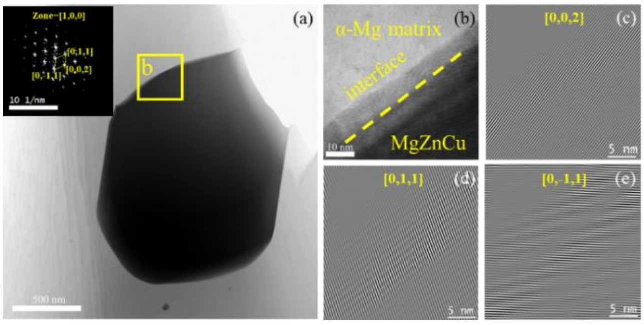

Fig. 2 TEM images of as-extruded Mg-2Zn-2Cu alloy: (a) Low magnification TEM, (b) High magnification TEM, (c-e) invers FFT images of (b).

In order to further determine the second phase in the extruded alloy, the micron-sized second phase in the extruded Mg-2Zn-2Cu alloy was characterized by TEM, and the results are shown in Fig. 2 SAED analysis was conducted on the micron-sized second phase in Figure a, and the micron-sized second phase in the extruded alloy was calibrated as the MgZnCu phase. The results in Fig. 2(c-e) show that the MgZnCu phase is semi-coherent with the α-Mg matrix. The interface of the second phase in the alloy will affect the thermal conductivity of the alloy. The coherent interface will cause significant lattice distortion, while the semi-coherent or non-coherent interface will release the lattice distortion in the alloy matrix, thereby affecting the thermal conductivity of the alloy [12, 13].

To further identify the secondary phases in the extruded alloy, TEM characterization was performed on micron-sized secondary phases within the extruded Mg-2Zn-2Cu alloy, with results presented in Fig. 2 Selected-area electron diffraction (SAED) analysis conducted on the micron-sized secondary phase in Fig. 2(a) confirms that these features correspond to the MgZnCu phase. As shown in Fig. 2(c-e), the MgZnCu phase exhibits a semi-coherent interface relationship with the α-Mg matrix. The interfacial characteristics of secondary phases significantly influence the alloy's thermal conductivity: Coherent interfaces induce substantial lattice distortion, whereas semi-coherent or non-coherent interfaces alleviate lattice distortion within the alloy matrix, consequently modifying the thermal conductive properties.

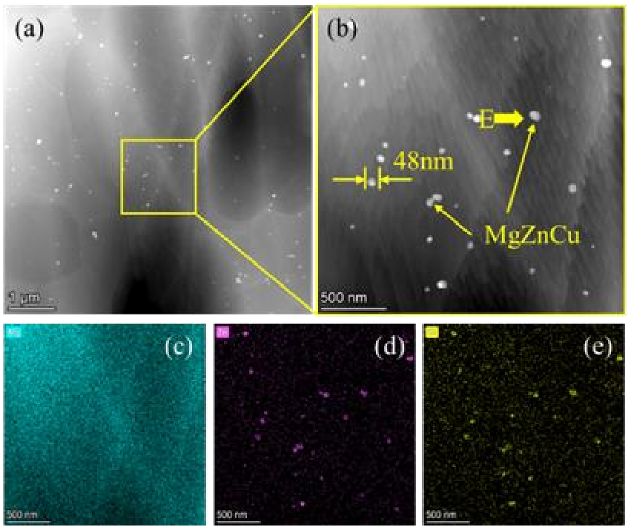

Fig. 3 TEM images of as-extruded Mg-2Zn-2Cu alloy: (a) Low magnification TEM image, (b) High-magnification TEM image, (c-e) The EDS surface scan image corresponding to Fig. b.

Further TEM characterization revealed additional notable features. As demonstrated in Fig. 3(a), numerous nanoscale secondary phases are dispersed within the matrix, exhibiting an average particle size of 48 nm.

Complemented by EDS mapping analysis, these nanophases were identified as ternary phases containing Mg, Zn, and Cu. EDS point analysis further revealed a Zn:Cu atomic ratio of 1:1 (Table 1), confirming these nanophases as MgZnCu phases. The formation mechanism of these nanophases involves two key stages: First, reduced alloying degree combined with homogenization treatment facilitates the creation of a supersaturated solid solution. Second, the subsequent hot extrusion process enables phase precipitation. These MgZnCu phases initially form in the as-cast alloy under specific conditions (controlled Zn/Cu contents, homogenization parameters, and extrusion processing), with the homogenization treatment establishing the supersaturated solid solution prerequisite for nanophase formation during extrusion.

The core mechanism governing the precipitation of nanoscale phases in magnesium alloys during hot extrusion stems from the synergistic interaction between high-temperature plastic deformation, alloying elements, and processing parameters. Building upon the supersaturated solid solution formed through homogenization treatment, the combined effects of elevated temperatures (240 °C) and severe plastic deformation during extrusion induce dynamic precipitation: Solute atoms (e.g., Zn, Al, rare earth elements)[14, 15] undergo shear stress-driven enrichment and rapid nucleation along dislocation lines, grain boundaries, or strain energy fields. Concurrently, the high-density dislocations introduced by deformation and the refined grain boundaries resulting from dynamic recrystallization provide preferential nucleation sites for nanophase formation. Critical process parameters, particularly restricted low-temperature diffusion and elevated extrusion ratios, suppress long-range solute migration while enhancing strain energy, effectively maintaining precipitated phases at nanoscale dimensions. This thermomechanical coupling process ultimately generates extrusion-aligned nanoparticles that significantly enhance the alloy's mechanical strength, heat resistance, and comprehensive performance.

3.2 Mg-2Zn-2Cu thermal conductivity and mechanical properties

As evidenced in Fig. 4, the thermal conductivity evolution demonstrates distinct processing-dependent characteristics: The as-cast alloy exhibits relatively high thermal conductivity (139 W/(m·K)), which decreases to 134 W/(m·K) after homogenization treatment, then increases remarkably to 153 W/(m·K) following hot extrusion. This performance variation originates from microstructural evolution: In the as-cast state, the formation of MgZnCu ternary phases effectively reduces matrix solute atom concentration, thereby minimizing electron and phonon scattering to maintain elevated conductivity [16, 17]. During homogenization, complete dissolution of solute atoms into the matrix intensifies scattering phenomena, resulting in conductivity reduction.

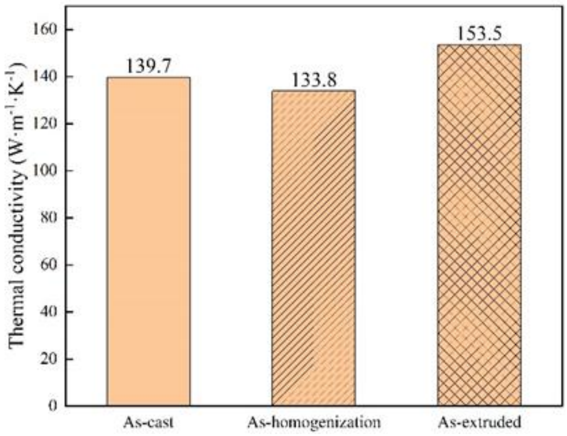

Fig. 4 The thermal conductivity of Mg-Zn-Cu alloys under different states.

Hot extrusion induces dual beneficial effects: First, reprecipitated secondary phases establish semi-coherent interfaces with the matrix, alleviating lattice distortion. Second, nanoscale phase precipitation further depletes solute atoms in the matrix [18]. The synergistic combination of these mechanisms - interface coherence improvement and solute concentration reduction - collectively enhances charge carrier mobility, ultimately achieving significant thermal conductivity improvement in the extruded alloy.

Table 1. Thermal conductivity and mechanical properties of Mg-2Zn-2Cu

State	Thermal conductivity (W/(m·K))	YS (MPa)	UTS (MPa)	EL (%)
As-cast	139.7	-	104.8	8
As-extruded	153.5	162.9	277.8	37.7

As can be seen from Table 2, after hot extrusion deformation, both the thermal conductivity and mechanical properties of the alloy have been improved. The ultimate tensile strength has increased to 277.8 MPa, and the elongation has increased to 37.7%. According to the microstructure, after hot extrusion deformation, the grain size of the alloy is greatly reduced, and the number of grain boundaries is increased. The resistance of grain boundaries to dislocation movement increases and the yield strength of the alloy is improved. At the same time, during the hot extrusion process, the second phase changes from a reticular structure to a dispersed granular structure in the matrix, which effectively hinders the dislocation movement and improves the tensile strength of the alloy [19, 20]. As for the thermal conductivity, casting defects have a great influence on the thermal conductivity. Hot extrusion can reduce the defects in the as-cast alloy and improve the thermal conductivity of the alloy. On the other hand, during the extrusion deformation process, the solute atoms are dynamically precipitated from the magnesium matrix to form the second phase, which reduces the content of alloying elements in the matrix and improves the thermal conductivity of the alloy.

4 Conclusions

- After hot extrusion, the MgZnCu phase in the Mg-Zn-Cu alloy changes from a network structure in the as-cast state to an island distribution at the grain boundaries along the extrusion direction
- After extrusion deformation, the casting defects and the content of solute atoms in the matrix are reduced, and the thermal conductivity of the alloy is improved. The highest thermal conductivity of the Mg-2Zn-2Cu alloy is 153.5 W/(m·K).
- Mg-2Zn-2Cu alloy obtained the best combination of strength and plasticity after hot extrusion deformation. The yield strength was 162.9 MPa, the tensile strength was 277.8 MPa, and the elongation was 37.7 %.

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Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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