Influence of Ca on Thermal Expansion and Mechanical Properties of Mg

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Abstract: The influence of Ca on the thermal expansion and mechanical properties of Mg are investigated in the present work. Alloying Ca is demonstrated to noticeably decrease the coefficient of thermal expansion (CTE) and increase the strength of Mg. A low CTE of ~18.7×10^{-6} K^{-1} in combination with the high ultimate compression strength of 291 MPa are achieved within the studied concentration interval. The reduced CTE and enhanced strength of Mg-Ca alloys is primarily emerging from the increased volume fraction of Mg_2Ca phase showing the relatively high melting point, elastic/shear moduli and low CTE. The low thermal expansion and high strength achieved in the Mg-Ca alloys provide a feasible route for the development advanced Mg alloys.

Keywords: Mg alloys; thermal expansion; mechanical properties, alloying

1 Introduction

Magnesium (Mg) alloys are very promising light metal materials applied in aerospace, transportation, and electronic industries [1-3]. However, Mg alloys generally have relatively high coefficient of thermal expansion (CTE) and low mechanical properties. The large thermal stress and volume change emerging from the high CTE of Mg alloys may cause hot-cracking during solidification and cooling process when preparing large and complex Mg alloy structural components. It is thus important to develop low-CTE Mg alloys with the improved mechanical properties. While the mechanical properties of Mg alloys have attracted extensive attention during last two decades [2, 3], the study on the thermal expansion behavior remains scarce. Among the available reports, the precipitation of low-expansion second phase is effective to depress the CTE of the alloys [4-6]. For instance, Si was reported to efficiently reduce the CTE of Mg owing to the precipitation of low CTE Mg_2Si phase [6]. Nevertheless, the brittle dendritic Mg_2Si phase was deemed to deteriorate mechanical properties of the alloys.

As a cheap non-rare earth element, low CTE and good strengthening effect of Ca [7-9], the influence of Ca on the thermal expansion and mechanical properties of Mg are investigated. Addition of Ca is demonstrated to noticeably decrease the CTE of Mg in a wide temperature interval and increase the strength simultaneously. The present advance is intended to provide a feasible route for the development of low-CTE and high-strength Mg alloys.

2 Experimental procedure

The Mg-xCa (x = 0, 4.1, 6.7, 10.1 and 12.4 wt.%) binary alloys were prepared in an electric resistance furnace using the commercial pure Mg (99.95 wt.%) and Mg-25 wt.% Ca master alloy. Second phases were characterized by a scanning electron microscope (SEM, JEOL JSM-7800F). Linear thermal expansion (dL/L_0) were measured using the NETZSCH DIL 402C dilatometer. The compressive mechanical properties were measured using the CMT6305-300 KN universal tensile testing machine.

3 Result and discussion

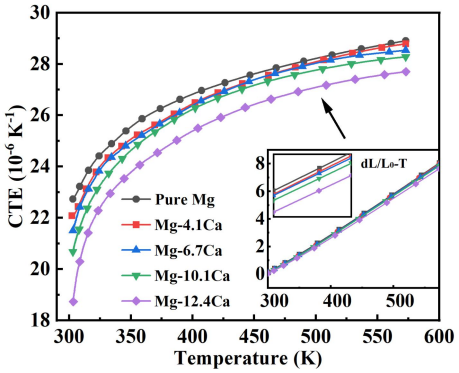

Fig.1 The CTE as a function of temperature

It is clear that linear thermal expansion (dL/L_0) increases with temperature while decreasing with Ca addition from the inserts of Figure 1. The CTE of Mg-Ca alloys gradually increase with temperature at a decreasing rate, which consists well with the Debye model [10]. As Ca content increased from 0 to 12.4 wt.%, the CTE noticeably decreases from ~22.7 to 18.7×10^{-6} K^{-1} at room temperature. At 573 K, the CTE slightly decreases from ~29 to 27×10^{-6} K^{-1} with Ca addition, indicating a rather weakened alloying influence at high temperature.

Figure 2 shows that with the addition of Ca, the compression yield strength (CYS) and ultimate compression strength (UCS) of the Mg-Ca alloy increases apparently. The CYS and UCS of Mg-12.4Ca alloy reach 252 and 291 MPa, respectively Nevertheless, the compression strain of Mg-Ca alloy gradually decreases with increasing Ca content.

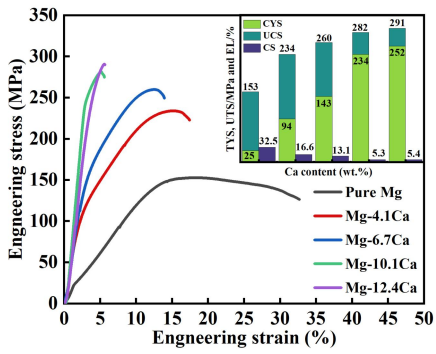

Fig.2 The compression curve of the Mg-Ca alloys

As mentioned above, Ca noticeably decreases the CTE of Mg and increase the strength simultaneously. To clarify the rationale behind, the physical parameters of pure Mg and Mg_2Ca phase are compared. It is found that Mg_2Ca phase exhibits the relatively high melting point, elastic/shear moduli, which are the physical quantities strongly correlating with the atomic bonding energy [11-13]. This results in a lower CTE for Mg_2Ca. Therefore, the increased volume fraction of Mg_2Ca phase induced by Ca addition (see Figure 3) will noticeably decrease the CTE of Mg-Ca alloys according to the rule-of-mixtures. In addition, Mg_2Ca phase is an efficient strengthening phase, the fraction of which noticeably increases with Ca addition, ultimately leading to the improved strength.

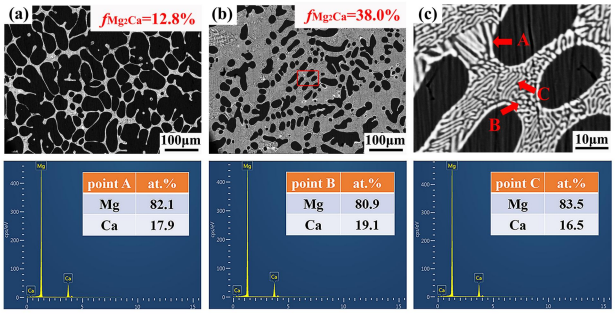

Fig.3 SEM-BSE images of the (a) Mg-4.1Ca and (b) Mg-12.4Ca alloys; (c) is the high magnification view for Mg-12.4Ca alloy

4 Conclusion

In summary, alloying Ca is demonstrated to noticeably decrease the coefficient of thermal expansion whilst increasing the strength of Mg. The lowest CTE of ~18.7 × 10^{-6} K^{-1} and highest UTS of 291 MPa are achieved at Ca content of 12.4 wt.%, respectively. The reduced CTE and enhanced strength of Mg-Ca alloys primarily emerge from the increased volume fraction of Mg_2Ca phase with Ca addition, which exhibits the relatively high elastic/shear moduli and low CTE.

Acknowledgments

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