Article

Microstructure, Mechanical and Thermal Properties of Mg-0.5Ca-xZr Alloys

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Abstract: To evaluate the potential values in heat dissipation applications, this study investigated the microstructure, mechanical and thermal properties of the Mg-0.5Ca-xZr alloys (x = 0.5 and 1 wt.%) under the as-cast, as-extruded and aged states. The phase constituents of the Mg alloys were examined by X-ray diffraction analysis, and the microstructure was inspected by optical microscopy and scanning electron microscopy. The thermal conductivity and mechanical properties of the Mg alloys were measured by the laser flash method and tensile tests, respectively. The results showed that the Mg alloys exhibited the equiaxed microstructure which is composed of α -Mg, Zr and compound Mg₂Ca. Both the extrusion process and increase of Zr content remarkably enhanced the mechanical strength of the Mg alloys and deteriorated the thermal performance simultaneously. It was also found that the thermal conductivity and mechanical strength of the Mg alloys increased gradually with the increase of aging time due to the higher precipitation of Zr and compound Mg₂Ca during the aging treatment. The Mg-0.5Ca-0.5Zr alloy aged at 473 K for 48 h demonstrated higher thermal conductivity than the required values of the Mg alloys used as heat dissipation materials. Moreover, the Mg-0.5Ca-0.5Zr alloy exhibited similar mechanical strength to the commonly-used Mg alloys, highlighting its potential become a potential heat dissipation material in the future due to its good combination of high thermal performance and mechanical strength.

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1. Introduction

The electronic, computer, communication and light-emitting diode (LED) lighting industries have grown rapidly in recent years, which raises high demand for materials that feature superior heat dissipation, high mechanical strength, low cost and light weight. Due to its desirable properties of low cost, lower density and relatively high thermal conductivity (TC) of 156 W/(m·K) at room temperature (RT) among metallic materials [1], magnesium (Mg) has attracted increasing research attention recently. Pure Mg is subject to poor strength and corrosion resistance, making it unsuitable for use as a structure material. In contrast, the commonly-used commercial Mg alloys, including AM60, AM20, AS21 and AZ91, have good mechanical strength, die castability and corrosion resistance [2,3]. The TC value of AM60, AM20, AS21 and AZ91 at RT, however, is 65, 97, 68 and 51.2 W/(m·K) [4–6], respectively, which is much lower than that of pure Mg and below the critical value of as-cast Mg alloys (100 W/(m·K)) standardized by Huawei Company, a world-famous manufacturer of information and communication [7]. Thus, the most commonly-used Mg alloys have the low TC values [1,4–6] and are unable to satisfy both the critically high thermal and mechanical properties of commercial products, especially for 3C (computer, communication and consumer product) products, LED radiators and the shells of automobile engines [8–10]. Although the addition of alloying elements to Mg can improve the mechanical strength of the Mg alloys by precipitation strengthening or/and solution strengthening, the formation of precipitates or/and solute atoms could inevitably deteriorate the TC of the Mg alloys [4–7,10–21], making it difficult to obtain one Mg alloy with

both high thermal performance and good mechanical strength for the heat dissipation applications. Thus, it is essential to develop new Mg alloys with both superior TC and mechanical strength. According to previous studies, increasing the alloying contents results in the decrease of TC of Mg alloys in different degrees [10–21], which may allow us to obtain Mg alloys with higher thermal property by adding only of small amount of alloying elements. If those added elements can effectively strengthen the Mg alloys at the same time, it is possible to obtain Mg alloys with both higher thermal performance and good mechanical strength. Fortunately, zirconium (Zr) has been found to be able to remarkably enhance the mechanical properties of Mg alloys by grain refinement [22–24], while calcium (Ca), with low density and low cost, could improve the high-temperature performance of Mg alloys [3,25–29]. Moreover, the strong effect of grain refinement in pure Mg could be realized by a small amount of both Zr and Ca [30,31]. Taken together, Mg alloys with a small amount of Zr and Ca are expected to have both high thermal performance and good mechanical strength. In recent years, the effects of Zr and Ca on the TC of Mg alloys have been investigated [13,15], and various Mg alloys containing Ca and Zr, such as the Mg-Sn-Ca alloy [15], Mg-Zn-Zr-Sm alloy [32], Mg-Ce-Zn-Zr alloy [33], Mg-La-Zr alloy [34] and Mg-2Zn-Zr alloy [35], have been developed and evaluated for their potentials in heat dissipation applications. However, so far, there have been few reports on the thermal properties of the Mg-Ca-Zr alloy. To bridge this gap, this paper aimed to evaluate the thermal property and mechanical strength of Mg-Ca-Zr alloys and identify new Mg alloys for the potential heat dissipation applications. Specifically, the plastic deformation usually enhances the mechanical strength of Mg alloys [36–38], and aging treatment improves the thermal properties of Mg alloys [35,39–41]. Therefore, the designed Mg alloys were also subjected to the plastic deformation and aging treatment, and the resulting thermal and mechanical properties of Mg alloys were also evaluated for potential applications in heat dissipation.

2. Material Preparation and Methods

The Mg-0.5Ca-xZr ($x = 0.5$ and 1 wt.%) alloys were fabricated by pure metal Mg (99.9 wt.%), Ca (99.9 wt.%) and master Mg-Zr alloy (33 wt.%) in appropriate proportions. Specifically, the mixture of N_2 and SF_6 was used as a protection gas during the melting process. The bars with a diameter of 46 mm were cut from the obtained ingots which were homogenized at 673 K for 24 h, and then extruded at 693 K with an extrusion ratio of 14.7. Some blank samples were machined from the as-extruded alloy bars and then aged at 473 K for 12, 24 and 48 h, respectively. The chemical compositions of the studied Mg alloys were determined by the X-ray fluorescence spectrometry. In particular, the Mg-0.5Ca-0.5Zr alloy was made of 0.35 wt.% of Ca, 0.44 wt.% of Zr and balance of Mg, while the Mg-0.5Ca-1Zr alloy was composed of 0.41 wt.% of Ca, 0.87 wt.% of Zr and balance of Mg.

The phase constituents of the Mg alloys were measured by X-ray diffraction analysis (XRD, Bruker, Germany) with Cu $K\alpha$ radiation. In addition, light optical microscopy (OM) and scanning electron microscopy (SEM, Hitachi Su-1500, Japan and Zeiss, Germany) with energy dispersive spectroscopy (EDS) were employed to observe the microstructure of the Mg alloys after the samples were polished and etched by the solution mixed with 5 mL nitric acid and 100 mL distilled water. Following ASTM E8-04, the rectangular tensile samples (Figure 1a) were wire-cut from the homogenized as-cast ingots, and round tensile samples (Figure 1b) were finely turned from the as-extruded bars, as well as aged blank samples along the longitudinal direction. The actual tensile samples are shown in Figure 1c. The ultimate tensile strength (UTS), tensile yield strength (YS) and elongation to failure were measured by tensile tests using Shimadzu Universal Testing Instruments with a speed of 1 mm/min.

Figure 1. Dimensioned schematics of the tensile samples used for (a) as-cast Mg alloys, (b) as-extruded and aged Mg alloys (unit: mm), and (c) actual tensile samples.

The disk specimens with ϕ 10 mm $\times$ 3 mm, which were machined from the as-cast ingots, as-extruded bars and aged samples at cross-section, respectively, were gauged by the laser flash method at RT to obtain the corresponding thermal diffusivity (TD). The TC of the studied Mg alloys was then calculated by the following formula [4]:

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

where λ is the TC (W/(m·K)), C_p is the specific heat capacity (J/(g·K)) calculated by the Neumann–Kopp rule [42,43] under constant pressure, ρ is the alloy density (g/cm³) obtained by Archimedes method and α is the TD (m²/s) of the Mg alloys. All of the above measurements were based on 5 samples.

3. Results and Discussion

3.1. Microstructure

Figure 2 shows the XRD patterns of the Mg-0.5Ca-xZr alloys. Briefly, all as-cast and as-extruded Mg alloys exhibited only α -Mg. The typical coarse microstructure of the as-cast Mg-0.5Ca-xZr alloys is shown in Figure 3. The average grain sizes of the as-cast Mg alloys, measured by the linear intercept method (the same below), were 308 ± 68 and 112 ± 35 μ m, respectively. This finding demonstrates that the addition of Zr can refine the structure and reduce the grain sizes of the Mg alloys, which is in accordance with previous studies [22–24,30]. The mechanism by which the Zr element refines the microstructure of as-cast Mg alloys is not very clear. It is commonly accepted that Zr and Mg have the same crystal structure (hcp) and close lattice parameters (Zr: $a = 0.323$ nm, $c = 0.514$ nm; Mg: $a = 0.320$ nm, $c = 0.520$ nm), which lead to more efficient nucleation during alloy solidification [30]. It is also believed that Zr has a very low solid solubility in the Mg matrix and very high melting point, so Zr particles may act as powerful nucleating centers of heterogeneous nucleation when the Mg alloy solidifies, resulting in an increase of the nucleation rate and grain refinement.

The microstructure of the cross-sections of the as-extruded Mg alloys became much finer (25 ± 9 and 22 ± 8 μ m, Figure 4a,b) than those of the as-cast Mg alloys after the hot extrusion, which could be due to the dynamic re-crystallization (DRX) during the hot extrusion.

Figure 2. XRD patterns of as-cast and extruded Mg alloys.

Figure 3. OM microstructure of (a) as-cast Mg-0.5Ca-0.5Zr alloy and (b) as-cast Mg-0.5Ca-1Zr alloy.

Figure 4. OM microstructure of (a) as-extruded Mg-0.5Ca-0.5Zr alloy and (b) as-extruded Mg-0.5Ca-1Zr alloy.

In order to identify the possible second phases, the microstructure of the as-cast Mg alloys was examined by SEM/EDS (Hitachi Su-1500), and the results are shown in Figure 5. The EDS analysis indicates that the matrix was α -Mg (Figure 5b). Figure 5c shows that the atomic ratio of Mg/Ca was about 1.9, suggesting that the phase along the boundary of grains was Mg_2Ca . Figure 5d reveals that a very small number of fine Zr particles were scattered in the matrix because there was no compound between Mg and Zr [44]. The particles of Zr and compound of Mg_2Ca were also detected by SEM/EDS analysis in the as-extruded Mg alloys, as shown in Figure 6. Some pits were also observed in Figure 6a because the above particles were washed away during the preparation of SEM samples. It is considered that the presence of Zr and compound of Mg_2Ca was not detected by XRD analysis, as shown in Figure 2, due to their very low amount in the as-cast and as-extruded Mg alloys.

Figure 7 shows the XRD patterns of the Mg alloys aged at 473 K for 12, 24 and 48 h, respectively, which exhibited three phases of α -Mg, Zr and Mg_2Ca . Some peaks of Zr and Mg_2Ca became clearly visible, indicating that the amount of Zr and Mg_2Ca increased after the aging treatment. The aged Mg alloys exhibited the similar equiaxed microstructure in Figure 8a–f. The grain sizes are shown in Table 1, which are close to those of corresponding extruded Mg alloys, respectively. Moreover, the SEM microstructure of the Mg alloys aged for 12 h is shown in Figure 9, and the EDS analysis identified the particles of Zr and compound of Mg_2Ca . This finding is consistent with the XRD results.

Figure 5. (a) SEM microstructure of as-cast Mg-0.5Ca-0.5Zr alloy, (b) EDS analysis of area 1, (c) EDS analysis of area 2 and (d) EDS analysis of area 3.

Figure 6. SEM microstructure of (a) as-extruded Mg-0.5Ca-0.5Zr alloy and (b) as-extruded Mg-0.5Ca-1Zr alloy. (c) EDS analysis of area 1 and (d) EDS analysis of area 2.

Figure 7. XRD patterns of aged Mg alloys.

Figure 8. OM microstructure of (a) Mg-0.5Ca-0.5Zr alloy aged for 12 h, (b) Mg-0.5Ca-1Zr alloy aged for 12 h, (c) Mg-0.5Ca-0.5Zr alloy aged for 24 h, (d) Mg-0.5Ca-1Zr alloy aged for 24 h, (e) Mg-0.5Ca-0.5Zr alloy aged for 48 h and (f) Mg-0.5Ca-1Zr alloy aged for 48 h.

Table 1. Mean grain sizes of the aged Mg alloys with the aging time (μm).

Alloy Code	12 h	24 h	48 h
Mg-0.5Ca-0.5Zr	17 ± 6	22 ± 6	27 ± 7
Mg-0.5Ca-1Zr	15 ± 5	21 ± 6	25 ± 7

Figure 9. SEM microstructure of (a) Mg-0.5Ca-0.5Zr alloy aged for 12 h and (b) Mg-0.5Ca-1Zr alloy aged for 12 h. (c) EDS analysis of area 1 and (d) EDS analysis of area 2.

The higher precipitation of Zr and Mg_2Ca from the aged Mg alloys was due to their limited solid solubility. According to the binary Mg-Ca and Mg-Zr phase diagrams, the solid solubility of Ca in Mg is 1.34 wt.% at 518 °C [15,44], and that of Zr in Mg is 0.58 wt.% at 654 °C [30,44], respectively. When the temperature decreases, the solid solubility accordingly drops, and precipitation of Zr and Mg_2Ca usually occurs. The temperatures of homogenization treatment (673 K) and hot extrusion (693 K) are much higher than that of the aging treatment (473 K). Therefore, the solid solubility of Zr and Ca in the aged Mg alloys is lower than that of the as-cast and as-extruded Mg alloys, which is the reason why more Zr and Mg_2Ca precipitate in the aging state than the other states. Phase Mg_2Ca was detected using the TEM (transmission electron microscopy) technique in the Mg-0.5Ca (wt.%) alloy aged at 473 K due to the limited solubility of Ca in Mg in previous study [45]. Very small amounts of dispersed Zr particles were identified by SEM in the as-cast Mg-0.5Zr alloy [13]. These help us to understand why the particles of Zr and the compound Mg_2Ca precipitate were present in the Mg-0.5Ca-xZr alloys in present study.

3.2. Mechanical Properties

Figure 10 shows the tensile properties of the as-cast and as-extruded Mg-0.5Ca-xZr alloys. Briefly, the tensile strength of the Mg alloys increased with the Zr content. The strength of metallic materials can be improved by fine strengthening, solid solution strengthening, precipitation strengthening and work hardening (dislocation accumulation, substructure

and texture, and so on). It is generally considered that the as-cast alloys have no work hardening (texture-free). The particles of Zr and Mg_2Ca were not detected by XRD analysis (Figure 2), implying that their amount was very low and the resulting precipitation strengthening could be neglected. According to Table 2, where the crystal parameters were calculated by the software of Jade 6.0 based on the XRD results, it can be seen that the distortion degree of the crystal lattice increased with Zr content, suggesting that the solid solution strengthening in the Mg alloys increased with the increase of Zr content. The grain sizes of the as-cast Mg alloys decreased from 308 μm to 112 μm (Figure 3), indicating that the fine strengthening increased significantly with the increase of Zr content according to the Hall-Petch formula. Therefore, the strength of the as-cast Mg alloys increased, which was mainly due to the enhanced fine strengthening and solid solution strengthening with the increase of Zr content.

Figure 10. (a) Nominal tensile strain stress curves, (b) tensile strength and (c) elongation of the as-cast and as-extruded Mg alloys.

Table 2. Lattice parameters of the α -Mg phase.

Composition (wt.%)	Lattice Parameters		
	a/nm	c/nm	c/a
Pure Mg [46]	0.32094	0.52108	1.6236
Cast Mg-0.5Ca-0.5Zr alloy	0.320936	0.521120	1.62375
Cast Mg-0.5Ca-1 Zr alloy	0.320968	0.521230	1.62393
Extruded Mg-0.5Ca-0.5Zr alloy	0.320930	0.521237	1.62415
Extruded Mg-0.5Ca-1 Zr alloy	0.320922	0.521581	1.62526

Since the as-extruded Mg alloys were subject to the same extrusion process, they had the same effect of work hardening. No un-recrystallized grains were observed after the hot extrusion at 420 °C (Figure 4), which demonstrates that the DRX was completed in those alloys and the resulting work hardening basically disappeared. The as-extruded Mg alloys exhibited similar grain sizes (Figure 4), indicating the similar effect of fine strengthening on those alloys according to the Hall-Petch formula. Thus, the strength improvement of the as-extruded Mg alloys with the increase of Zr content was mainly associated with the enhanced solution strengthening, as well as with the increase of Zr content, because the precipitation strengthening in those alloys was negligible due to the very low precipitation content. The significantly higher strength of the as-extruded Mg alloy than that of the corresponding as-cast Mg alloy was primarily related to the fine strengthening and possible texture caused by the extrusion. Normally, the ductility of metallic materials decreases while the strength increases. The ductility of the studied Mg alloys, however, increased with the Zr content, which was related to the decreased grain sizes with Zr content because fine structure can improve both the strength and plasticity of metallic materials.

As shown in Figure 11, the tensile properties of the aged Mg alloys increased gradually with the aging time. This occurred because more Zr and Mg_2Ca precipitated with aging time, as mentioned above, and Mg_2Ca has a moderate hardening effect on the Mg alloys [47]. It can be seen from Table 1 that there was no obvious difference in the grain sizes for the aged Mg alloys, indicating the similar fine strengthening on the aged alloys. As mentioned above, the work hardening almost disappeared when the DRX was finished. Therefore, the strength of the aged Mg alloys increased with the increase of Zr content, which was mainly related to the continuous precipitation strengthening from more particles of Zr and Mg_2Ca during the aging treatment and the enhanced solution strengthening with the increase of Zr content. The aged Mg alloy exhibited higher strength than the corresponding as-extruded Mg alloy, which was principally due to more effective precipitation strengthening from the aging treatment. There is no obvious difference among the grain sizes of the aged Mg alloys according to Table 1, which indicates the similar effect of fine structure strengthening on the aged Mg alloys. Therefore, the ductility of aged Mg alloys decreased naturally with the aging time when their tensile properties increased gradually, which is normal.

(a)

(b)

Figure 11. Cont.

Figure 11. (a) Normal tensile strain stress curves, (b) tensile strength and (c) elongation of the aged Mg alloys.

3.3. Thermal Conductivity

The TD and TC of the studied Mg alloys calculated from the Equation (1) are displayed in Figure 12a,b, respectively. It is noticed that the TD and TC of the Mg alloys decreased with the increasing Zr and increased gradually with the increase of aging time. Apparently, the hot extrusion process deteriorated both the TD and TC of the Mg alloys.

Figure 12. (a) Thermal diffusivity and (b) thermal conductivity of the Mg alloys.

In general, the TC of the alloys consists of the electronic TC and lattice TC, since the phonons and electrons are the main carriers of heat in alloys [11,20,48]. When Mg forms an alloy with the other elements, a solid solution or metallic compound is usually formed, and the crystalline lattice of the α -Mg matrix is distorted. Solute atoms, metallic compounds and lattice defects are the scattering centers of electrons and phonons, which can prevent the free movement of electrons and thus deteriorate the thermal properties of the alloy [10,12,48]. Generally, metallic compounds, solute atoms, lattice defects (dislocation, vacancy, grain boundary) and temperature influence the TC of Mg alloys [21,48]. Among them, the TC of alloys is greatly influenced by metallic compounds and solute atoms [21]. TC, as the most important heat dissipation property of Mg alloys, is also sensitive to the microstructure of Mg alloys.

In this study, the distortion degree of crystal lattice increased, as shown in Table 2. In addition, the grain sizes decreased (Figures 3 and 4), and more Mg_2Ca and Zr (both scattering sources of electrons and phonons) precipitated with the increase of Zr content. These led to the reduction in the TC of the Mg alloys with an increase of the Zr content, which is in agreement with previous investigations [11–21]. The as-extruded Mg alloys demonstrated much finer microstructures than the as-cast Mg alloys (Figures 3 and 4), which accounts for the lower TC observed in the as-extruded Mg alloys compared to the corresponding as-cast Mg alloys. Several studies have shown that finer structure generally decreases the TC of Mg alloys [11,12,18,49,50].

The texture is usually developed by plastic deformation, and its effect on the thermal properties of Mg alloys has been studied by many researchers [11,12,33,49,50]. Trojanová et al. [50] investigated the microstructure and TC of an AX52 alloy performed by ECAP (equal channel angular pressing) at 250 °C, and found that the grain size rapidly decreased from 63 μm to 3.4 μm with an increase of the ECAP passes from 1–8. In addition, the texture strengthening increased accordingly, which certainly changed the conductivity of the AX52 alloy. The individual effect of fine grain size and texture on the conductivity, however, was not analyzed separately. Yuan et al. [49] investigated the anisotropy of TC and mechanical properties of an ZM51 alloy extruded at 350 °C, and reported that the TC value in the extrusion direction, transverse direction and normal direction was 110.7, 117.9 and 117.4 W/(m·K), respectively. This finding indicates that the difference in TC anisotropy was about 6% for the ZM51 alloy. Therefore, the effect of the extrusion texture on the TC of the Mg alloy was much weaker compared to other factors such as the alloying element and precipitate.

The microstructure evolution of an extruded Mg alloy is dependent on the extrusion temperature [7,33,51]. Peng et al. [7] studied the influence of extrusion temperature on the microstructure and thermal properties of Mg-2Zn-1Mn-0.2Ce alloys, and reported that the volume fraction of un-recrystallized grains decreased from 30.4% to 15.1% when the extrusion temperature increased from 340 °C to 430 °C. Moreover, the increase of TC was due to the combined effect of the volume fraction of un-recrystallized structure, grain size and solid solution of Mn. For the extruded Mg-Ce-Zn-Zr alloy, the work hardening was dominant at a lower extrusion temperature of 150–200 °C, and was replaced by the combination of dynamic recovery and work hardening at the intermediate temperature of 200–300 °C. The DRX finally took the dominant place at a higher temperature of 300 °C [51]. Hu et al. [33] investigated the microstructure, thermal and mechanical properties of an Mg-Ce-Zn-Zr alloy extruded at 300 °C, 350 °C and 400 °C, and proved that the extrusion texture was weakened due to the recovery, DRX and grain growth. In addition, the authors showed that the TC of the Mg-Ce-Zn-Zr alloy tended to be isotropic at the extrusion temperature of 400 °C. In this study, the DRX was completed, and the extrusion temperature was 420 °C higher than that of the abovementioned investigations [33,49]. Therefore, the texture caused by extrusion was expected to be weak, and its influence on the TC of the Mg alloys was estimated to be very low. According to Table 1, no obvious difference was observed among the grain sizes with the aging time, indicating that the effect of grain boundaries on the TC of the aged Mg alloys was similar. As mentioned above, more Mg_2Ca and Zr precipitate during the aging treatment, which results in the increment of the TC of Mg alloys with the aging time. This occurs because the TC reduction caused by the alloying element, as solute atoms dissolved in the Mg matrix is about one order of magnitude larger than those caused by metallic compounds [21,52]. This result is consistent with the findings in previous experimental studies [35,39–41].

Aging treatment usually alters the microstructure (phase precipitation, recovery, grain growth and so on) of a Mg alloy, which influences the conductivity. Some research work has been conducted to investigate the influence of aging time on the TC of Mg alloys [35,39–41]. For example, the TC value of an Mg-2Zn-1Zr alloy aged at 175 °C for 36 h increased with the prolongation of aging time, reached the maximum value at 24 h and then almost remained unchanged [35]. The conductivity of Mg-2Zn and Mg-2Sn alloys continued

to increase with the increase of aging time when those alloys were aged at 160 °C for 60 h [39,40]. The similar change trend of the conductivity was also observed for an Mg-5Sn alloy aged at 240 °C for 120 h [41]. The TC increase in these Mg alloys was the result of more precipitation with the prolongation of aging time [35,40,41], which is consistent with this study.

Aging temperature is another important factor in aging treatment, which also inevitably influences the microstructure and conductivity of an Mg alloy. However, so far, there have been few reports on the effect of aging temperature on the TC of Mg alloys. Thus, additional research is needed in this respect. The aging parameters of this study were determined by reference to the abovementioned investigations [35,39–41]. It can be noticed that both the tensile strength and TC of the aged Mg alloys increased with the aging time, and did not reach their respective maximum values after 48 h of aging. Therefore, more aging experiments with different aging parameters are needed to optimize the mechanical and thermal properties of the Mg-0.5Ca-xZr alloys for better heat dissipation applications.

As stated in the introduction, the materials used in electronic devices should have good heat dissipation and high mechanical properties. Better heat dissipation is due to the higher TC of the material [16,53]. Therefore, the heat dissipation materials should have high TC to prevent overheating of the electrical devices, and to extend the life and stability of the devices. Table 3 summarizes the tensile strength and TC of the Mg-0.5Ca-xZr alloys with some commonly-used Mg alloys (AZ91D, AM60, AS21 and AM20). It shows that the Mg-0.5Ca-xZr alloys exhibited much higher TC than those Mg alloys. In addition, the aged Mg-0.5Ca-xZr alloys exhibited good mechanical properties similar to the commonly-used Mg alloys. In particular, the Mg-0.5Ca-0.5Zr alloy aged for 48 h at 473 K demonstrated higher TC than the 120 W/(m·K) of the wrought Mg alloys required by Huawei Company [7], and good mechanical strength close to that of the commonly-used Mg alloys, highlighting its potential to become a potential heat dissipation material in the future.

Table 3. Tensile strength and TC values of the Mg-0.5Ca-xZr alloys and some commonly-used Mg alloys.

Alloy Cod	YS	UTS	TC	Reference
	(MPa)	(MPa)	(W/(m·K))	
Extruded Mg-0.5Ca-0.5Zr alloy	125	185	95.4	this study
Extruded Mg-0.5Ca-1Zr alloy	152	215	91.5	this study
Mg-0.5Ca-0.5Zr alloy aged for 48 h	162	202	125.9	this study
Mg-0.5Ca-1Zr alloy aged for 48 h	186	236	114.8	this study
AM60	115	205	65	[4,26]
AM20	90~120	160~210	97	[5,54]
AS21	130	240	68	[5,26]
AZ91D	150	230	51.2	[6,26]

4. Summary

In the present study, we investigated the microstructure, mechanical and thermal properties of the Mg-0.5Ca-xZr alloys under the as-cast, as-extruded and aged states for heat dissipation applications. The results indicate that the Mg-0.5Ca-xZr alloys exhibited the equiaxed microstructure, which is composed of α -Mg, Mg₂Ca and Zr. Both extrusion process and the increase in Zr content remarkably enhanced the mechanical strength of the Mg alloys while reducing the thermal properties. Furthermore, the mechanical strength and TC of the Mg alloys gradually increased with the aging time. The Mg-0.5Ca-0.5Zr alloy aged at 473 K for 48 h demonstrated higher thermal conductivity than the required values of the Mg alloys used as heat dissipation materials. In addition, the Mg-0.5Ca-0.5Zr alloy exhibited good strength similar to that of the commonly-used Mg alloys. Therefore, this Mg alloy is expected to be a potential heat dissipation material in the future due to its good combination of high thermal and mechanical properties.

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