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MINI REVIEW

Strengthening-toughening methods and mechanisms of Mg–Li alloy: a review

Xiang Peng, Wen-Cai Liu*, Guo-Hua Wu

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Abstract Magnesium–lithium (Mg–Li) alloy, as the lightest metal structure material, has unparalleled market prospects in aerospace, weapons and equipment, electronic technology, transportation, and many other fields. However, it is hard to balance the superlight and high strength of Mg–Li alloy, and the inferior high-temperature strength and poor high-temperature stability limit the wide application of Mg–Li alloy. At present, the main methods to improve the mechanical properties of Mg–Li alloy are alloying, grain refinement, and compound strengthening. The domestic and overseas research progress in the strengthening and toughening methods and mechanisms of Mg–Li alloy are reviewed, and the future development of the high strength and high toughness Mg–Li alloy is prospected.

Keywords Mg–Li alloy; Solution strengthening; Precipitation strengthening; Grain refinement strengthening; Compound strengthening

1 Introduction

With the rapid development of the automobile industry, air pollution caused by automobile exhaust is becoming more and more serious. Using lightweight materials to replace original parts can reduce the weight of transportation vehicles, which not only reduces exhaust emissions but also saves energy. Therefore, many researchers have carried out projects on lightweight materials. As the lightest structural material, Mg–Li alloy has been extensively studied and developed [1–5]. Mg–Li alloy also has the unique characteristics of high specific strength, good electromagnetic shielding, and machining performance besides the advantages of lightness, resulting in wide potential use in military, 3C (computer, communication, and consumer electronics), aerospace, and other fields [6, 7].

The Mg–Li binary alloy is formed by adding metal lithium (Li) to magnesium (Mg) [8]. Up to now, Mg–Li alloy has the lowest density in the commercial alloy system. Since the density of Li is only 0.534 $g \cdot cm^{-3}$, the density of Mg–Li alloy decreases with the increase of the amount of lithium. When adding each 1% Li in Mg, the density of the alloy can be reduced by 0.032 $g \cdot cm^{-3}$. Therefore, Mg–Li alloy is also known as a superlight alloy with a density of 1.35–1.65 $g \cdot cm^{-3}$ [9].

According to the binary phase diagram of Mg–Li alloy, the phase structure of the matrix closely depends on the Li addition [1]. When Li content is lower than 5.7 wt%, the alloy is composed of a single-phase α-Mg with hcp structure. When Li content is higher than 10.3 wt%, the alloy is composed of a single-phase β-Li with bcc structure. Between 5.7 wt% and 10.3 wt%, there is a dual-phase $\alpha + \beta$ with hcp + bcc structures. When Li content exceeds 5.7 wt%, the plasticity of the alloy will be greatly improved due to the formation of the relatively soft β-Li phase. In addition, metal Li can also reduce the axis-to-diameter ratio (c/a value) of magnesium alloy, decrease the atomic spacing, thus lowering the critical shear stress of cylinder and cone slip systems during deformation. Therefore, the basal plane slip and non-basal plane slip can

X. Peng, W.-C. Liu*, G.-H. Wu
National Engineering Research Center of Light Alloy Net Forming and State Key Laboratory of Metal Matrix Composite, School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
e-mail: liuwc@sjtu.edu.cn

be activated at room temperature, which further effectively improves the room temperature ductility of magnesium alloy. However, it is hard to balance the superlight and high strength of Mg–Li alloy, and the inferior high-temperature strength and poor high-temperature stability limit its wide application. The tensile strength of common Mg–Li alloys is shown in Table 1 [8, 10–18]. It is particularly urgent and important to improve the comprehensive properties of Mg–Li alloy. In this review, we attempt to tell a short story about the strengthening and toughening methods and mechanisms of Mg–Li alloy, covering the alloying, strengthening, grain refinement strengthening, and compound strengthening.

2 Alloying strengthening

At present, one of the main methods to improve the strength and toughness of as-cast Mg–Li alloy is alloying [19], that is, adding alloying elements, using solid solution strengthening, and precipitation strengthening to improve the room-temperature and high-temperature properties of the alloy. Alloying design starts from the crystallography, relative size of the atom, valence as well as electrochemical factors. And the alloying elements should have higher solid solubility in the Mg–Li matrix and can form a transition phase strengthening effect in the aging process. In addition to the optimization of mechanical properties, the corrosion resistance, machinability, and oxidation resistance of alloying elements are also considered.

2.1 Solid solution strengthening

In the process of solution strengthening, the alloying element (solute) atom replaces the matrix (solvent) atom when the solute completely dissolves into the solvent, thus strengthening the matrix through atomic dislocation and the difference of elastic modulus between the solute and the solvent atom [12]. The main factor to evaluate the solution strengthening effect of an alloying element is its solubility in the magnesium matrix, and the second is to consider the difference between its radius size and that of the magnesium matrix. In particular, Al and Zn have high solid solubility in Mg–Li alloy, and they are the most common solution strengthening elements, which can produce a good solution strengthening effect in the alloy [20–22].

Guo et al. [23] investigated the influence of solid solution parameters on the microstructure and hardness evolution of Mg–9Li–6Al alloy. The results showed that the $MgLi_2Al$ phase was dissolved in the β-Li phase, and the AlLi phase precipitated from the α-Mg phase under the condition of 340 °C, 0.5 h. With the holding time prolonging to 1 h, the precipitated AlLi distributed in the whole phase of α-Mg. In addition, the hardness of Mg–9Li–6Al alloy treated by solid solution was obviously improved compared with as-cast ones. Dong et al. [24] studied the microstructure and mechanical properties of Mg–6Li and Mg–6Li–1Y alloys. When 1% Y was added to Mg–6Li alloy, it was solid soluble in the matrix to form Y-rich zone. The yield strength and tensile strength of the alloy were increased by 43% and 26%, respectively, and the elongation was increased by 32%.

Fei et al. [25] investigated the effect of solid solution treatment on the microstructure and hardness of Mg–9Li–6Al–*x*La (x = 0, 2, 5). When the solution temperature was 350 °C, the lamellar AlLi would precipitate from α-Mg, while the $MgLi_2Al$ was dissolved in the matrix. However, during solution treatment at 450 °C, the AlLi phase was wholly dissolved into the matrix, while the $MgLi_2Al$ was precipitated from β-Li. The addition of La could reduce the size of α-Mg, restrain the formation of AlLi, as shown in Fig. 1. With the addition of La, the decrease of the AlLi and $MgLi_2Al$ led to a descent of hardness, while the

Table 1 Tensile properties of common Mg-Li alloys

Composition	Microstructure	Ultimate tensile strength/MPa	Elongation/%
Mg–5Li–1Al–1Zn–1Sn–0.4Mn	α	290.0–300.0	8.0
Mg–8Li–1Al	α + β	313.9	3.2
Mg–8Li–2Al–RE	α + β	165.0	35.0
Mg–8Li–3Al–2Zn–0.5Nd	α + β	243.0	23.7
Mg–8Li–5Al–2Zn–0.2Ce–0.2Mn–5Cd	α + β	210.0–280.0	8.0–25.0
Mg–9Li–3Al–3Zn	α + β	152.0	12.0
Mg–10Li–1Al	α + β	172.5	28.9
Mg–11Li–1Al–2Zn-0.2Ce–0.4Mn	β	160.0–220.0	15.0–40.0
Mg–11Li–1Al–0.5Y	β	276.0	20.0
Mg–14Li–1Al	β	139.0	22.0

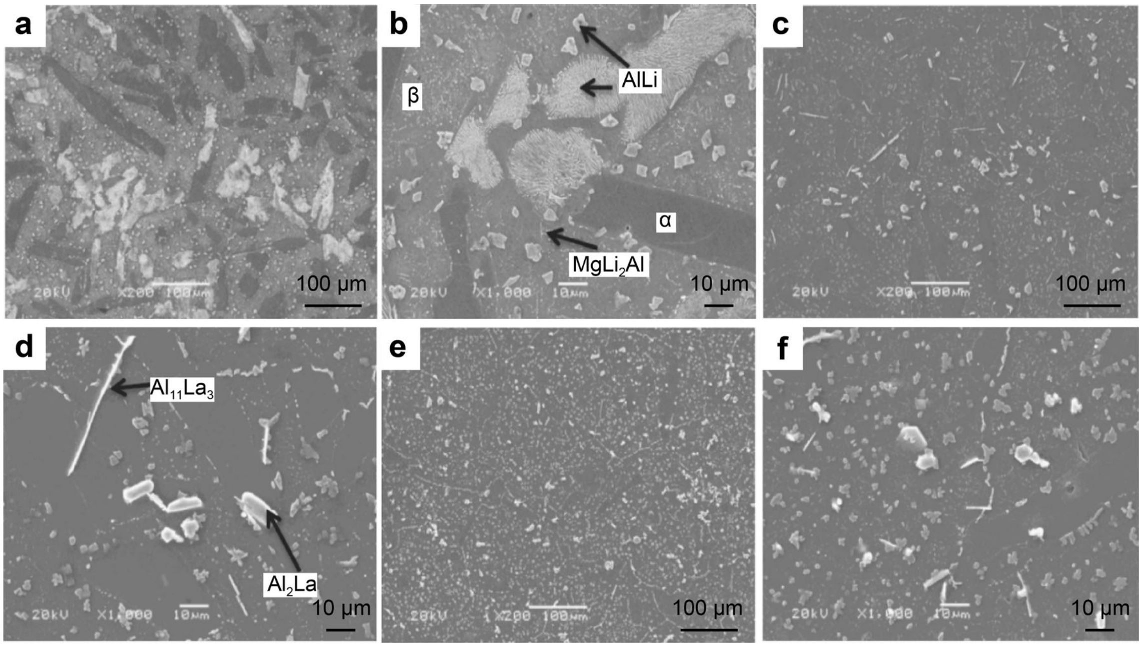

Fig. 1 SEM images of Mg–9Li–6Al alloys with different La contents: **a, b** 0%; **c, d** 2%; **e, f** 5%. Reproduced with permission from Ref. [25]. Copyright 2014, Elsevier B.V

refinement, Al–La phase precipitation, and solution of Al atoms improved the hardness of the alloys.

2.2 Precipitation strengthening

Precipitation strengthening, also called second-phase reinforcement, is an important mechanism for strengthening of as-cast Mg–Li alloy. An alloying element has its own fixed solubility in the matrix. When the alloying element is added to the matrix beyond this fixed value, the extra alloying element will form a second phase with the matrix element. The structure of the second phase can be classified into three types as follows [8]: (1) AB type, simple cubic CsCl structure, e.g., MgTi, MgAg, MgCe, and MgSn; (2) AB_2 type, Laves phase, e.g., $MgCu_2$, $MgZn_2$, and $MgNi_2$; (3) CaF_2 type, fcc structure, e.g., Mg_2Si and Mg_2Sn. However, the solubility of alloying elements in the matrix decreases with the decrease in temperature, accompanied by precipitation of the second phase. And the second phase hinders the dislocation motion and slip, thus increasing the yield strength of the alloy. The size and shape of the precipitated phase as well as the interfacial properties between the precipitated phase and the matrix have a great effect on the strengthening effect. The fine and dispersed second phase particles are distributed evenly in the matrix of the magnesium alloy, resulting in an important strengthening effect. However, the size of the precipitated phase in the alloy is relatively large and not uniform, which leads to the decline of mechanical properties.

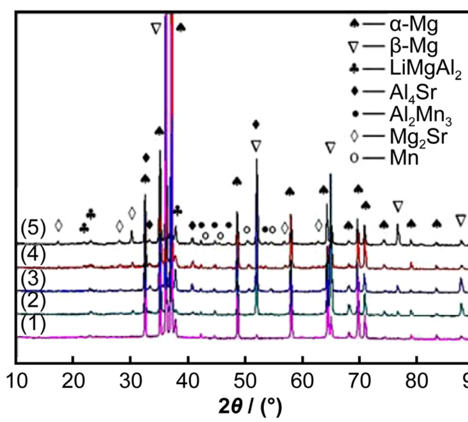

Fig. 2 XRD patterns of different alloys: (1) Mg–8Li–3Al–0.5Mn; (2) Mg–8Li–3Al–0.5Mn–0.25Sr; (3) Mg–8Li–3Al–0.5Mn–0.5Sr; (4) Mg–8Li–3Al–0.5Mn–0.75Sr; (5) Mg–8Li–3Al–0.5Mn–1.0Sr. Reproduced with permission from Ref. [26]. Copyright 2014, the Nonferrous Metals Society of China

Xu et al. [26] studied the microstructure and performance of Mg–8Li–3Al–0.5Mn–xSr (x = 0–1). The as-prepared Mg–8Li–3Al–0.5Mn alloy contained α-Mg, β-Li, Al_2Mn, and $MgAl_2$ phases according to Fig. 2. The new Al_4Sr and Mg_2Sr were dispersed between α-Mg and β-Li as Sr was added to this alloy. The as-extruded Mg–8Li–3Al–0.5Mn–0.75Sr alloy showed an optimal tensile strength of 265.46 MPa, which was increased by 19.38% compared with that of the matrix.

Li et al. [27] investigated the effect of Cu additions (0.5%–2.0%) on the microstructure and hardness of Mg–

5Li–3Al–2Zn alloy. As Cu addition increased, the AlCuMg phase existed in the alloy. This phase could partially restrained the formation and growth of the AlLi phase. In addition, the hardness of AlCuMg and Al_2Cu was higher than that of AlLi phase, resulting in a higher hardness of Mg–5Li–3Al–2Zn–2Cu alloy.

Tang et al. [28] prepared Mg–*x*Li–3Al–2Zn–0.2Y ($x = 5$, 8, 11) by extruding and annealing process and studied their microstructural evolution and precipitation strengthening behavior. After annealing at 250 °C, in the Mg–8Li–3Al–2Zn–0.2Y and Mg–11Li–3Al–2Zn–0.2Y, a great deal of intermetallic compounds (1.8–2.5 mm) extensively precipitated from β phase. The large number of dispersive precipitates in β phase significantly enhanced the strength of the alloys.

3 Grain refinement strengthening

Grain refinement is one of the most effective ways to improve the properties of as-cast Mg–Li alloy. This method not only improves the yield strength of Mg–Li alloy but also increases its plasticity and toughness. The relationship between grain size and yield strength of metal can be expressed by the Hall–Petch formula [29]:

$$\sigma_{\mathrm{y}} = \sigma_0 + kd^{-1/2} \tag{1}$$

where σ_{y} is the yield stress of the alloy, σ_0 is the yield stress of a single crystal, k is the stress intensity factor of plastic deformation, also known as the Hall–Petch coefficient, and d is the grain diameter of the alloy. σ_{y} will increase gradually when d decreases gradually.

According to metallic theory, the more the metal grains per unit volume is, the larger the number of grain boundaries is. The grain boundary hinders the dislocation movement. The larger the number of grain boundaries is, the more ability they have to hinder the dislocation movement, thus increasing the strength of the metal. Besides, the refined grain improves the plasticity and high-temperature properties of the alloy. The common grain refinement strengthening methods consist of controlling the solidification process [30], adding grain refiner [31], and severe plastic deformation [32].

3.1 Controlling solidification process

The degree of undercooling (ΔT) is increased by increasing the cooling rate, and then the nucleation rate is improved, so as to achieve grain refinement. With the increase of ΔT, the nucleation rate and growth rate increase simultaneously, and the faster nucleation rate results in a refined grain. The common fast cooling methods include: the use of metal mold with good thermal conductivity, such as copper mold [33]; applying forced cooling to a mold, such as water-cooled mold [34].

Muga et al. [30] prepared Mg–14Li–3Al–3Ce alloy through a fast cooling and aging process. Prolonged aging and fast-cooling initiated the formation of thermal second phase intermetallics. The presence of $Mg_{17}Al_{12}$, $Mg_{12}Ce$, and $Al_{11}Ce$ precipitates induced grains/grain boundary refinement of Mg–14Li–3Al–3Ce alloy and enhanced its tensile strength. The prepared Mg–14Li–3Al–3Ce alloy that was aged for 15 h depicted yield strength ($\sigma_{0.2}$) of 105.5 MPa, ultimate tensile strength (σ_{b}) of 136.8 MPa and an elongation of 19.2%. Fast-cooling enhanced the strength of Mg–14Li–3Al–3Ce alloy through grain refinement, crystallization and solid solution strengthening. The increase of ΔT can also be achieved by rapid solidification techniques [9]. Non-equilibrium solidification will occur when the alloy solidifies at a high enough cooling rate and produces a metastable phase. Then the solid solubility of the metastable phase will increase in the alloy and the grain will be refined, therefore improving the strength, plasticity, wear resistance, and corrosion resistance of the alloy.

Matsuda et al. [35] developed Mg–15Li–4Si–1Al by melt spinning method. The results showed that the melt-spun Mg–Li alloy possessed a microstructure consisting of a fine dispersion of Mg_2Si phase in a fine-grained bcc Mg–Li solid solution, resulting in the improvement of thermal stability and mechanical properties. Zhou et al. [36] fabricated near-eutectic Mg–Li binary alloys through rapid solidification conditions by using the copper-mold suction casting technique. The microstructure of the near-eutectic Mg–Li binary alloy by rapid solidification technique was remarkably distinct from those by the conventional gravity casting. The well-developed dendritic and complex/quasi-regular eutectic microstructures were formed in Mg–6.8Li alloy except for considerable primary α-Mg equiaxed dendrites. Also, the rapid solidification induced α-Mg grains with a much finer size and larger volume fraction than those by the conventional gravity casting.

3.2 Adding grain refiner

Modification is a method of adding a small amount of substance to metal liquid to promote the nucleation of metal liquid or change the crystal growth process. For as-cast alloys, modification is to refine the second phase or to change its morphology and distribution through adding a grain refiner. The casting and machining properties, strength, and plasticity of the alloy can be improved by modification treatment. The modifier can be divided into two kinds: one is rare earths [31]; the second is traditional elements such as Zr, Mn, Ca, Cu [27, 37, 38].

Rare earth elements have been the most effective alloying elements in magnesium alloys because of their unique physical and chemical properties, which come from their special extranuclear electron structure. During the solidification, the accumulation of rare earths at the front of the solid–liquid interface leads to undercooling, and the formation of new nucleation zones in the undercooling zone leads to the formation of fine equiaxed grains. Besides, rare earths can react with Mg and other elements in the alloy to form rare earth compounds dispersed in the matrix. Owing to the high melting point of these rare-earth compounds, they solidify first, which not only increases the nucleation particles but also prevents the grains from growing up, therefore refining the grains. Among the rare earths, Nd has the best comprehensive performance, which can improve the strengthening effect at both room temperature and high temperature [39]. The average grain size of Mg–5Li–3Al–2Zn alloy with the addition of rare earth elements Nb and Y is ~ 30 μm [40]. The addition of La can also restrain the formation of AlLi phase and reduce the size of α-Mg in Mg–Li alloy [25].

Besides, Zr is a grain refiner in the smelting process of Mg alloys except for rare earth elements. Adding a small amount of Zr in the smelting process of Mg–Li alloys can remove H and refine the grain size. The precipitation of α-Zr acts as nucleation particles, which increases the nucleation rate, thus refining the as-cast alloy and enhancing the cold processing ability. The grain size decreased to 20–25 μm with the addition of 0.5% Zr, but the grain size was still flaky. When the addition of Zr reached 0.72%, the grain size decreased to 15–20 μm, and the smallest grain was basically equiaxed with a size of 4–6 μm [41].

Mn is another grain refiner in Mg–Li alloy. During the solidification of alloy, part of Mn is squeezed to the grain boundary of α phase as a result of low solid solubility of Mn in Mg–Li alloy, forming encapsulation on the alloy, inhibiting the growth of α phase, and realizing the spheroidization and refinement of α phase, therefore improving the strength and plasticity of the alloy. When 0.2% Mn was added to Mg–9Li–2Zn alloy, the α phase was refined and spheroidized. The change of α phase was not obvious with Mn addition from 0.5% to 0.8%. The strength of Mg–9Li–2Zn–0.5Mn alloy was significantly improved (σ_b = 224 MPa, $\sigma_{0.2}$ = 190 MPa). However, when the content of Mn was 0.8%–1.5%, the strength and elongation decreased with the increase of Mn [42].

Ca can also refine the α-Mg or β-Li grains, resulting in a higher strength of Mg–Li alloys [43]. The addition of Ca to Mg–9Li–2Zn alloy from 0.1% to 1.0% refined the α-Mg and the best effect of refinement occurred when the Ca content was 0.4%–0.5%. The adsorption of proper Ca on the grain boundaries refined α-Mg and improved the tensile properties, but the presence of excess Ca and stable $Ca_2Mg_6Zn_3$ phase worsened the elongation [44]. Zhou et al. [36] found that a small amount of Ca addition increased the α-Mg volume fraction significantly. The irregular randomly oriented α-Mg plates with 2–4 μm in diameter and 10–20 μm in length in hypereutectic Mg–8.4Li alloy had transformed into extremely dense and regular couple eutectic colonies consisting of alternative α-Mg and β-Li rods with a rod spacing of 1–2 μm after Ca addition, as shown in Fig. 3a, b, which contributed to the highest yield strength of Mg–8.4Li–0.5Ca alloy (Fig. 3c).

3.3 Severe plastic deformation (SPD)

SPD is a plastic deformation technology developed in the 1930s and 1940s. It generates large numbers of crystal defects and refines the grain to submicron or nanometer scale by large plastic deformation amount, and finally, obtains high strength and complete large-size bulk materials [32, 45, 46]. At present, SPD technology has been known as the most effective and promising method for the preparation of ultrafine crystalline materials. Typical SPD techniques include equal channel angular pressing [47], high pressure and torsion [48], accumulative roll bonding [49], and multi-directional forging.

3.3.1 Equal channel angular pressing (ECAP)

The principle of ECAP is shown in Fig. 4a [50]. In the extrusion die, there are two channels with a certain angle and the same section. In the process of ECAP, the alloy is pressed from the upper end and out from the right end under the pressure. When it passes through the corner of the channel, ideal shear deformation can be produced. As the pass number of ECAP increases, the shear strain gradually accumulates, and finally, the microstructure and properties of the alloy can be effectively improved [51–54].

Karami and Mahmudi [55] studied the microstructural and textural evolution of Mg–6Li–1Zn (LZ61), Mg–8Li–1Zn (LZ81), and Mg–12Li–1Zn (LZ121) alloys in the as-extruded condition and after being ECAPed. The results showed that the multipass ECAP could develop reasonably homogeneous and well-refined microstructures in both LZ61 and LZ121 alloys through continuous dynamic recovery and recrystallization. The microstructure evolution of LZ61 alloy in the as-cast, extruded, and ECAPed conditions is shown in Fig. 5. The relatively large α grains with some β phase in the grain boundary areas could be observed in the as-cast microstructure (Fig. 5a). The grain size of LZ61 alloy varied from 82 μm in the as-cast condition to 9.6 μm in the extruded condition to 6.3 μm in the ECAPed condition. The grain refinement mechanism occurring during the ECAP process was described as a combination of mechanical shearing and subsequent

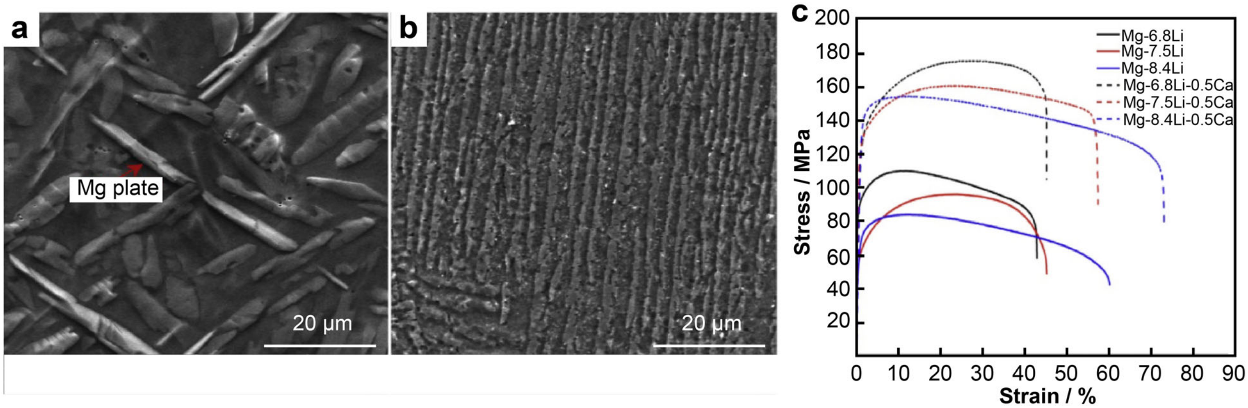

Fig. 3 Microstructural evolution of Mg–8.4Li alloys **a** before and **b** after Ca addition; **c** corresponding room-temperature tensile engineering stress–strain curves of Mg–*x*Li alloys before and after Ca addition. Reproduced with permission from Ref. [36]. Copyright 2015, Elsevier B.V

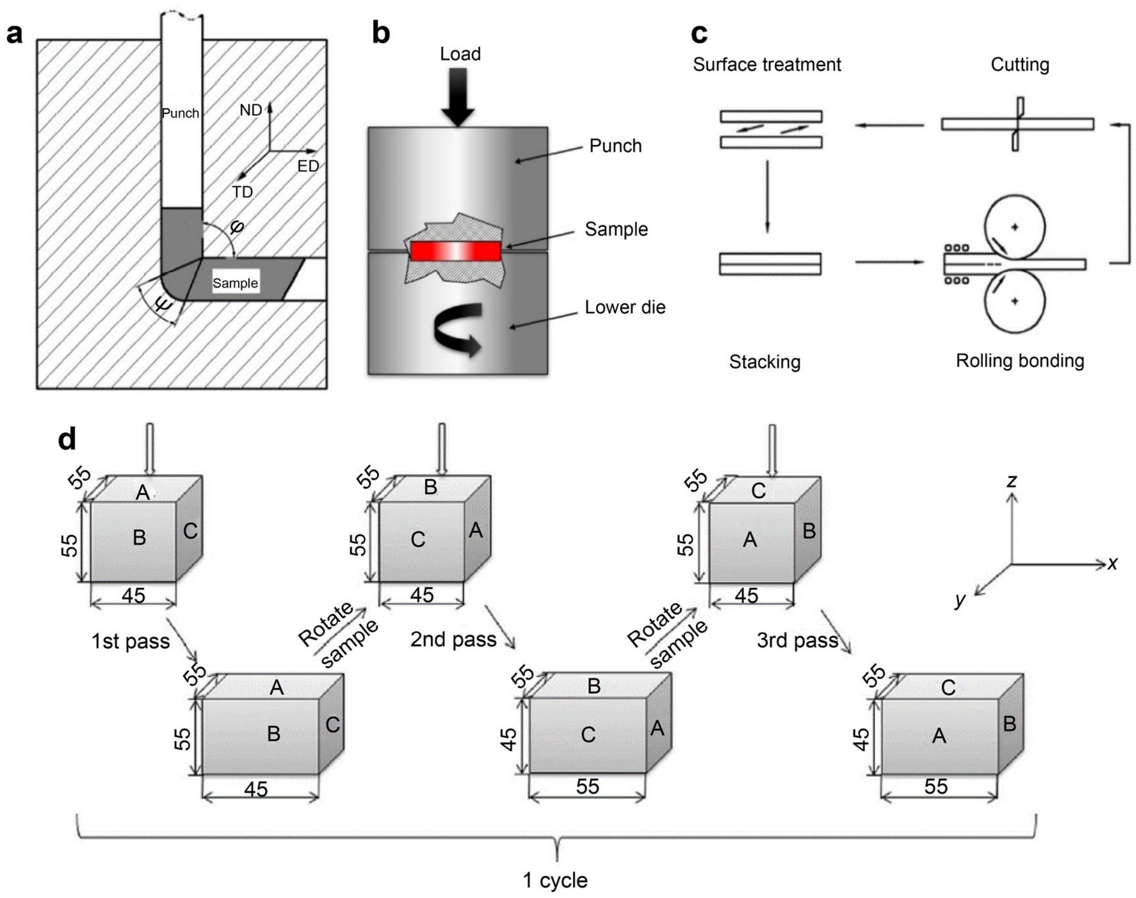

Fig. 4 Schematic diagram of SPD techniques: **a** ECAP, **b** HPT, **c** ARB, and **d** MDF. Reproduced with permission from Refs. [50, 52–54]. Copyright 1994-2021, China Academic Journal Electronic Publishing House; Copyright 2015, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; Copyright 2016, the Indian Institute of Metals - IIM

dynamic recovery and recrystallization. The growth of grains and subgrains produced refined and equiaxed grains.

Wei et al. [56] used double ECAP on Mg–9Li–3Al–2Sr–2Y alloy at 280 °C with an extrusion ratio of 17:1. The grain size of the alloy was refined from 132 to 3–8 μm, and the tensile strength and elongation reached 246.6 MPa and 19.9%, respectively. Compared with the as-cast alloy, the tensile strength increased greatly while the elongation

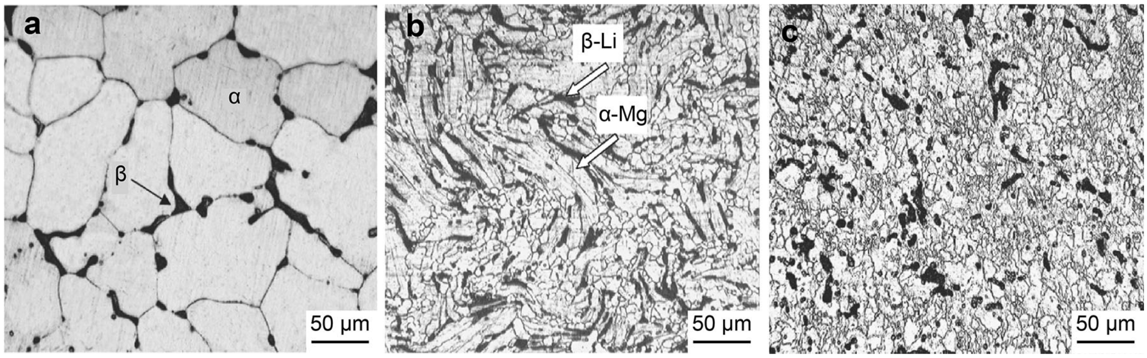

Fig. 5 Micrographs of LZ61 alloy for **a** as-cast, **b** extruded and **c** ECAPed conditions. Reproduced with permission from Ref. [55]. Copyright 2013, The Minerals, Metals & Materials Society and ASM International

decreased slightly. ECAP technology is a common method to prepare fine grain alloy materials, but it can only prepare small-size materials. At the same time, due to the poor plasticity of magnesium alloy, it is very easy to crack during ECAP, so the successful extrusion pass is very limited.

3.3.2 High pressure and torsion (HPT)

HPT is also a type of SPD that is highly suited to produce bulk ultrafine-grained and nanocrystalline materials, as it introduces many grain boundaries as well as dislocations and point defects [57]. The principle of HPT is shown in Fig. 4b. The disk-like alloy sample is put in a mold. Then the lower die is turned, when the punch provides downward pressure, the alloy will endure friction effect and produce shear torque. Finally, ultrafine-grained material is obtained under the synergistic effect of the axial compressive stress, friction, and tangential shear stress.

Matsunoshita et al. [58] obtained uniform ultrafine microstructures of Mg–8Li alloy by HPT technique at room temperature, with an average grain size of 500 nm (Fig. 6a–c). At the same time, the Mg–8Li alloy had good superplasticity, the elongation reached 350%–480% as the initial strain rate was 1×10^{-3}–1×10^{-2} s^{-1} (Fig. 6d). Srinivasarao et al. [59] carried out HPT deformation on Mg–9Li, Mg–12Li and Mg–20Li alloys at room temperature. The results showed that the alloys changed from β phase to α phase under a certain pressure, and the transition became more obvious with the increase of pressure. This is of guiding significance for improving the properties of β phase Mg–Li alloy. Su et al. [60] investigated the microstructural evolution and mechanical properties of LZ91 Mg–Li alloy processed by HPT at ambient

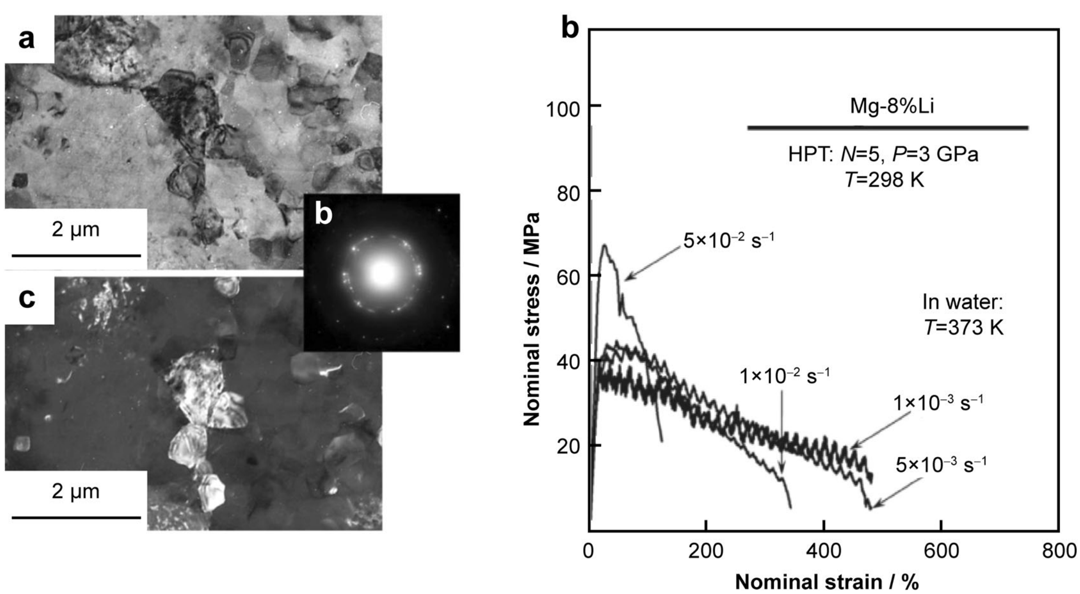

Fig. 6 TEM observation after HPT processing 5 turns: **a** bright-field image, **b** SAED pattern, and **c** dark-field image; **d** nominal stress versus nominal strain curves obtained in boiling water for samples processed by HPT 5 turns. Reproduced with permission from Ref. [58]. Copyright, 2015 Elsevier B.V

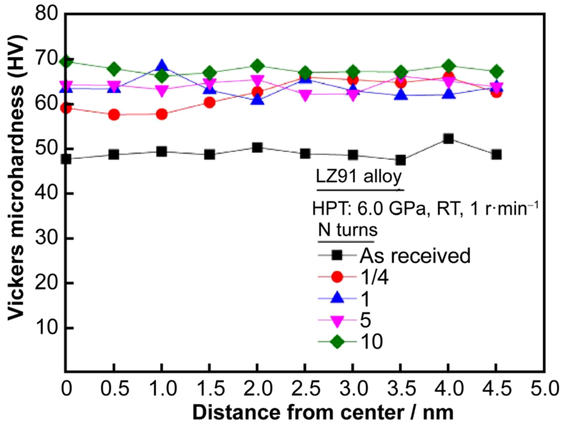

Fig. 7 Vickers microhardness of LZ91 alloy along the radius of disk. Reproduced with permission from Ref. [60]. Copyright 2018 by the authors

temperature. After HPT processing for 10 turns, the grain refinement was achieved with an average grain size reducing from 30 μm (the as-received condition) to ~ 230 nm. The mean value of hardness increased with the increasing number of HPT turns as a result of Hall–Petch strengthening (Fig. 7). Meanwhile, the ultra-fine grain LZ91 Mg–Li alloy exhibited excellent mechanical properties: tensile elongation was ~ 400% at 200 °C with an initial strain rate of $1 \times 10^{-2}\ s^{-1}$.

HPT produces bulk ultrafine-grained and nanocrystalline materials. As-prepared materials have the advantages of uniform deformation and small deformation resistance, but there are still many problems, such as limited material size, which cannot be used for large-scale industrial production; the strength and plasticity are not as desirable as the hardness of the material; the deformation process control has certain difficulty and so on.

3.3.3 Accumulative roll bonding (ARB)

ARB technology [49] was first proposed by Professor Saito of Osaka University in Japan in 1998 and was successfully used to make the grain size of pure aluminum refine to below 1 μm, obtaining the bulk ultrafine-grained material. The principle of ARB is shown in Fig. 4c.

Wang et al. [52] used ARB to manufacture fine-grained and high-strength Mg–8Li–3Al–1Zn alloy. The ARBed sample possessed the grain size of about 3 μm and the tensile strength, elongation, and hardness of 287.02 MPa, 12.5%, and $HV_{0.05}$ 77.2, respectively. Hou et al. [61] prepared ultrafine-grain and high-strength Mg–5Li–1Al sheets by ARB process, and investigated the microstructure and mechanical properties of ARBed Mg–5Li–1Al sheets. The evolution of the deformation mechanism of the Mg–5Li–1Al alloy was as follows: twinning deformation, shear deformation, forming macro shear zone, and finally, dynamic recrystallization, as shown in Fig. 8. The grain refining mechanism changed from twin dynamic recrystallization to rotation dynamic recrystallization. With the increase of ARB cycles, the strength of Mg–5Li–1Al sheets was enhanced, while the elongation varied slightly. With the increase in rolling cycles, the anisotropy of mechanical properties decreased. It was conclusive that strain hardening and grain refinement dominated the strengthening mechanism of Mg–5Li–1Al alloy.

ARB process is not only a cumulative deformation process but also a solid diffusion process, that is, atoms on two contact surfaces diffuse each other under the action of pressure. There are still many problems to be overcome in the preparation of Mg–Li alloy by ARB, such as the interface bonding between the laminates and how to improve the plasticity without greatly sacrificing the strength.

3.3.4 Multi-directional forging (MDF)

MDF achieves severe plastic deformation through multi-pass and multi-directional upsetting and stretching, which is an advanced technique to obtain fcc and hcp ultra-fine grains [62]. The principle of MDF is shown in Fig. 4d [54]. In the MDF process, the material must endure ultrahigh pressure and large strain, as well as keep the cross-sectional dimensions of the sample. When the plasticity of the sample is poor, it can be preheated and then forged. Usually, the temperature is between 0.1 T_m and 0.5 T_m (T_m: melting point temperature). Cao et al. [48] studied the microstructure, mechanical properties, deformation mechanism, and cavitation growth of Mg–10.2Li–2.1Al–2.23Zn–0.2Sr alloy subjected to multi-directional forging and rolling (MDFR). A thin-banded-grain microstructure with a grain size less than 3.75 μm was obtained via MDFR and annealed at 250 °C for 1 h, as shown in Fig. 9, resulting in an ultimate tensile strength and elongation. Compared with other machining processes, in the MDF process, the deformation in different forging regions of the material will not be uniform because of the rotating changes in the axial direction.

4 Compound strengthening

Compound strengthening is adding hard ceramic or other material particles, fibers, or other whiskers to the metal matrix as the reinforcement through a certain process to obtain composite material with excellent performance. The main preparation processes include vacuum impregnation, pressure impregnation, thin section metallurgy, and powder metallurgy. And the common reinforcements are carbon

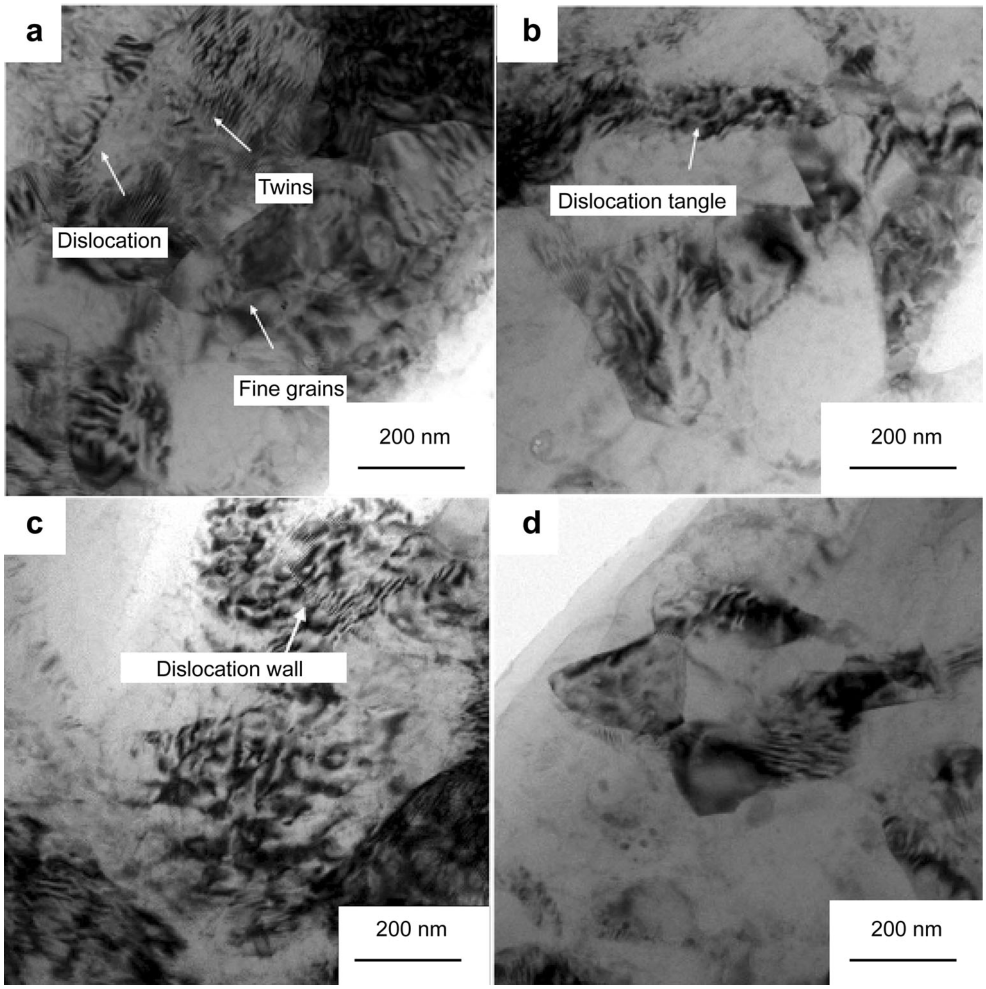

Fig. 8 High magnification TEM images of ARB-processed Mg–5Li–1Al sheets: **a** ARB1; **b** ARB2; **c** ARB4; **d** ARB6. Reproduced with permission from Ref. [61]. Copyright 2017, Published by Elsevier Ltd on behalf of the editorial office of Journal of Materials Science & Technology

fiber, SiC whisper, B_4C particle, Al_2O_3 fiber, stainless steel wire, titanium alloy wire, SiO_2 particles, and Al_2Y particles [13, 63, 64].

Trojanova et al. [19] prepared Mg–xLi (x = 4, 8, 12) matrix composites reinforced with short δ-Al_2O_3 fiber by the pressure infiltration process and Mg–8Li composites reinforced with SiC particles by the powder metallurgical technology. The microstructures of Mg–8Li with δ-Al_2O_3 fiber and SiC particles are displayed in Fig. 10a, b. The results showed that short δ-Al_2O_3 fibers were randomly distributed in the matrix. And the distribution of SiC particles in the matrix was not uniform, accompanied by an obvious agglomeration phenomenon. Wu et al. [65] prepared B_4C_p/Mg–8Li–1Zn and B_4C_p/Mg–8Li–1Al–1Y composites by hot-extrusion solid-state composite processing. The microstructure of the as-cast Mg–8Li–1Al–1Y alloy and B_4C_p/Mg–8Li–1Al–1Y composite is shown in Fig. 10c, d. The strengths of the composites were increased obviously compared with those of the as-cast ones. The B_4C_p/Mg–8Li–1Al–1Y composite possesses a peak strength of 257.23 MPa. Cui et al. [66] investigated the influence of Y on microstructure and mechanical properties of the as-cast Mg–5Li–3Al–2Zn alloy. The Mg–5Li–3Al–2Zn consisted of α-Mg and AlLi phases. Adding Y to the alloy resulted in the formation of Al_2Y compound and facilitated grain refinement. The addition of 0.8% Y produced the smallest grain size. The tensile tests performed at room temperature showed that Y additions could improve the mechanical properties of the alloy; the tensile strength and ductility reached peak values when Y additions were 0.8% and 1.2%, respectively. The mechanisms of improvement were related to grain refinement and compound strengthening effects.

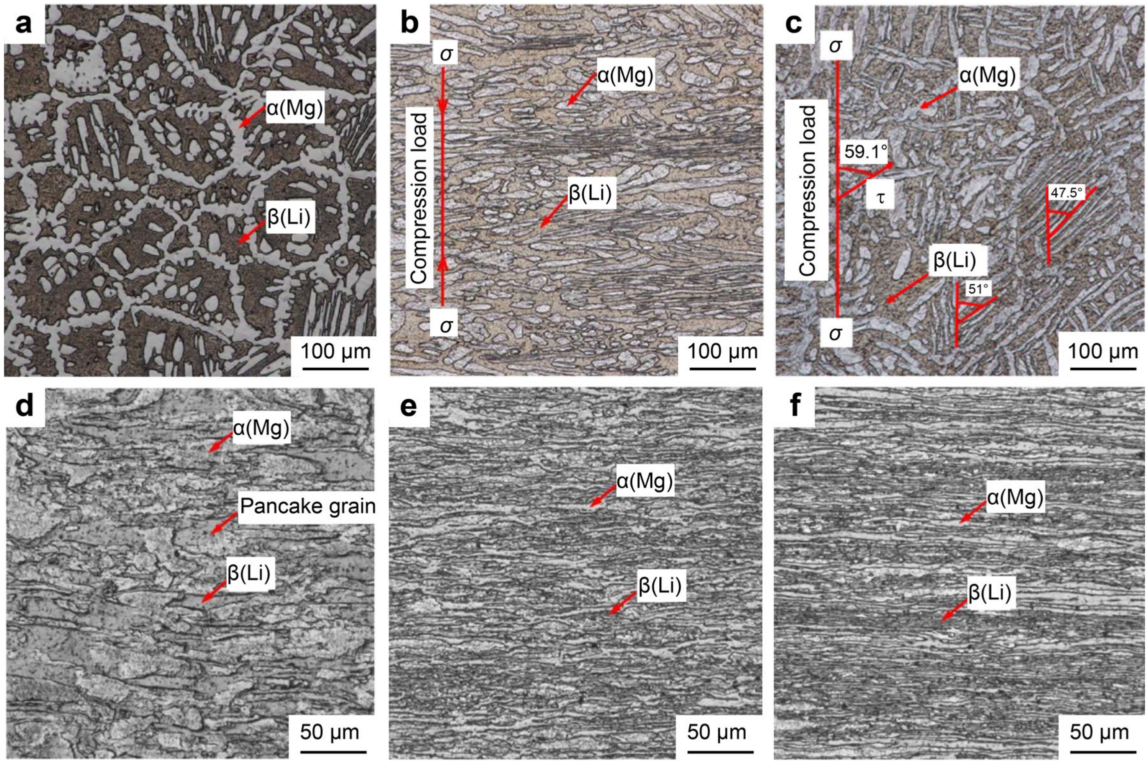

Fig. 9 OM images of Mg–10.2Li–2.1Al–2.23Zn–0.2Sr alloy at different status: **a** as-cast; **b** 1st pass of MDF, 573 K, pass strain of 0.5; **c** 6th pass of MDF, 573 K, accumulative strain of 3.0; **d** cold rolling, ND; **e** cold rolling, TD; **f** cold rolling, RD. Reproduced with permission from Ref. [48]. Copyright 2017, Elsevier B.V

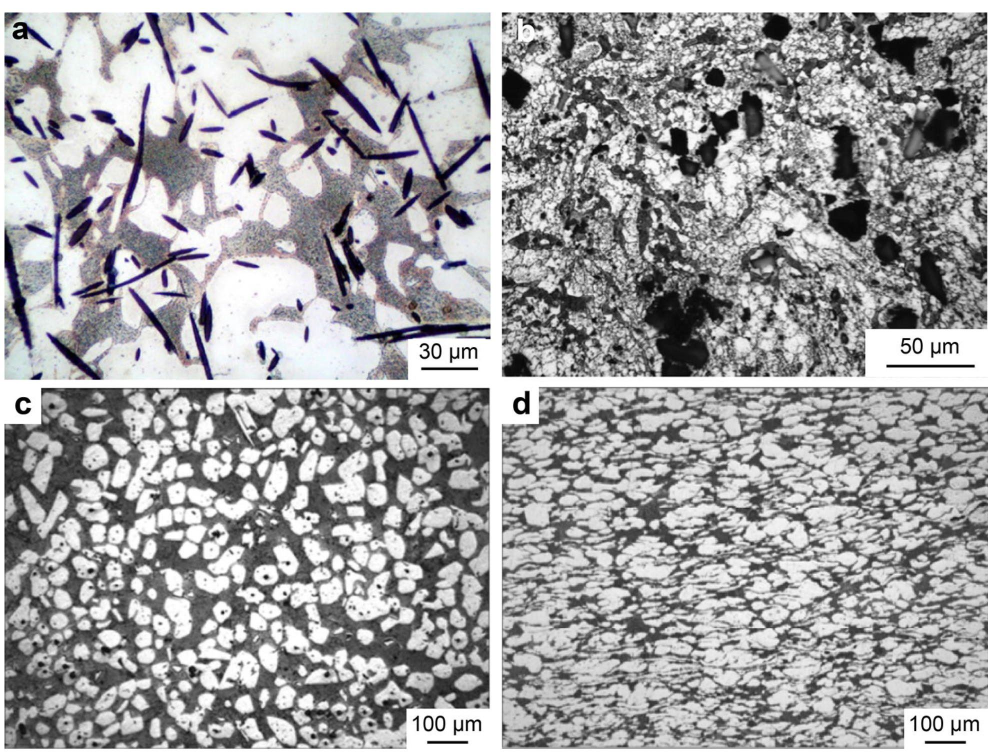

Fig. 10 Microstructures of Mg–8Li with **a** δ-Al_2O_3 fiber, **b** SiC particles, **c** as-cast Mg–8Li–1Al–1Y alloy and **d** B_4C_p/Mg–8Li–1Al–1Y composite. Reproduced with permission from Refs. [19, 65]. Copyright 2006, Elsevier Ltd.; Copyright 2011, the Nonferrous Metals Society of China

5 Summary and outlook

In the recent years, magnesium–lithium (Mg–Li) alloys have attracted considerable interest due to their high strength-to-density ratio and damping characteristics; and have found potential use in structural and biomedical applications. Mg–Li alloy has a low density and high specific strength. However, the application of dual-phase Mg–Li alloys is still limited because of the low strength and high-temperature instability. Although this paper reviewed the strengthening and toughening methods and mechanisms of Mg–Li alloy, the toughening mechanism in practice is a synergistic effect of the enhancement mechanism. It is hard but urgent to build a proper model to clarify this synergy principle. In addition, there is still a long way to realize large-scale application of Mg–Li alloy: development of new solidification techniques with high cooling rate to obtain ultrafine microstructure; investigation of new deformation processes to obtain ultrafine or nanocrystalline structures; research of new composite process and fiber/particle reinforced composite on the basis of fully understanding the advantages and disadvantages of the existing composite process.

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Declarations

Conflict of interests The authors declare that they have no conflict of interest.

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Wen-Cai Liu mainly engaged in the R&D of high-performance Mg alloy for a long time. As the project leader, he has presided over more than 20 R&D projects. He has published more than 110 academic papers; 86 invention patents have been applied for, of which 65 have been authorized. Selected as Shanghai Young Science and Technology Star Scholar. Served as the editorial board of ‘Materials’, the youth editorial board of ‘Journal of Magnesium and Alloys’, ‘Transactions of Nonferrous Metals Society of China’ and ‘Journal of Central South University’, etc.