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ScienceDirect
Trans. Nonferrous Met. Soc. China 35(2025) 3533−3560
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Research progress on magnetoplastic effects of light alloys assisted by magnetic field

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Received 14 March 2024; accepted 10 December 2024

Abstract: Light alloys have irreplaceable advantages such as high specific strength and low density. They are indispensable structural materials in aerospace, military, and marine engineering. It is an enduring research hotspot to prepare high-strength and high-toughness light alloys to play a more significant role in advanced engineering applications. As a new method to improve the mechanical properties of light alloys, the magnetic field-assisted process can produce magnetoplastic effects. Therefore, in this paper, research progress on the magnetoplastic effects of light alloys assisted by magnetic fields was reviewed, and the effects of magnetic fields on dislocations, grain refinement, precipitation kinetics, phase transformation, and mechanical properties of light alloys were elucidated. Magnetic field treatment transforms radical pairs from the ground state to the excited state, which reduces the resistance between dislocations and obstacles, facilitating dislocation depinning. Moreover, magnetic field can promote grain refinement and phase transformation, increase precipitation kinetics, and synergistically improve strength and elongation. Finally, the prospects of magnetic field-assisted processes of light alloys were discussed.

Key words: light alloys; magnetic field; magnetoplastic effect; dislocation; precipitation kinetics; mechanical properties

1 Introduction

Aiming at the goals of “carbon neutrality” and “emission peak”, light alloys are an important focus in the industrial field to achieve these goals [1,2]. Light alloys represented by titanium (Ti) alloys, aluminum (Al) alloys, and magnesium (Mg) alloys, have received attention for their irreplaceable advantages of high specific strength and lightweight [3−6]. Light alloys have been widely used in commercial aircraft and fighters such as Boeing 787, C919, A320 Neo, and F22 [7−9]. However, the poor formability of light alloys greatly restricted their applications in frontier equipment and many structural components [10,11]. Furthermore, the dilemma of the trade-off between strength and toughness of light alloys leads to their lack of competitiveness in engineering applications [12]. Therefore, the preparation of high-strength light alloy with high toughness is of great significance.

There are two main research hotspots for improving mechanical properties: one is severe plastic deformation (SPD) [13] and the other is heat treatment [14]. It is well known that the mechanical properties of light alloys are enhanced using SPD methods [15,16]. The SPD can effectively introduce a larger strain than the conventional plastic deformation, thus obtaining uniform ultra-fine grain microstructure [17,18], which can significantly synergistically improve the strength and toughness of the alloy [19,20]. SPD methods have been successfully used to improve the mechanical properties of light alloys [21−23]. Unfortunately,

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https://doi.org/10.1016/S1003-6326(25)66898-1

the product size obtained by SPD is small, and the deformation process usually requires multiple deformations, mold changes, and repeated heating treatment, which greatly limits their application scope [24−26]. Therefore, it is important to explore new processes and methods to improve the plasticity and strength of light alloys.

In contrast, the latter approach is to improve the mechanical properties of light alloys mainly through solution and aging treatment without changing the shape of the alloy [27,28]. The preparation of Ti alloys [29,30], Mg alloys [31], and Al alloys [32] with high strength and good ductility combining the solution and aging processes has been widely reported. However, heat treatment usually needs to be performed with conventional heating equipment, which has disadvantages of high energy, long time consumption, and low efficiency [33,34]. Moreover, the size and efficiency of process parts are limited. Therefore, new approaches need to be explored to meet the needs of alloy applications.

Currently, magnetic field (MF)-assisted process has attracted widespread attention. This is a process that uses static magnetic field (SMF) or pulsed magnetic field (PMF) to assist in the deformation and heat treatment of alloys [35,36]. The magnetic field can provide energy, changing the dislocation state, morphology, distribution, and density [37−39], and promoting atomic diffusion and phase transformation [36,40]. Light alloys are paramagnetic materials [41−43], which exhibit excellent magnetoplastic effect (MPE) under magnetic field-assisted processes [44,45]. Besides, magnetic field treatment (MFT) has the advantages of non-contact, cleanliness, no pollution, reduced resource consumption, and high efficiency [46,47]. MFT has been successfully used to assist in the deformation and heat treatment of Ti alloys [48], Al alloys [49,50], and Mg alloys [51]. Therefore, magnetic field-assisted processes have gradually become a more effective strategy and research hotspot for improving the mechanical properties of light alloys.

This paper reviewed solid-state light alloys' microstructure and mechanical properties after magnetic field-assisted treatment. The magneto-plastic effect of alloys under the magnetic field was introduced. The research statuses of dislocation characteristics, precipitation kinetics, phase transformation, grain refinement, and mechanical properties of alloys under the magnetic field were systematically delineated. This helps us understand the effect and mechanism of introducing the magnetic field on the microstructure of light alloys, and further explain the mechanisms of strengthening and toughening under the magnetic field.

2 Historical development of magnetoplastic effect

Magnetoplastic effects are believed to be a phenomenon that enhances the mobility of dislocations and macroscopic ductility of materials under the magnetic field without changing their strength. The schematic diagram of magnetoplastic effect of dislocation movement induced by the magnetic field in light alloy when plastic deformation conditions are not met is shown in Fig. 1. Gradually, with the in-depth development and research of external magnetic fields, various phenomena leading to changes in the mechanical properties and microstructural defect states of materials due to the magnetic field are also known as magnetoplastic effects [42,47].

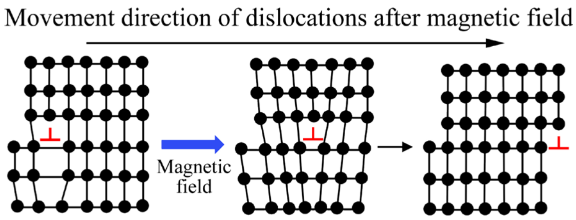

Fig. 1 Schematic diagram of magnetoplastic effect

Figure 2 exhibits a timeline of the historical background of the study on the magnetic field-assisted processes and magnetoplastic effect of light alloys. These research processes can be roughly divided into three stages. Firstly, starting in the 1960s, researchers pioneered the discovery of the magnetoplastic effect and conducted preliminary research and exploration. Secondly, by 2000, the literature focused on the effects of weak magnetic fields on the internal friction and structural relaxation of non-magnetic materials, which stagnated the research on magnetoplastic by magnetic fields in the primary stage for a long time.

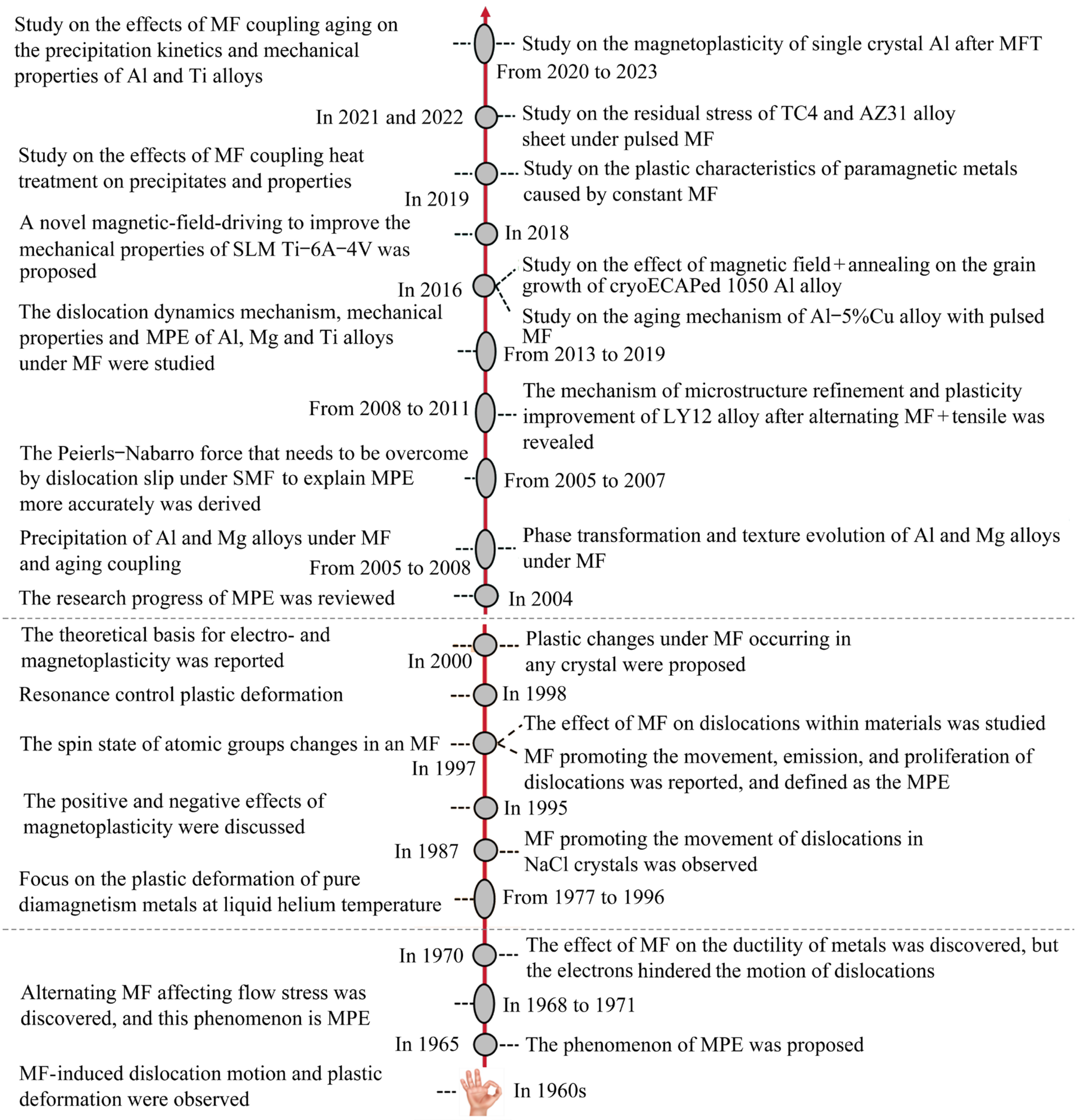

Fig. 2 Timeline of historical background of research and development of magnetic field-assisted treatment and magnetoplastic effects of light alloys

Fortunately, the effects of magnetic fields on dislocation motion and the spin state of atomic groups have begun to be discovered and studied. Finally, from 2004 to now, magnetoplastic effects and magnetic field-assisted processes in light alloys have gradually been developed. The following section will describe the research progress in this field.

Since the 1960s, researchers have observed that magnetic fields can induce dislocation motion and plastic deformation [52]. In 1965, the magnetoplastic effect was first proposed, based on the observed influence of both static and alternating magnetic fields on dislocation motion and macroscopic plasticity of materials. In 1968, HAYASHI et al [53] discovered that the flow stress increased and decreased when an alternating magnetic field was applied to the elastic and plastic regions of the nickel single crystal, respectively. Subsequently, the phenomenon of applying an alternating magnetic field to reduce the flow stress of nickel single crystal during plastic deformation at −194 °C is called the magnetoplastic effect and is qualitatively explained based on the concept of forces exerted by oscillating magnetic domain walls on dislocations [54]. In 1970, KRAVCHENKO [55] showed that magnetic fields can affect the ductility of metals and pointed out that electrons under the magnetic field can hinder the movement of dislocations. However, some researchers believed that this theory could not affect the plasticity of materials in principle, resulting in the magneto-plastic theory not being developed in time.

It was not until 1987 that AL'SHITS et al [56] discovered that the magnetic field can promote the dislocation motion of NaCl crystals, and this was repeatedly verified, which prompted the theory of magnetoplasticity to receive widespread attention, research, and development. To study dislocations more directly, LI et al [57] used TEM in situ to investigate the emission, multiplication, and movement of dislocations in Fe−Ni alloys under the magnetic field. MOLOTSKII and FLEUROV [58] reported that the depinning of dislocations under the magnetic field caused an increase in plasticity. The reason is that magnetic field induction causes the radical pair between the kink and the obstacle to transform from the binding state to the anti-binding state with lower binding energy. Similar results were reported by FLEUROV and MOLOTSKII [59], who also pointed out that magnetic fields can affect the dynamics of dislocations.

To clarify the mechanism of magnetic field affecting material plasticity, LIU et al [60] used the Peierls−Nabarro (P−N) model to study the maximum crystal lattice resistance required for dislocation slips in the SMF. For paramagnetic dislocations, the Peierls−Nabarro force decreases, the resistance of the lattice to slip decreases, and the dislocations move more easily, favoring enhanced material plasticity. Moreover, WANG et al [61] pointed out that high magnetic fields (HMF) lead to magnetoplastic effects, which cause the motion of dislocations, increase the dislocation density, and improve the plastic deformability of Al matrix composites. The above studies show that the magnetoplastic effect is the effect of the magnetic field on the dislocations.

The effect of the magnetic field can weaken the bonding energy that dislocation motion needs to overcome, and the bonding energy is closely related to the state of the radical pair. The radical pair state can be divided into the ground state (singlet state and S state) and the excited state (triplet state, namely T+, T0, and T− state) [37,62], as shown in Fig. 3(a). For the S state, the spin directions of the electron pairs are opposite, the spin magnetic moments are canceled, and the energy required for dislocations to overcome obstacles is high [37]. For the T state, the bonding energy between the dislocation and the obstacle is weak, making it easier for the dislocation to move and cross the obstacle [52]. This condition is beneficial for the depinning of the dislocation. The transition from the S state to the T state is severely forbidden without the magnetic field. Under the magnetic field, excited electron pairs are generated between the dislocation and the obstacle (Fig. 3(b)), which is

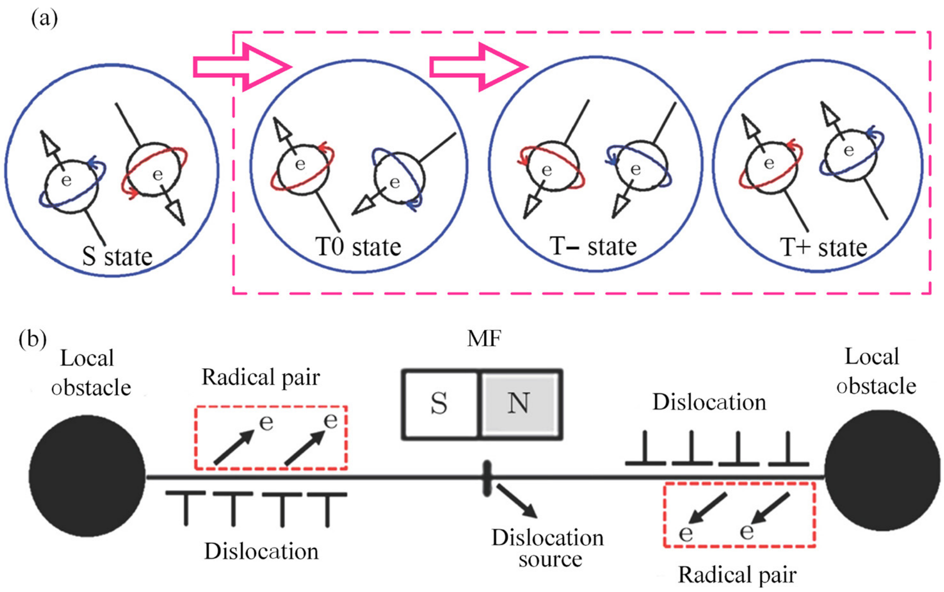

Fig. 3 (a) Four states of radical pairs [37,62]; (b) Schematic diagram for free electron stimulation between dislocation and obstacles [37]

conducive to the transition into the T state. The radical pair transitions into the T state due to the magnetic field, which enhances the depinning of the dislocation by weakening the resistance between the dislocation and the obstacle, thereby increasing plasticity [39]. This is the essence of the magnetoplastic effect.

3 Effect of magnetic field on dislocation

3.1 Force and energy analysis of dislocation

Crystal slips only occur under external forces, indicating that dislocation motion needs to overcome some resistance. The Lorentz force should be the first to be excited under the magnetic field, and then the magnetic pressure (*P*) is generated [48]. LI et al [48] reported a *P* value of 6.37 MPa at B=4 T (B is the magnetic induction intensity), which is much lower than the yield strength (YS) of Ti alloys, and noted that the Lorentz force is not the driving force for dislocation motion. Next, the influence of magnetizing force (*F*) on dislocations is considered. According to the calculations, when B=4 T, F is 3.69×10^{-5} N, which is much smaller than the YS of TC4 alloy [48], indicating that *F* is not the driving force of dislocation motion. Moreover, the stress (σ_M) experienced by dislocations under the magnetic field has also been reported [52]. The Peierls force (σ_P) required to drive dislocation motion on the slip plane [111] of the Al matrix is 20 MPa [52]. Interestingly, LI et al [52] observed an increase in dislocation density even when σ_M is smaller than σ_P, indicating that σ_M is not the main factor driving dislocation movement. Therefore, the dominant driving force of dislocation motion in the presence of the magnetic field needs to be considered from other aspects.

In addition to force, energy is also a factor that cannot be ignored. Under the magnetic field, the Zeeman energy (ΔU_m) and the thermal energy (U_T) of the alternating magnetic field can contribute to the movement of dislocations [52]. The energy obstacles that need to be overcome when dislocations move include the activation energy U_a (0.1−1 eV) and the exchange energy U_{ex} (~1 eV) between the dislocation and the obstacle. LI et al [52] reported that the ΔU_m is 10^{-4} eV and the U_T is 10^{-2} eV, and the sum of the two cannot meet the energy required for the dislocation to overcome the obstacle. From the perspective of dislocation strain energy, the magnetic field can increase dislocation strain energies, which operates in two ways: firstly, to enhance interactions between existing dislocations, and secondly, to promote dislocations to depin from obstacles [37]. To further explore the nature of the dislocation motion under the magnetic field, it is necessary to analyze the spin of the electron and the radical pair on the quantum scale.

3.2 Action mechanisms of dislocations

The state of radical pairs between dislocations and obstacles can reflect the influence of the magnetic field on dislocations. The magnetic field changes the spin multiplicity of the radical pairs, making it easier to depin the dislocations, thereby enhancing their modility. The radical pairs can be in various spin states with diverse bonding energies. Typically, the S state with electron spins antiparallel has a strong binding energy, while the T state with parallel spins has a weak or even non-existent binding energy [39]. The binding energy of the S state is too high to be excited without the magnetic field. After the magnetic field provides energy, the extranuclear electrons are excited to higher energy levels, and the atomic magnetic moment changes, causing the electrons to be excited to the T state, as shown in Figs. 4(a−c) [49]. This conclusion is also consistent with the report of ZHANG et al [35] and LUO et al [36]. When the S state changes to the T state, the bonding energy weakens, which promotes the depinning of the dislocations from the barrier and exhibits a magnetoplastic effect.

Dislocation motion is affected by the crystal's critical shear stress and energy. The critical shear stress (σ_p) for the dislocations and dislocation line movements is described by the formulation of the P−N model, as shown in Fig. 5 [36]. With the magnetic field, the motion of the atoms becomes easier due to the excited electronic state and change of the atomic magnetic moment, causing the spacing of the slip plane (*d*) to increase, as shown in Figs. 4(c, d). According to the P−N model, it can be seen that σ_p decreases, facilitating the movement of dislocations and dislocation lines.

Compared with the *d*-spacing of the slip plane of the alloy without the magnetic field (d_1), the

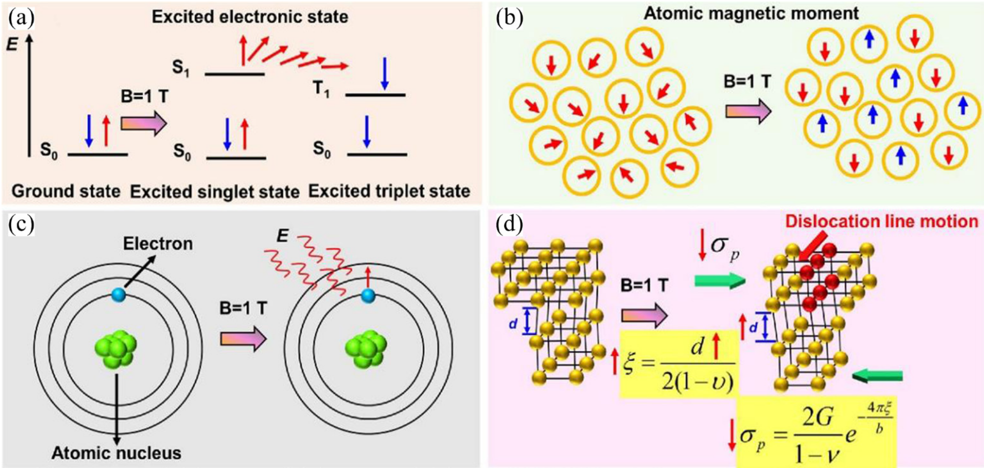

Fig. 4 Schematic illustration of electronically excited state, atomic magnetic moment, and dislocation line motion in magnetic field [49]

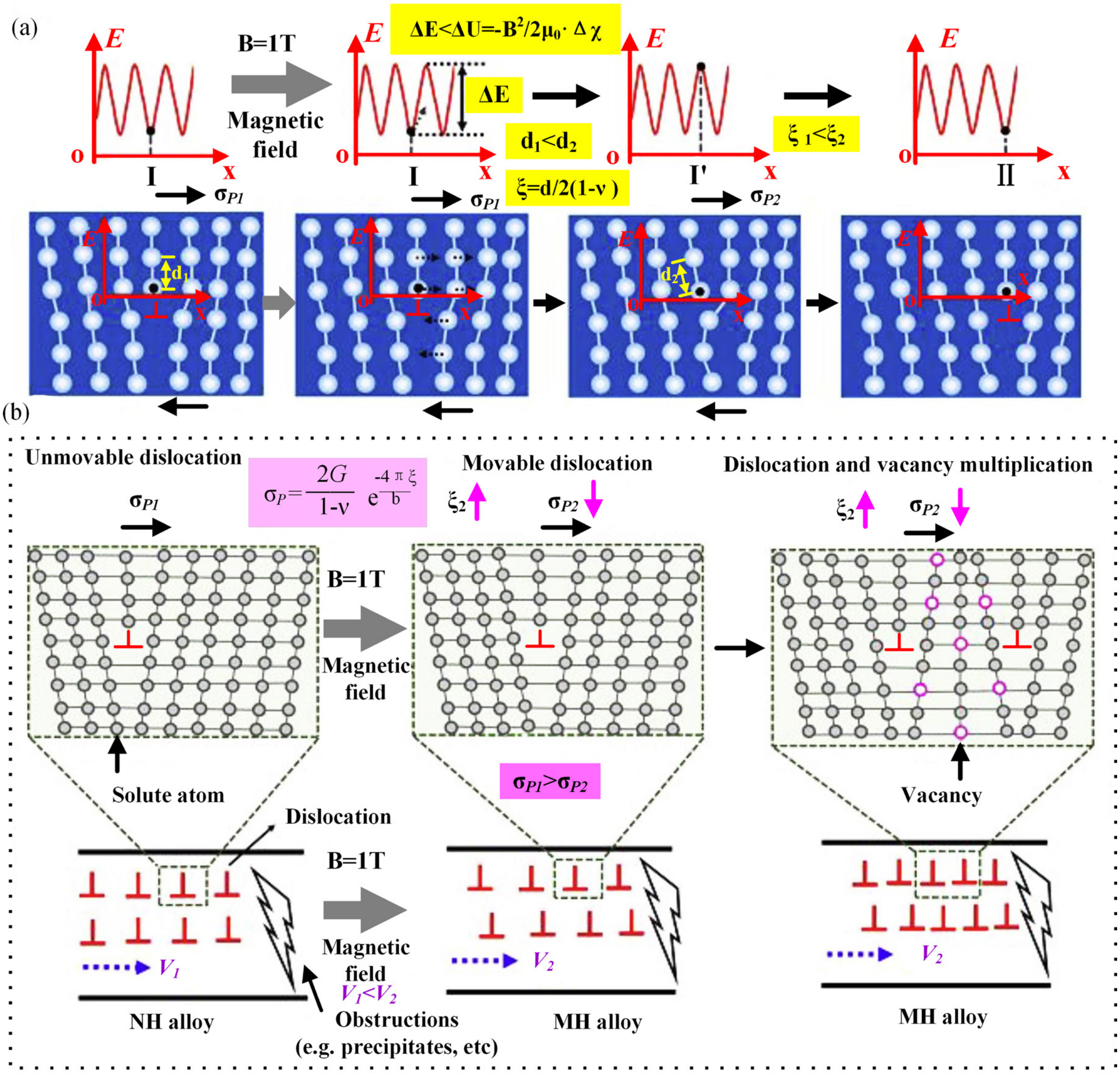

Fig. 5 Dislocation evolution of NH (0 T) and MH (1 T) alloys: (a) Schematic diagram of dislocation movement; (b) Dislocation and vacancy proliferation in magnetic field [36]

d-spacing of the slip plane of the alloy with the magnetic field (d_2) increases due to the movement of atoms, that is, $d_1 < d_2$. Subsequently, the value of the half-width of the dislocation core (ξ) with the magnetic field is greater than that of the without the magnetic field, i.e. $\xi_2 > \xi_1$, as shown in Fig. 5(a). Then, the critical shear stress with the magnetic field is smaller than that without the magnetic field, i.e. $\sigma_{p2} < \sigma_{p1}$, as shown in Fig. 5(b), indicating that the magnetic field can promote dislocation slip. Besides, the non-uniformity distribution of stress due to MFT further accelerates the movement speed of dislocations [36]. From an energy perspective, alloys without the magnetic field have higher potential energy due to dislocation movement barriers, making it difficult for dislocations to move, as shown in Fig. 5(a). When an external magnetic field is applied, it can provide magnetization energy (ΔU) to the solute atoms that is greater than the potential energy of the obstacle (ΔE) (Fig. 5(a)), which can promote the dislocation slip.

The depinning process of dislocations at a local obstacle on the slip plane is shown below [38]. In the initial state of one cycle, the dislocation breaks away from the obstacle under external stress and moves forward unhinderedly along the slip direction. The characteristic time required for a dislocation to slide between local obstacles is 10^{-3}−10^{-8} s. When the dislocation slip approaches the next obstacle, two situations will occur. Firstly, when the distance between the dislocation and the obstacle (L) is greater than the critical length (L^*) (~10^{-9} m), the moving dislocation will pass through the S and T resonance regions with a random electron spin direction. Secondly, when L is smaller than L^*, the free electrons will be excited between the dislocation and the obstacle due to the magnetic field, and the two free electrons will originate some new radical pairs. The characteristic time required for this process is 10^{-14}−10^{-6} s.

Under the magnetic field, the state of the spin of the electron is changed, and the atoms are rearranged, leading to spin-lattice relaxation, which causes the S state to transform into the T state [52]. The characteristic time of atomic rearrangement between the dislocation and the obstacle is 10^{-12}−10^{-8} s. As the dislocation slides, it will further encounter obstacles. Even if the radical pair is in the T state with lower bonding energy, energy is still needed to promote the dislocation to break through the obstacle. Once the energy reaches a critical value, the dislocations will break through the obstacles and continue to move forward.

3.3 Dislocation characteristics

The magnetoplastic effect was studied based on the influence of the magnetic field on dislocation paths. When the magnetic induction intensity B is smaller than the critical magnetic field intensity (3 T), the magnetoplastic effect will have a positive impact as B increases; conversely, the magneto-plastic effect will weaken [38]. The dislocation path length is related to the magnetic field intensity (H). When H is less than the critical magnetic field intensity H_m, the dislocation line length with the critical magnetic field intensity $L(H_m)$ will be 36−100 times that of the initial state $L(0)$, and the plastic deformation ability of the material will increase [52].

The effect of the magnetic field on dislocations can be reflected by dislocation morphology and structures. LI et al [63] found that the dislocation characteristics of the magnetic field-treated samples were “high density and multi-morphology”, among which the dislocation morphology was aligned, tangled, annular, and spiral. Among these, annular dislocation is the dominant mode of dislocation motion and internal stress release, which helps to enhance the strength of the material. In addition, for the alloy after the magnetic field treatment, researchers also discovered other dislocation characteristics, such as dislocation cells [64,65], dislocation walls [66], dislocation pile-up [49], pile-up group [41], network structure [66], sub-grain boundaries [67], and parallel dislocation [68]. Magnetic fields can promote dislocations to depin from the obstacle and increase dislocation length and mobility. Once a dislocation encounters an obstacle during slip, the morphology and structure of the dislocation will change.

The dislocation density cannot be ignored because the magnetic field affects the dislocation morphology. Introducing the magnetic field produces a magnetoplastic effect and increases the dislocation density [69,70]. WANG et al [44] found that due to the magnetoplastic effect, dislocations accumulated at grain boundaries and inside grains, and the number of dislocations in γ_e grains and lamellar colonies increased. After being pulsed MFT of 2.4 T for 50 pulses, the dislocation density of TC4 alloy increased by ~32% (Figs. 6(a, b)), and the dislocation multiplication phenomenon can be seen in the KAM maps in Fig. 6(c) [42]. This is because the pulsed magnetic field causes the change of the electron energy state at the dislocation pinning site, making it easier for vacancies or impurity atoms at the obstacle to move.

The positive effect of the magnetic field on the dislocation density can be seen from the above analysis. Table 1 summarizes the variation in the dislocation density of alloys after the MFT. To quantitatively study the dislocation density of alloys, researchers have used some formulas to characterize the variation of dislocation density through XRD test results. According to LI et al [37,66] and ZHAN et al [71], the Dunn formula

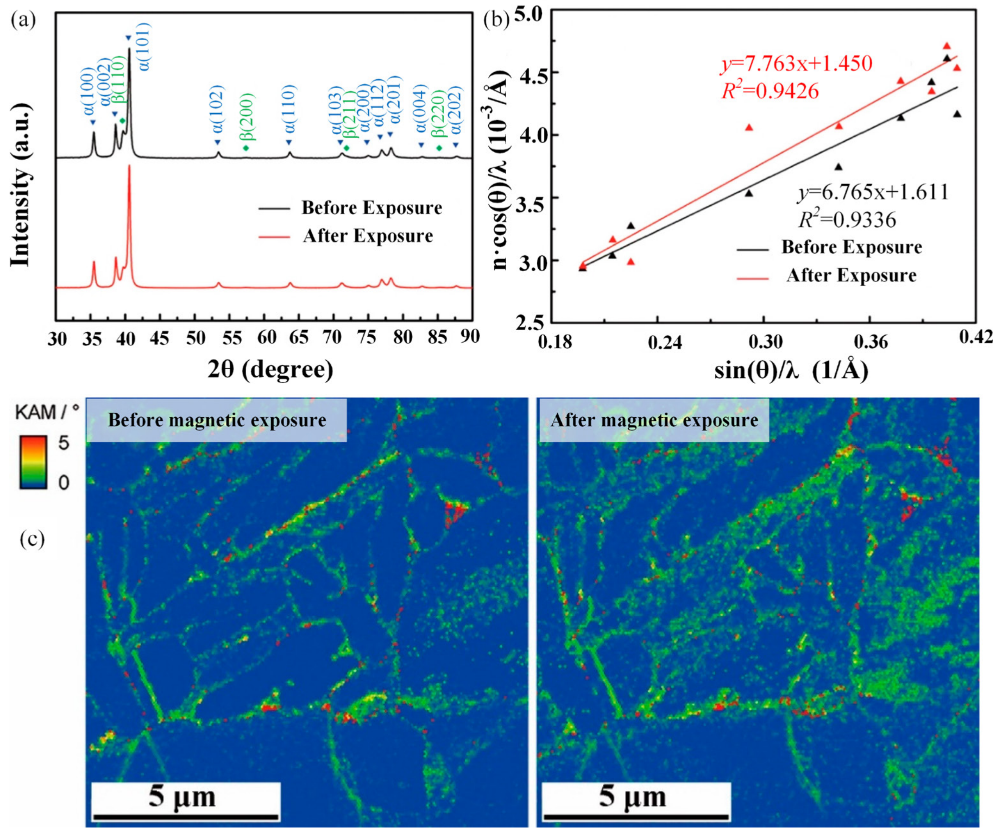

Fig. 6 Characteristics of Ti−6Al−4V specimen before and after magnetic exposure: (a) XRD patterns; (b) $n\cos\theta/\lambda$−$\sin\theta/\lambda$ linear fitting of strongest nine α-phase peaks; (c) Kernel average misorientation (KAM) maps [42]

Table 1 Variations of dislocation density for alloys with magnetic field

Alloy	Process	Dislocation density increment	Ref.
TC4 Ti alloy	High PMF 3 T + tensile test	26.91 times	[37]
	PMF 2 T	10.9%	[72]
	High PMF 3 T	4.8 times	[48]
	High PMF 3 T + tensile test	26.95%	[73]
Ti−6Al−4V alloy	MF 2.4 T	32%	[42]
Al	AMF 0.1 T + (325 °C, 6 h)	8.3%	[69]
	Annealing + MF 0.1 T	9.9%	[71]
7055 Al matrix composites	High PMF 5 T	42.6%	[70]
2024 Al alloy	High MF 1 T	1.28 times	[74]
AZ31 Mg alloy	High PMF 3 T + tensile test	2.55 times	[41]

and the full width at half maximum (FWHM) parameter can be used to quantitatively characterize the changes of dislocation density induced by the magnetic field. After treating the TC4 alloy with a 3 T pulsed magnetic field, the dislocation density is 26.91 times higher than that of the initial alloy [37]. The dislocation density of AZ31 Mg alloy tensile specimens with 3 T was increased by 2.55 times compared with the specimens without the magnetic field [41]. Moreover, the Williamson-Hall formula reported by LUO et al [36], and WANG et al [70], was also used to study changes in dislocation density. LUO et al [36] used the Williamson−Hall formula to quantitatively describe the changes in dislocation density caused by MFT of 1 T and found that the dislocation density of the alloy after MFT was higher.

However, the negative effect of magnetic fields on dislocation density has also been observed. Researchers reported that introducing the magnetic field enhances dislocation mobility, accelerates the interaction between dislocations, and promotes their rearrangement and mutual annihilation. Such as, DING et al [75] used 7A62 alloy, CAO et al [76] and HU et al [77] utilized cryoECAPed 1050 alloy, and MOLODOV et al [78] employed cold-rolled AA3103 alloy in their magnetic field-assisted treatment experiments, and pointed out that the reduction of dislocation density by dislocation motion under the magnetic field is not negligible. SONG et al [79] also found that the magnetic field can reduce the dislocation density of the Al−Cu−Mg alloy. They indicated that the magnetic field promotes dislocation motion. When two dislocations with opposite signs meet in the same slip plane, they will attract each other, resulting in dislocation annihilation.

4 Effect of magnetic field on grain refinement

4.1 Status of grain boundaries

MFT can promote dislocation depinning, increase the flexibility of dislocation motion, and enhance dislocation density. As the number of dislocations increases, they will become entangled with each other. When dislocations accumulate to a certain extent, the low-angle grain boundaries (LAGB) are formed, on which further pile-up of dislocations transforms the LAGB into subgrain boundaries. ZHAO et al [67] reported that the number of dislocation nets in the coarse α-laths increased significantly after high MFT (3 T). This result shows that high magnetic field may promote the proliferation of dislocations, thus improving the formation of sub-grain boundaries in the α-laths. Similarly, high magnetic fields promote dislocation depinning and form more sub-grain boundaries in cryoECAP 1050 alloys after annealing with a magnetic field of 12 T [77].

Astoundingly, the phenomenon that MFT decreases the proportion of the LAGB was found in TC4 alloy [42,72], while the dislocation density distribution near the grain boundaries changes. XU et al [72] speculated that the dislocations attached to the LAGB may enter or detach from the grain boundary region because of the movement. The dislocations of the same sign plugged up to increase the angle of the grain boundaries, and the dislocations of the opposite sign meet and annihilate, thus decreasing the angle of the grain boundary, and ultimately making the angle of the LAGB change.

Dislocations encountering obstacles at grain boundaries will undergo pile-up, traversing, and annihilation behaviors, which can change the grain boundary angle. ZHANG et al [42] found that coincidence site lattice (CSL) grain boundaries of Σ7, Σ13, Σ19, Σ35, Σ37, and Σ46 were formed in the α-phase of Ti−6Al−4V alloy after MFT, as shown in Fig. 7. It can be seen that the content of the CSL grain boundaries increases in the alloy after MFT of 2.4 T for 50 pulses, and the total proportion increases from ~5.98% to ~8.10%, while the Σ37 grain boundaries, which account for the highest percentage of the CSL grain boundaries, increase from ~2.58% to ~3.58%.

Moreover, WANG et al [44] also reported an increase in the proportion of the CSL boundaries, where the proportion of the CSL boundaries of Ti−48Al−2Cr−2Nb alloy increased from 22.5% to 29.1% after high MFT (10 T), with the proportion of Σ3 reaching 27.9%. They explained that the high magnetic field can lead to this increase. Besides, the presence of Σ11 CSL grain boundaries at an angle position of ~36.5° in TC4 alloy after a pulsed magnetic field (2 T for 100 pulses) was found by XU et al [72]. CSL grain boundaries are a special class of grain boundaries with relatively low grain boundary energies [42], which is favorable for mechanical properties. An increase in the CSL grain

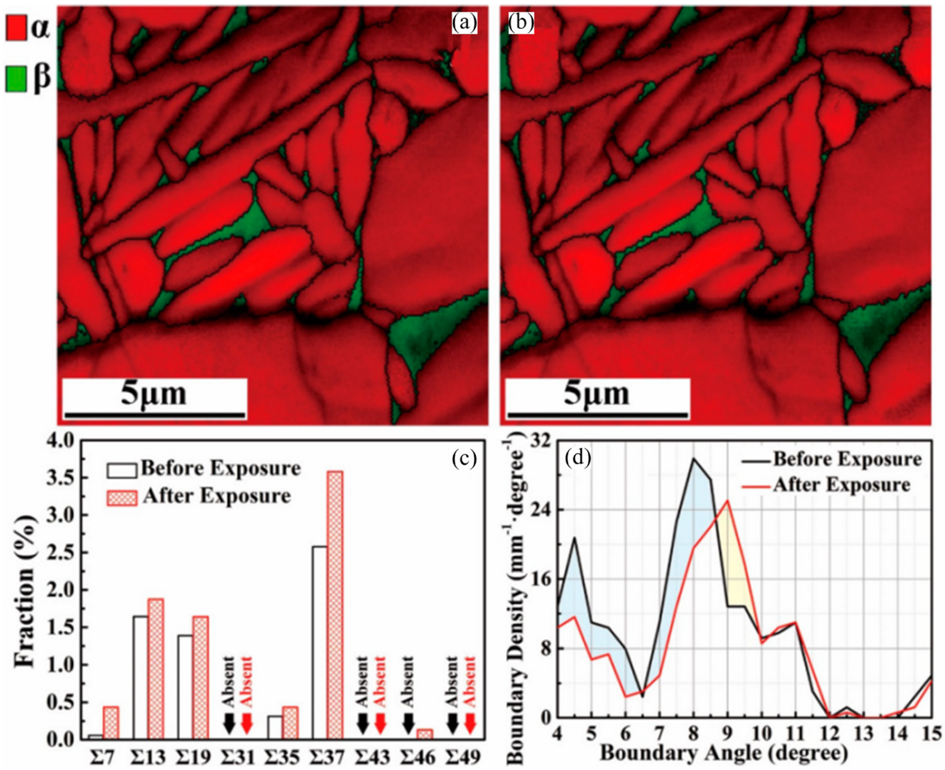

Fig. 7 Maps of phases and grain boundaries of Ti−6Al−4V specimen: (a, b) Before and after magnetic exposure, respectively; (c) Statistical chart of coincidence site lattice (CSL) grain boundaries; (d) Low-angle grain boundaries before and after magnetic exposure [42]

boundary content implies a decrease in the grain boundary energy, which is beneficial to making the material more stable.

4.2 Grain refinement

Grain refinement is an important method for strengthening and toughening alloys. After treatment with a magnetic field, the alloy exhibits a significant grain refinement effect. LI et al [74] showed that the grain size of the 2024 alloy was reduced by 35.2% when subjected to 1 T magnetic induction intensity compared to the case without MFT. WANG et al [41] reported that the average grain size of AZ31 alloy was reduced by 18.1% after 3 T pulse MFT. The grain size of LY12 Al alloy after alternating MFT treatment was 60% smaller than that without alternating MFT treatment [80]. The grain refinement mechanism facilitated by the magnetic field is analyzed in the following section.

As the dislocations move towards the grain boundary, they will accumulate near the grain boundary due to the strong hindrance of the grain boundary. The magnetic field promotes the proliferation and motion of dislocations, and as the dislocations continue to pile up, the ones closest to the grain boundaries create stress concentration and gradually form sub-grain boundaries. With further movement and accumulation of dislocations, the sub-grain boundaries are connected to the surrounding grain boundaries or sub-grain boundaries to form fine sub-grains [74].

On the other hand, the magnetic field increases the diffusion capacity, which adjusts the orientation of some sub-grains, forming more sub-grains. These sub-grains will serve as nuclei for recrystallization and gradually evolve into recrystallized grains [41]. The average grain of the AZ31 alloy with 3 T pulsed MFT is refined from 5.41 to 4.43 μm. The accumulation of dislocations promotes the formation of sub-grain boundaries, which results in the grain refinement [44]. Besides, FU et al [81] and ZHANG et al [80] treated LY12 Al alloy with alternating magnetic field (2 T) after cold and hot tensile deformation, and found that MFT can homogenize the microstructure and refine the grain. They also found that magnetic fields can release and homogenize entangled and fibrous structures caused by plastic deformations.

5 Effect of magnetic field on precipitation kinetics

As an important strengthening method of the alloy, precipitation strengthening can improve the comprehensive properties of the alloy and achieve the goal of strengthening and toughening. Magnetic fields have received much attention for their ability to provide an external energy field that affects the size, content, morphology, and transformation of precipitates in alloys. The formation of precipitates is related to precipitation kinetics, atomic diffusion, nucleation, and growth. Therefore, it is necessary to understand the effect of magnetic field on precipitation kinetics and atomic diffusion.

5.1 Diffusion of atoms in magnetic field

The effect of the magnetic field can provide energy for the diffusion of solute atoms, thereby promoting atomic diffusion. The schematic diagram of the atomic diffusion of Al−Cu−Mg alloy under the magnetic field (1 T) is shown in Fig. 8 [35]. Under the thermal motion, the magnetic moments of Mg, Al, and Fe atoms are oriented chaotically. Due to the introduction of the magnetic field, the magnetic moments of Mg, Al, and Fe atoms tilt toward the direction of the magnetic field (Fig. 8(a_1)), which increases the diffusion driving force. LUO et al [36] also reported that the magnetic moments of Mg and Al atoms in the magnetic field tend to the magnetic field direction, leading to changes in the magnetization energy. Similar results were also noted by LUO et al [49].

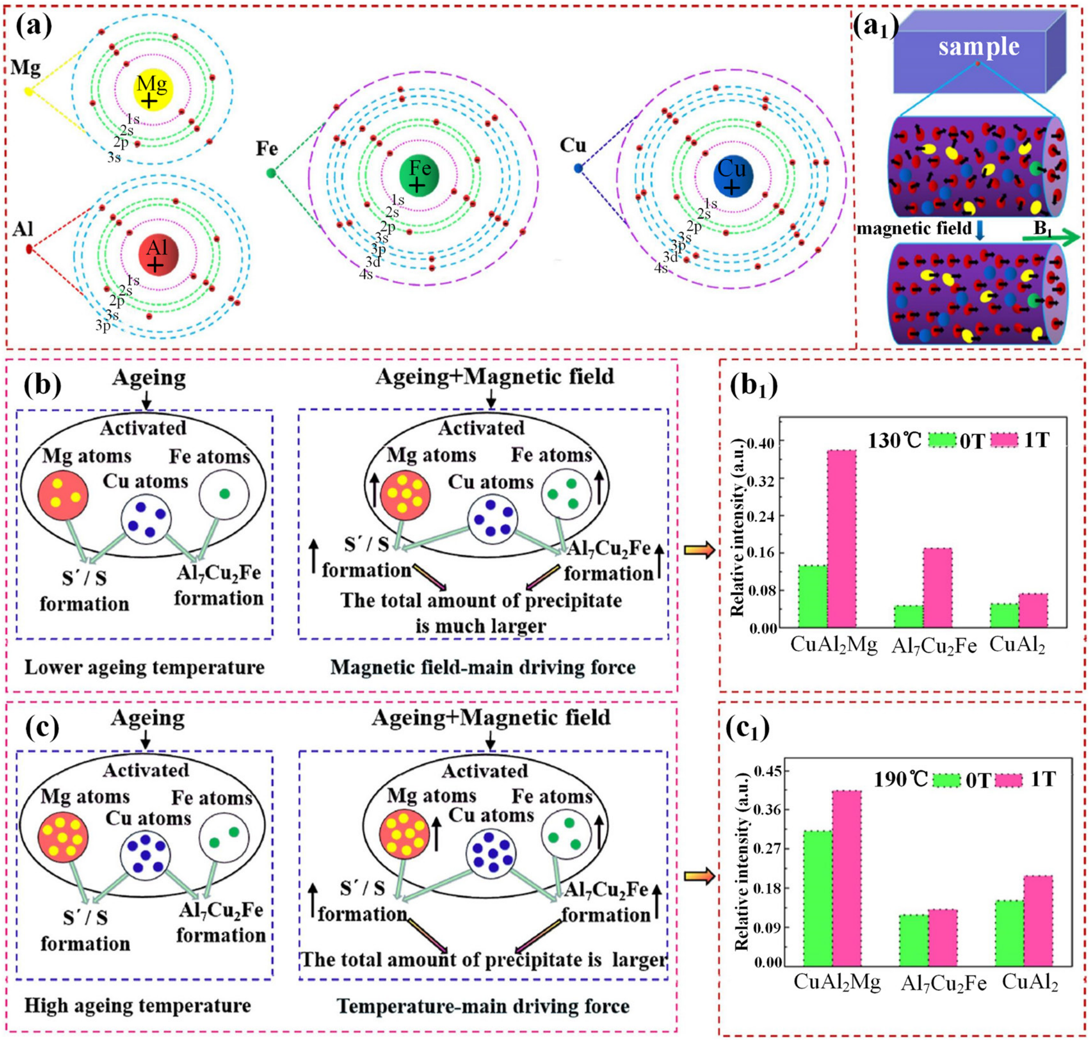

Fig. 8 (a, a_1) Schematic diagrams of electron orbital, electron distribution, and magnetic moment of solute atoms; (b, c) Schematic diagrams of enhanced precipitation kinetics in magnetic field; (b_1, c_1) Relative intensity of precipitates calculated from WAXS [35]

Driving force is the main factor affecting the atomic diffusion process. Solute atoms diffuse slowly under the action of low-temperature aging. After the action of the magnetic field, the magnetic field provides a driving force for atomic diffusion, leading to a higher atomic concentration and a faster nucleation rate, which further increases the content of precipitates under magneto-thermal coupling, as shown in Figs. 8(b, b_1). It can be seen from Fig. 8(c_1) that under the magnetic field, the relative intensity of $CuAl_2Mg$, Al_7Cu_2Fe, and $CuAl_2$ phases are 1.30, 1.11, and 1.38 times higher than that of high-temperature aging, respectively, which indicates that although the temperature is the main driving force of atomic diffusion, the magnetic field still has a positive role in promoting atomic diffusion.

For the diffusion driving force, ZHANG et al [35] reported a diagram of the influence of the magnetic field (1 T) on the precipitates during aging (130−240 °C), as shown in Fig. 9. They pointed out that Fe atoms in the ferromagnetic material are magnetized in the B_1 magnetic field, generating an additional B_0 magnetic field, and the diffusion driving force enhances from ΔE_T (ΔE_T is the energy provided by temperature field) in the aging to ($\Delta E_T + \Delta E_M$) (ΔE_M is the energy provided by original magnetic field) and ($\Delta E_T + \Delta E_M + \Delta E_{T0}$) ($\Delta E_{T0}$ is the energy provided by Fe atoms magnetization) in the aging + magnetic field (Fig. 9). Compared with aging alone, aging combined with a magnetic field increases the diffusion driving force, and causes an increase in the frequency factor of atom diffusion, the atomic diffusion coefficient, and the average atom diffusion rate. As a result, the magnetic field favors the nucleation of precipitates and accelerates their growth and coarsening during aging. ZHAO and WANG [82] pointed out that the magnetic field provides energy for the nucleation of the β phase, which makes the nucleation and growth of the β phase easier. At the same time, the magnetic field increases the solid solubility of the Al atoms in the matrix of AZ91D Mg alloy, which increases the content of the β phase. Introducing a high magnetic field during the aging of Al−Cu alloy can accelerate the diffusion of the Cu atom and reduce the solution active energy of the GP zone, thus accelerating the aging process [83,84].

In general, the diffusion rate of solute atoms significantly affects solute diffusion. According to previous reports [36,85,86], the magnetic field can change the frequency factor of atoms, thereby affecting the atomic diffusion coefficient. It has been reported many times that the diffusion rate of atoms with magnetic field treatment is faster than that without magnetic field [83,84]. Moreover, the solute diffusivity (D) can also be described by the Arrhenius formula of Eq. (1) [36]. LUO et al [36] indicated that due to the migration and proliferation of dislocations under the magnetic field, the vacancy formation energy (ΔU_V) and atomic transition activation energy (ΔU_A) values decrease, thereby increasing the solute diffusivity value and promoting the diffusion of solute atoms. The magnetic field will increase the flexibility of the dislocation motion, which is hindered by the precipitates, resulting in an enhancement of the dislocation density and vacancy concentration, providing a channel for the diffusion of atoms [36].

$$\ln D = \ln D_0 - \frac{Q}{RT} = \ln D_0 - \frac{\Delta U_V + \Delta U_A}{RT} \quad (1)$$

where D_0, Q, R, and T are the diffusion constant, the diffusion activation energy, the molar gas constant, and thermodynamic temperature, respectively.

5.2 Kinetics of precipitation in magnetic field

The action of the magnetic field can promote the precipitation kinetics of precipitates. To more specifically understand the effect of magnetic field on precipitation kinetics during aging, ZHANG et al [35] used the small angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) to scientifically study the precipitation kinetics of Al−Cu−Mg alloys aged at 130−240 °C for 10 min with and without 1 T magnetic field, as shown in Fig. 10. The area and area ratio of 1 T magnetic field is larger than those without the magnetic field under the same aging process, which proves that the size or volume fraction of precipitates under magnetic field is larger. Similar phenomena after the coupling of aging and magnetic field were reported by LIU et al [87] for AA2219 alloy, DONG et al [88] for AZ91 Mg alloy, and also by SUN et al [89,90] for TC4 alloy. To clarify the type of precipitates, $CuAl_2Mg$, Al_7Cu_2Fe, and $CuAl_2$ phases are observed in Fig. 10, and it is found that in the whole aging process, the relative intensity of the above three phases under 1 T is 1.30−2.86 times, 1.01−3.62 times and 1.18−1.78 times higher than that under 0 T, respectively.

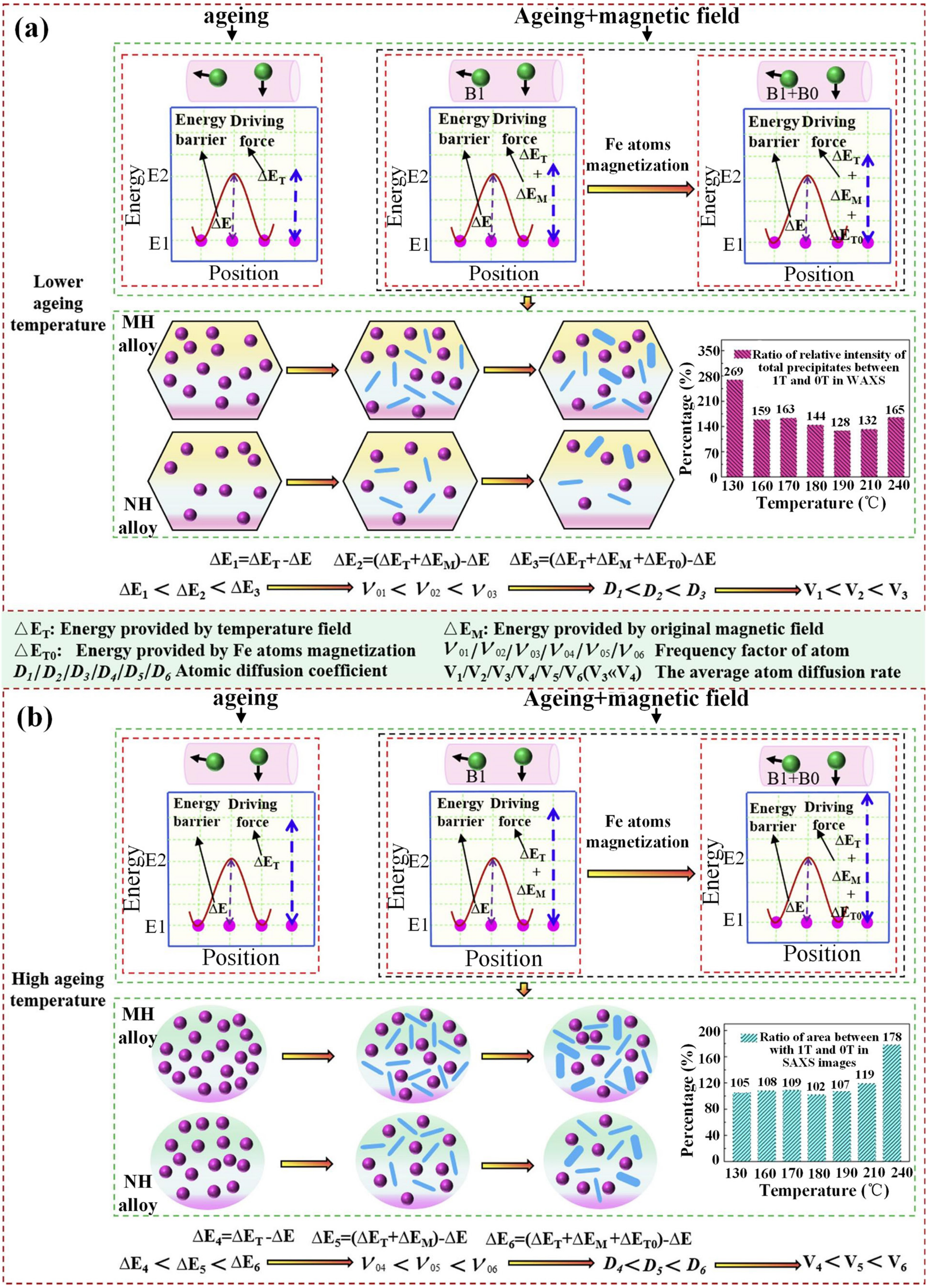

Fig. 9 Schematic illustration showing effect of magnetic field on precipitates at lower (a) and higher (b) aging temperatures [35]

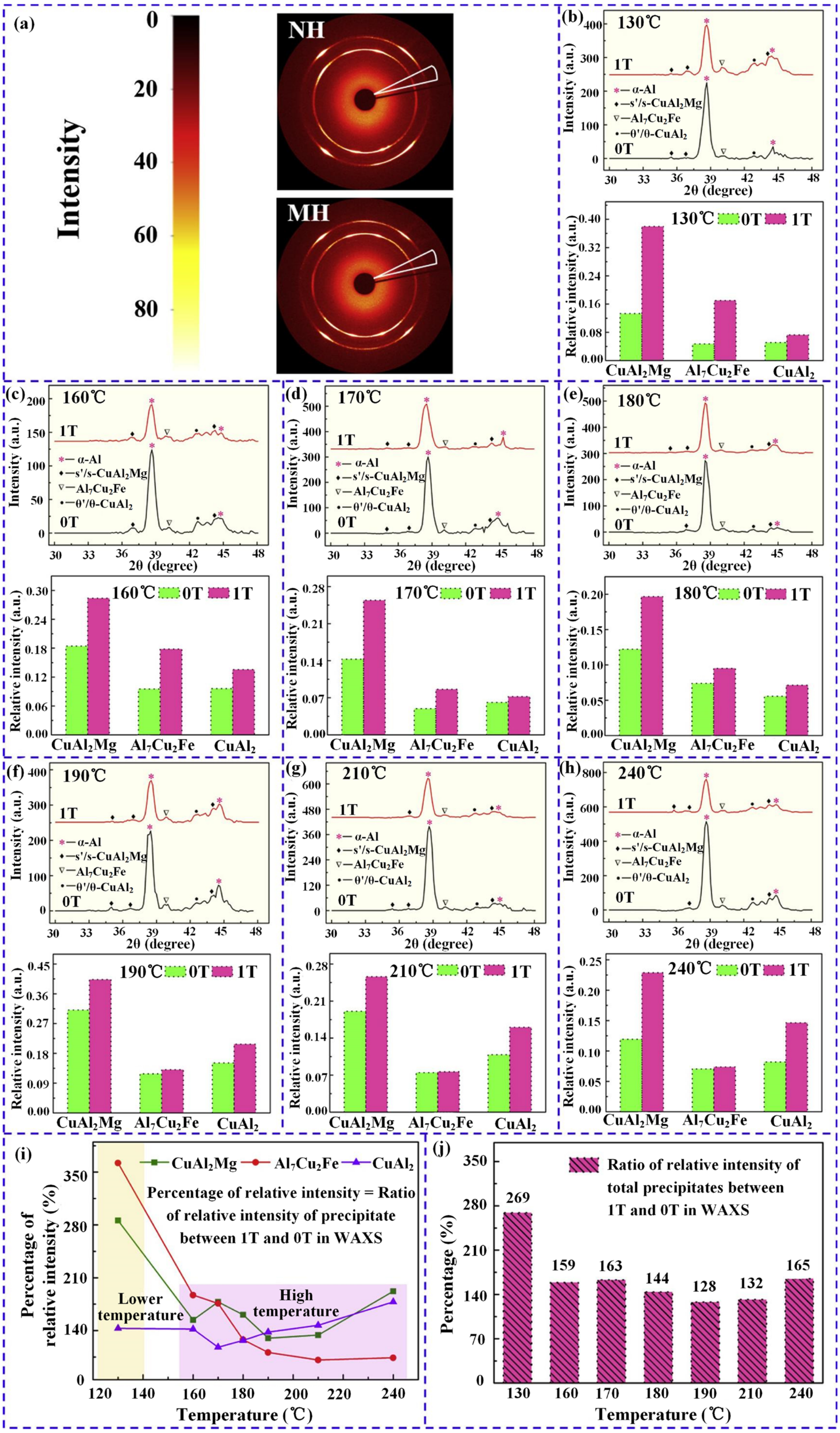

Fig. 10 WAXS patterns of Al−Cu−Mg alloys aged at 130, 160, 170, 180, 190, 210 and 240 °C with and without magnetic field [35]

Magnetic fields can promote precipitation kinetics through multiple mechanisms. This acceleration stems from dislocations providing rapid diffusion pathways for solute atoms, a view supported by LUO et al [49]. In addition, due to the formation of numerous dislocation cells, the activation energy associated with the nucleation of precipitates is reduced, thereby promoting the precipitation of precipitates, resulting in rapid enhancement of kinetics. WANG et al [44] showed that the accumulation of dislocations facilitated by the magnetic field can provide more nucleation sites for the precipitation of the secondary phase. Mobile dislocations can act as atomic diffusion channels, promoting the accumulation of atoms near the dislocations and coarsening the GP zone. In addition, the vicinity of the dislocations can serve as a preferential nucleation site for the precipitates, and the high dislocation density under the action of the magnetic field accelerates the nucleation rate of the η' phase [36].

Other researchers firmly believe that atomic clusters are coupled by electron wind force and magnetization stress when subjected to pulsed magnetic fields, leading to enhanced diffusion flux and facilitating the precipitation of the secondary α phase [89]. For precipitation kinetics, the Johnson−Mehl−Avrami−Kolmogorov is usually used to describe the relationship among the volume fraction of precipitates, activation energy, and reaction time during the phase transformation process [90,91]. The authors reported that applying a pulsed magnetic field (19.17 mT) can provide electromagnetic energy, reduce the activation energy required for phase transformation, and simultaneously obtain a larger volume fraction of precipitates. Therefore, pulsed magnetic fields can effectively accelerate the aging process.

In addition, nucleation under the magnetic field can also significantly affect precipitation kinetics. The critical nucleation energy (ΔG^*) and the critical nucleation rate (N) required for the formation of precipitates are expressed by Eqs. (2) and (3), respectively [35]. Since the magnetic field can provide magnetic field energy (ΔG_m), Eqs. (2) and (3) are further described as Eqs. (4) and (5), respectively. By comparing Eqs. (2) and (4), we can see that ΔG_1^* is smaller than ΔG^*, indicating that the magnetic field energy can reduce the critical nucleation energy for the precipitation of the new phase. Similarly, observing Eqs. (3) and (5), it can be seen that N_1 is greater than N, manifesting that the magnetic field can increase the critical nucleation rate of the new phase.

$$\Delta G^* = \frac{16\pi\sigma^3}{3(\Delta G_V)^2} \tag{2}$$

$$N = K \cdot \exp\left(\frac{-\Delta G^*}{kT}\right)\exp\left(\frac{-Q}{kT}\right) \tag{3}$$

$$\Delta G_1^* = \frac{16\pi\sigma^3}{3(\Delta G_V + \Delta G_m)^2} \tag{4}$$

$$N_1 = K \cdot \exp\left(\frac{-\Delta G_1^*}{kT}\right)\exp\left(\frac{-Q}{kT}\right) \tag{5}$$

where ΔG_V and σ are the free energy and interfacial energy per unit volume for the new phase, respectively; K is a constant that is related to the material and environment; k is the Boltzmann constant.

Moreover, according to the classical nucleation theory reported by SONG et al [79] and LIU et al [87], the nucleation rate ($\dot{N}$) can be expressed as Eq. (6). They pointed out that the ΔG_A is several orders of magnitude higher than the ΔG_k under magnetic thermal coupling, and it can be considered that (ΔG_k+ΔG_A) is equal to the ΔG_A. The action of the magnetic field is favorable to increasing the atomic vibration frequency and reducing the diffusion activation energy [35,75]. From Eq. (6), it can be seen that the nucleation rate increases, resulting in a more uniform and thinner Al_2CuMg phase being found in the magnetic field-treated alloy [79].

$$\dot{N} = nv \cdot \exp\left[-\frac{\Delta G_k + \Delta G_A}{kT}\right] \tag{6}$$

where n is the number of atoms per unit volume of the original phase; v, ΔG_k, and ΔG_A are the atomic vibration frequency, the nucleation work, and the diffusion activation energy, respectively.

According to the homogeneous nucleation theory, the energy relationship during phase transformation is shown in Eq. (7) [90]. When a pulse magnetic field is applied, the TC4 alloy produces a difference in magnetic energy due to the magnetic torque, which is the magnetic Gibbs free energy. For TC4 alloy, SUN et al [90] pointed out that the magnetic permeability of metastable α' phase is lower than that of α phase, and the magnetic Gibbs free energy is negative, which can be used as the driving force in the aging process. The critical nucleation energy (ΔG_e) is closely related to the driving force and can be expressed as Eq. (8) [90]. It can be seen that an increase in the nucleation driving force will reduce the critical nucleation energy and make nucleation easier. The pulsed magnetic field provides the driving force for nucleation through magnetic Gibbs free energy, which reduces the critical nucleation energy and ultimately promotes nucleation in the early aging process.

$$\Delta G=\frac{4}{3}\pi r^3(\Delta G_m+U_A)+4\pi r^2\sigma \quad (7)$$

where ΔG is the total change in free energy; r is the atomic radius; U_A is the atomic strain energy; σ is the surface energy of the crystal nucleus, both of which together act as the resistance of solid-state phase transformation; ΔG_m is the driving force in solid-state phase transformation, usually the difference of Gibbs free energy of the old and new phases.

$$\Delta G_e=\frac{4}{27}\cdot\frac{\eta^3\sigma^3}{(\Delta G+U_A)^2} \quad (8)$$

where η is the form factor.

5.3 Size and distribution of precipitates

As the atomic diffusion rate increases, it will inevitably lead to the coarsening of the precipitates. Figure 11 shows the schematic evolution of the GP zones and η' phase with and without magnetic field [36]. LUO et al [36] suggested that the effect of the magnetic field can increase the movable dislocation, which provides diffusion channels for solute atoms, thus accelerating the aggregation of solute atoms near the GP zone and making them coarse. The GP zones are enhanced to a stable size as the aging temperature increases, and additional solute atoms will accelerate the transformation of the GP zones into the η' phase. Under the same aging process, the magnetic field can produce higher dislocation density and solute atom concentration, causing the number and size of the GP zone and η' phase in the magnetic field + aging to be larger than that in the aging, as shown in Fig. 11. DING et al [75] found that the size and number density of the precipitates in the thermal magnetic coupling aging were higher than those in the conventional aging. They explained that this result is because the magnetic field increases the movement of dislocations, accelerates the movement of solute atoms, and promotes the coarsening of the GP II region.

Some researchers believe that introducing the magnetic field also plays an important role in the refinement and dispersion distribution of the precipitates. For example, SONG et al [79] found that the Al_2CuMg phase of Al−Cu−Mg alloy treated with the thermal-magnetic field (523 K and B=0.3 T) is more uniform and thinner, which is attributed to the magnetic field increasing the nucleation rate of atoms. SUN et al [89] pointed out that under the pulsed magnetic field, the amount of precipitates in TC4 alloy increased significantly, the size was smaller, and the distribution was more dispersed. This result is due to the coupling effect of the electron wind force and magnetization stress, which increases the diffusion flux and accelerates the secondary α phase precipitation. LIU et al [87] showed that the precipitates in the AA2219 alloy sample subjected to aging and a magnetic field are smaller and more dispersed than the conventional aging sample. This reduction is attributed to a

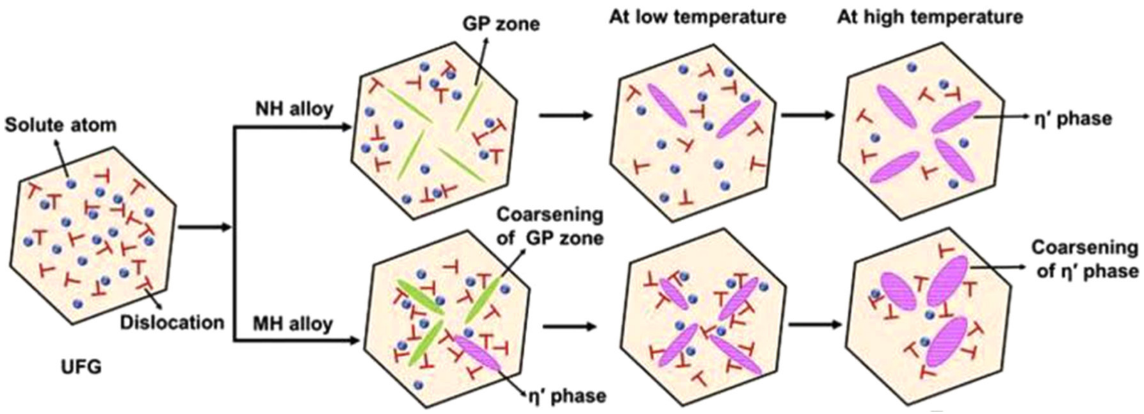

Fig. 11 Schematic illustration of evolution of GP zones and η' phases without and with magnetic field [36]

decreased driving force for precipitate growth. According to HAN et al [92], the alternative magnetic field increases the nucleation rate of the precipitates of aging, reduces the driving force for the growth of the precipitates, and makes the θ' phase finer and more uniformly distributed.

6 Effect of magnetic field on phase transformation

As an external energy field, the magnetic field can provide the driving force for phase transformation. In addition to the impact on dislocations, the magnetic field also affects the phase transformation of alloys, such as changes in size, distribution, and quantity of the phase [47]. For instance, LI et al [93] found that the magnetic field not only promoted the $\alpha'\rightarrow\alpha+\beta$ phase transformation by changing the thermodynamic driving force, but also reduced the width of the α'/α phase. LI et al [37] reported that the volume fraction of the α phase increased from 49.7% to 55.9%, suggesting that the high PMF is an exciting factor in facilitating the transformation of β phase to α phase. This result is also consistent with the findings of LI et al [48]. ZHAO et al [67] reported that a high magnetic field of 3 T can facilitate the $\alpha'\rightarrow\alpha+\beta$ transformation of Ti−6Al−4V alloy, expedite coarsening and spheroidization of α phase, and increase the volume fraction of β phase.

The high magnetic field promotes the phase transformation process by compensating the Gibbs free energy with the magnetization free energy [94]. Compared with heat treatment, applying a high magnetic field increases the magnetic free energy, changes the thermodynamic driving force, and promotes the phase transformation. The authors in Refs. [48,65] suggested that the phase transformation from β phase to α phase was due to the excitation effect of the pulsed magnetic field, which is caused by the following three reasons. Firstly, the magnetic field reduces the phase transition temperature by a certain amount [95]. For the volume susceptibility, β phase is smaller than α phase, causing the phase transformation temperature difference to be less than 0, so it is easier for a high pulse magnetic field to transform from β phase to α phase. A similar magnetic field lowering the phase transformation temperature was also reported in Al−4wt.%Cu alloys [96]. Secondly, the interface energy between α phase and β phase was reduced due to the magnetic field, which facilitates the transformation from β phase to α phase. Finally, the alloy gives rise to magnetoplastic effects and an increase in internal stress, which will act as a driving force leading to phase transformation from β phase to α phase [97].

7 Mechanical properties of alloys under magnetic field

Due to the magnetoplastic effect, the magnetic field significantly affects the mechanical properties of the alloy. This section summarizes the changes in residual stress, strength, and elongation of alloys induced by magnetic fields to understand the magnetoplastic effect.

7.1 Residual stress

The magnetic field plays an important role in eliminating residual stress. LI et al [38] found that the residual stress of the 7055 Al alloy was significantly reduced at 3 T magnetic field, and its minimum residual stress was 16 MPa. Similarly, LI et al [66] reported that the residual stress of 7055 alloys with 3 T magnetic field reached a minimum value of 38 MPa, which was 68.9% lower than that of the untreated specimen (122 MPa). WANG et al [61] and LI et al [98] reported that the residual stress of Al matrix composites treated with 3 T magnetic field was reduced from 41 MPa in the absence of magnetic field to −1 MPa, which is 102.4% lower than that of the specimens without magnetic field. After the magnetic field treatment (2.5−10 Hz), the residual stress of AZ31 alloy decreased in varying degrees, of which the elimination effect of residual stress after 10 Hz PMF was the most significant, with the average and maximum reduction rates of 26.6% and 30.3%, respectively [68].

According to the reasons for the elimination of residual stress by the magnetic field, there are mainly the following aspects [68]: Firstly, the local deformation of the alloy under the magnetic field makes the strain distribution uniform, harmonizes the new internal stress generated between the grains, and then eliminates the residual stress. Secondly, under the magnetic field and Lorentz force, the motion and proliferation of basal dislocations and dislocation density are increased, promoting a parallel distribution of dislocations and generating local plastic deformation that subsequently leads to the redistribution of residual stresses. Thirdly, the temperature rise caused by Joule heating enhances the irregular movement of the atom and the energy of the atom near the dislocations, reducing the pinning effect on the dislocations and releasing lattice distortions due to internal stresses. Fourthly, long-distance internal stress and uniformly distributed dislocations in the alloy were generated under the magnetic field. These two factors exert a positive interaction, namely, internal stress promotes dislocation mobility, and dislocation movement relaxes long-distance internal stress [38]. Besides, the residual stress can be eliminated by normal lattice distortion, increased dislocation motion, and uniform microstructure distribution under an SMF [66].

7.2 Strength and elongation

Magnetic field assistance is one of the valid approaches to improve the mechanical properties of alloys. Table 2 summarizes the mechanical properties of light alloys assisted by magnetic field.

Dislocation strengthening is believed to be the primary strengthening mechanism. SHI et al [69] pointed out that the YS and EL of single-crystal Al alloy with 0.1 T alternating magnetic field increased by 49.3% and 24.7%, respectively, compared to those of the alloy without magnetic field due to the magnetoplastic effect and dislocation strengthening. The results of synergistic enhancement of tensile properties of 2024 Al alloys and AZ31 Mg alloys due to magnetoplastic effect were also reported by WANG et al [41] and LI et al [74], respectively. CHENG et al [99] increased the maximum ultimate tensile strength (UTS) of the Al−Zn−Mg−Cu Al matrix composites with the magnetic field (4 T with 30 pulses) by 20.7%. This is mainly due to the dislocation strengthening caused by increasing dislocation density. Further, the Bailey−Hirsch model shown in Eq. (9) is used to express the relationship between the dislocation density (ρ) and flow stress (τ) [71,103]. It can be seen from Table 1 that the magnetic field can increase the dislocation density, and according to Eq. (9), it can increase the stress and strengthen the alloy [98].

$$\tau = \tau_0 + \alpha G b \sqrt{\rho} \quad (9)$$

where τ_0 is the shear stress required without work

Table 2 Mechanical properties of light alloys assisted by magnetic field

Alloy	Process	Process parameter	Mechanical property increment/%			Ref.
			YS	TS or UCS	EL	
AZ31 Mg alloy	Tensile + MF	3 T	−	2.2	28.7	[41]
TC4 alloy	Tensile + MF	3 T	−	−	23.98	[37]
	High PMF	4 T	−	2.3	4.8	[48]
	Cryogenic treatment + SMF	(−196 °C, 12 h) + 0.3 T	−	3.01	11.29	[95]
Ti−6Al−4V alloy	Annealing + MF	(400 °C, 0.5 h) + 8 T	3.7	5.5	60	[93]
Ti−48Al−2Cr−2Nb alloy	Heat + high MF	(1260 °C, 3 h) + 10 T	−	16.7	150	[44]
Al	Heat + MF	(250 °C, 6 h) + 0.1 T	49.3	−	24.7	[69]
Al−Zn−Mg−Cu matrix composites	High PMF	2 T, 4 T	−	20.7	12	[98,99]
7055 Al alloy	Tensile + MF	3 T	−	7.9	20	[38]
7055 Al matrix composite	MF		−	10.3	16.2	[100]
7055 Al alloy	PMF + two-stage aging	32 mT + (102 °C, 1 h) + (136 °C, 1 h)	26.56	23.10	9.85	[101]
2024 Al alloy	MF	1 T	−	3.9	16.7	[102]
	Tensile + MF		−	9.3	30.8	[74]

hardening, α, G, and b are the constant, the shear modulus, and the magnitude of Burgers vector, respectively.

Precipitation strengthening usefully enhances the strength of alloys [104]. SUN et al [89,90] pointed out that applying a pulse magnetic field (19.17 mT) during the aging process (900 °C + (500 °C, 1−4 h)) can promote the precipitation of the secondary α phase, and increase and reduce the volume fraction and size of the precipitates, thereby strengthening the TC4 alloy. CAI et al [46] found that the ultimate compressive strength of Mg−Al−Gd alloys with 1 T increased from 447 to 473 MPa. The strength was improved because of the solid solution of Gd, the reprecipitation of fined Mg_5Gd laths, and the precipitation of Al_2Gd phase and refined long-period stacking ordered. The magnetic field can increase the contents of the Al_2Gd phase and GdH_2 phase, and refine the Al_2Gd phase, which has a positive effect on the improvement of mechanical properties [51]. Numerous fine precipitates were dispersed and distributed in the matrix of Al alloy with magnetic field and aging treatment, and its tensile strength (TS) and hardness were significantly improved compared to conventional aging [87,92]. According to Orowan strengthening mechanism, precipitation strengthening contributes 99.42 MPa to material strength [98]. However, a single strengthening factor is not significant in improving the mechanical properties of the alloy.

In addition, the type, shape, and size of the secondary phase can significantly affect the mechanical properties of the material. LI et al [38] found that 7055 alloys with 3 T caused the η phase, incoherent interface with the matrix, at the grain boundary to transform into η' phase that was coherent or semi-coherent with the matrix, which helped to improve the strength and toughness of the material [66]. The TS and EL reach 610 MPa and 9.0%, respectively, which are 7.9% and 20% higher than those without magnetic fields. LI et al [93] reported that the SLM-fabricated Ti−6Al−4V under the action of 8 T exhibited moderate strength and excellent elongation (YS=1092 MPa, UTS=1227 MPa, and EL=15.1%) because of the full of ultrafine lamellae $\alpha+\beta$ phases and a part of martensite α', as shown in Fig. 12. The synergistic improvement in strength and ductility was enhanced as the brittle martensite α' can obstruct grains nucleating and growth, restrict the morphology size of α' and α, and encourage the formation of fine lamellae $\alpha+\beta$.

Synergistic effect of multiple strengthening mechanisms is usually required to improve the mechanical properties of alloys. LI et al [48,65] found that after applying the magnetic field of 4 T,

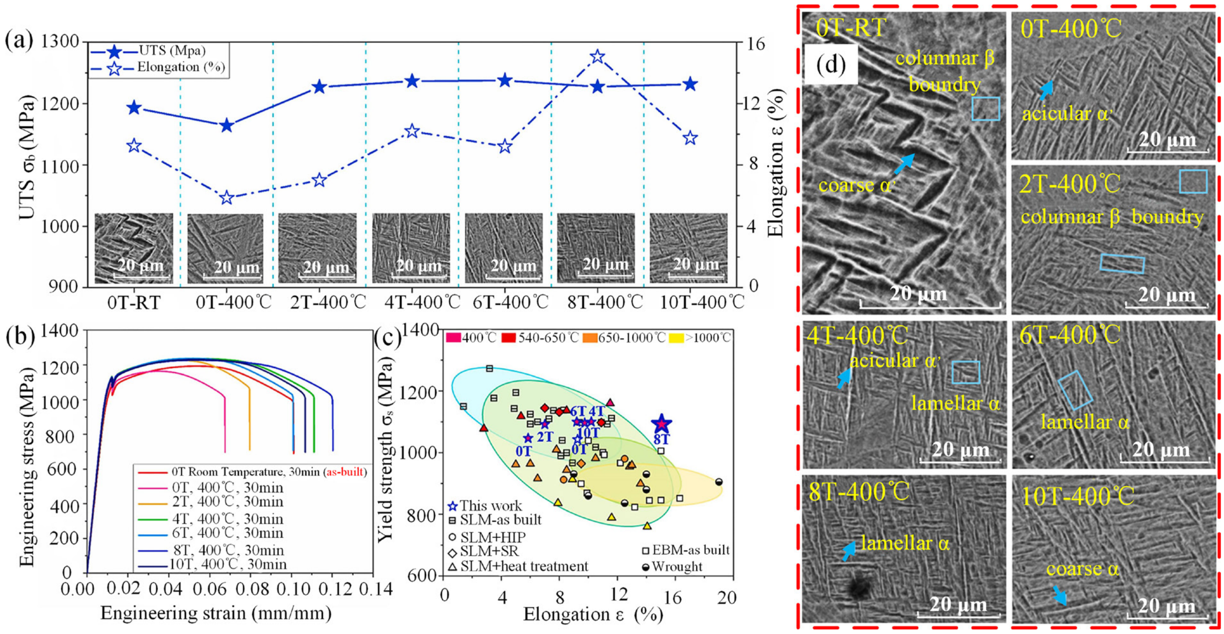

Fig. 12 Mechanical properties and microstructure of SLM-fabricated Ti−6Al−4V alloy at different states: (a) UTS and EL; (b) Engineering stress−strain curves; (c) Strength−elongation plot of Ti−6Al−4V alloy fabricated by different technologies; (d) SEM morphology [93]

the strength and plasticity of TC4 alloy can be synergistically improved. The TS and EL are 1265 MPa and 15.66%, respectively, which are 2.3% and 4.8% higher than those of the alloy without the magnetic field. Applying the magnetic field leads to more dislocations, *α* phase, and *α*/*β* phase boundary, resulting in dislocation strengthening, precipitation strengthening, and grain boundary strengthening. LI et al [95] pointed out that the TS and EL were increased by 3.01% and 11.29%, respectively, for the coupled static magnetic field (0.3 T) and cryogenic treatment (−196 °C, 12 h) sample compared to those of the untreated sample. The mechanical properties were enhanced due to the increase in *α* phase content, recrystallized grains, and dislocation density. WANG et al [44] pointed out that the improved strength and elongation of Ti−48Al−2Cr−2Nb alloy is due to the refinement of the duplex microstructures and the increase of the CSL boundary ratio of the *γ* phase by high magnetic field.

Some researchers reported different reasons why magnetic fields enhance the ductility of alloys. For example, JI et al [64] pointed out that the magnetic field increases the number of slip bands during the tensile test, and dislocations can move on more slip planes, weakening the degree of dislocation accumulation and the interaction between dislocations. DING et al [75] reported that the EL of 7A62 Al alloy after thermal-magnetic peak aging (B=0.5 T, 120 °C) was increased by 15.6% compared to that of peak-aged alloy due to the dislocation depinning effect and the broadening of the grain boundary precipitation-free zone. LI et al [66] pointed out that the EL of 7055 alloys at 3 T is 40% higher than that without the magnetic field. The high EL is attributed to the dislocation walls and lines formed by dislocation climbing and rearrangement, some precipitates dissolve into the matrix, the recrystallized grains grow up to be equiaxed, and the grain orientation aligns into the (111) and (200) planes.

Moreover, LI et al [73] reported that the maximum EL of TC4 alloy was 12.41% at 3 T, which was 23.98% higher than that without magnetic field alloy. This was attributed to the transformation of *β* phase to *α* phase and the generation of the preferred orientation of crystal planes along the slip direction. ZHAO et al [67] reported that, firstly, the ductility was enhanced because the produced thick *α*-laths and globular *α*-phase particles can accommodate high dislocation density. Secondly, the texture of the *α*-variant tends to align in the $\langle 11\bar{2}0\rangle_\alpha$ direction, easily activating prismatic and basal slip. Finally, the volume fraction of the *β* phase increases from 6.5% to 13.4%, with more slip systems than the *α* phase.

8 Summary and outlook

8.1 Summary

This paper reviews the magnetoplastic effects of solid light alloys under the magnetic field-assisted process, including the effects of the magnetic field on dislocation, grain refinement, precipitation kinetic, and phase transformation. On this basis, the mechanisms of strengthening and toughening of light alloys in the presence of magnetic fields are further elaborated. Magnetic field-assisted processes have received much attention compared to conventional plastic deformation and heat treatment methods. They have been increasingly used to improve the mechanical properties of light alloys due to their advantages, including the facilitated dislocation depinning, increased flexibility of dislocation motion and content of the CLS grain boundary, promoted grain refinement, phase transformation, precipitation of precipitates, and reduced residual stress.

For the magnetoplastic effect in light alloys, the main advantage over alloys without a magnetic field is that the magnetic field changes the radical pairs from the S state to the T state. This transition reduces the resistance between dislocations and obstacles, thereby promoting the depinning of dislocations. Meanwhile, the magnetic field provides energy that facilitates atomic motion, increases the slip plane spacing, and decreases the critical shear stress for dislocation motion, which are key factors contributing to the magnetoplastic effect in alloys. In addition, the grain boundaries status, grain refinement, atomic diffusion, precipitation kinetics, content, size and distribution of precipitates, phase transformation, and mechanical properties of magnetic field-treated alloys are summarized, which can provide attractive theories for the study of magnetic field-assisted processes for light alloys. Therefore, the attractive insights can be summarized as follows: magnetic field promotes dislocation motion, grain refinement, and phase transformation, accelerates atomic diffusion and secondary phase precipitation, and synergistically improves the strength and plasticity of the alloy.

8.2 Challenges and prospects

With the continuous demand for high-strength, lightweight, and safety materials in the fields of aerospace and transportation, high-strength light alloy materials are applied to complex components. High-strength light alloys usually have the characteristics of high manufacturing difficulty and difficult-to-control forming defects. The special energy field-assisted forming technology using energy fields such as magnetic fields and electro-magnetic fields has obvious advantages and great potential in overcoming and alleviating the manufacturing bottleneck of high-strength and difficult-to-deform light alloy materials. The key difficulties and challenges faced by the special energy field-assisted manufacturing technology in the future mainly include two aspects: one is the quantification and clarification of the action mechanism of the special energy field, and the other is the mechanical modeling under the influence of the special energy field.

In recent years, due to the advantages of light alloys and magnetic fields, magnetic field-assisted processes have received increasing attention in the processing of light alloys. These processes have shown significant advantages and potential for magneto-plastic effects, promotion of dislocation motion, acceleration of the secondary phase precipitation, and enhancement of mechanical properties. However, in the wide range of applications of magnetic field-assisted processes, numerous challenges and problems have to be overcome and solved. The reasons for this are the lack of in-depth and systematic understanding and study of the magnetic field-assisted processes and mechanisms, the absence of predictive models, the difficulty of equipment to meet the requirements, and the dilemmas of multi-energy field coupling. Challenges and future perspectives include innovating multi-energy field coupling processes, developing lightweight and efficient energy field equipment, studying the mechanism of action of magnetic field coupling, and establishing accurate prediction models, as shown in Fig. 13 [34,47,105−108].

8.2.1 Development of innovative multi-energy field coupling process

Introducing energy fields into light alloy forming and heat treatment as new processes and methods to expand traditional processing technologies is an effective approach for forming high-performance parts. Magnetic fields have the

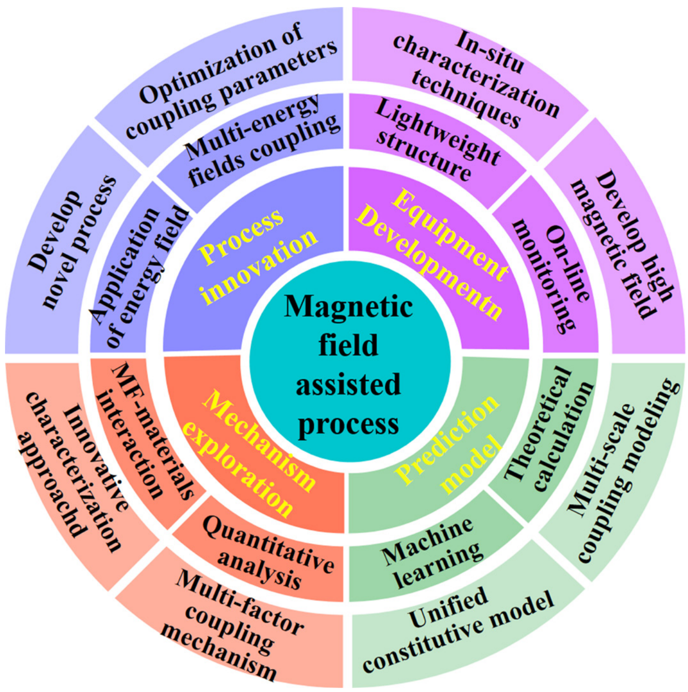

Fig. 13 Prospects for magnetic field-assisted processes in light alloys [34,47,105−108]

advantage of generating magnetoplastic effects, but single-energy field treatments have certain limitations. The coupling treatment of magnetic and other energy fields has gained effects. However, currently, most multi-energy field-assisted treatments are only used to study and analyze the mechanisms and effects of single-energy fields.

Using multi-energy field coupling technology can bring more opportunities for customizing the microstructure and mechanical properties of light alloys and is expected to manufacture key components that meet the needs of high-end equipment. The mechanism of the coupling effects, stacking effects, and interaction effects of multi-energy field coupling processes can help to optimize the microstructure and properties of alloys [105]. For instance, the coupling treatment of pulsed magnetic field and pulsed current can reduce the residual stress by 60%, while the single pulsed magnetic field and pulsed current treatments can only reduce 10% and 20%, respectively [109]. CAI and HUANG [109] reported that the magnetic field can promote the depinning of dislocations, and the pulse current can provide conduction electrons and promote the dislocations to move farther and faster. The electro-magneto-plasticity generated by this coupling effect eliminates residual stresses. Existing electroplasticity and magnetoplasticity can reduce the flow stress and improve the ductility of metals [110]. Therefore, coupling magnetic fields with other energy fields is necessary to explore innovative magnetic field-assisted processes and promote their industrial applications.

For multi-energy field coupling processes, optimizing the process parameters is also crucial to regulate the microstructure and mechanical properties of the alloy. Through the innovative multi-energy field coupling process collaborative manufacturing, it is possible to elucidate the mechanisms and principles under the action of multi-energy field coupling process, realize the collaborative design and analysis of the entire multi-process chain, prepare high-performance target parts of light alloys, to ensure its stability and consistency, and provide a means to solve the current "pain point" problems in plastic forming manufacturing.

8.2.2 Development of lightweight and efficient magnetic field equipment

The low resource consumption, non-contact nature, high efficiency, and magnetoplastic effects of the magnetic field are exploited. The design of high-end equipment with a high magnetic field with adjustable magnetic field strength, simple structure, lightweight, and high efficiency will be of great importance in promoting and accelerating the green and efficient development of the multi-energy field-coupled auxiliary processes for industrial applications. High-end equipment is developing rapidly in the direction of material diversification, size extremity, cross-scale structure, and ultra-high precision [111]. Therefore, it is crucial to develop such a high-end magnetic field equipment and to realize the integration of composite multi-energy field processing and manufacturing methods and the intelligentization of process equipment in its preparation.

The magnetic field distribution is not uniform during the magnetic field-assisted treatment, and it is difficult to accurately determine and control the magnetic field distribution during the deformation. It is an important research direction of struggle to develop systems and equipment with online monitoring functions and in-situ characterization technology to realize precise regulation of the microstructure and properties during deformation. The development of digital twin systems and intelligent equipment for magnetic field-assisted processes based on accurate predictive modeling, online monitoring, and in-situ characterization techniques is of great significance for fabricating high-performance light alloys and achieving efficient forming.

8.2.3 Revealing action mechanism of magnetic field-assisted processes

The magnetic field-assisted processes will certainly become an effective and promising method to improve the properties of light alloys and their key components, but there are still deficiencies. Although the magnetoplasticity effect can reflect the influence of the magnetic field on light alloys to a certain extent, the mechanisms of the magnetic field on the microstructure (such as dislocations and grain boundaries), and the material dynamics still needs to be studied in depth. To facilitate the innovation and application of magnetic field-assisted processes, various measures need to be improved, including process route innovation, process parameter determination and optimization, forming quality assurance and control, and property customization and enhancement. For these improvements, it is necessary to establish a systematic theoretical framework and knowledge system that reveals the scientific mechanisms of the mechanism of the magnetic field-assisted process for further research and application.

The action mechanism of the magnetic field on the physical processes and mechanical properties of light alloy materials needs to be explored in depth. To understand comprehensive theoretical knowledge of the magnetic field-assisted process, including the mechanisms of interaction between the magnetic field and material, microstructure evolution, and the relationship between the magnetic field and performance, is important for guiding the development and advancement of magnetic field-assisted process technology. For this purpose, innovative characterization methods and more quantitative analyses are necessary to understand the mechanisms by which magnetic fields affect alloys.

8.2.4 Establishment of accurate and efficient prediction models

Magnetic field-assisted processes often require coupling with conventional or multiple/special energy fields, posing numerous challenges such as process complexity, poor predictability, scheme optimization difficulties, and challenges in real-time monitoring. Establishing accurate and efficient predictive models is of significant importance for gaining a deeper understanding of the mechanical behavior, microstructural evolution, deformation mechanisms, process parameter optimization in magnetic field-assisted processes, and aspects that traditional experimental methods struggle to reveal and comprehend. Existing constitutive models do not fully consider the influence of many factors, resulting in the absence of relevant predictive models. In addition, the study of the deformation mechanism of magnetic field-assisted processes under the multi-coupling of energy fields is not in-depth or even poorly understood. Therefore, constructing a unified constitutive model regarding the action of magnetic fields has become an urgent issue to be addressed.

The prediction models available for reference at this stage are mainly based on first principles, molecular dynamics, dislocation dynamics, crystal plasticity, and finite element models [105]. Magnetic field-assisted treatment is usually coupled with thermal, force, electric, or other energy fields. Considering the complexity of multi-factor interactions and coupling effects, multi-scale modeling is an effective method to study and explore the magnetic field-assisted process. Multiscale coupling modeling methods include internal-state-variable methods, sequentially coupling methods, fully coupling methods, and cross-scale coupling methods [108]. Moreover, machine learning, digital twin modeling, and theoretical computational modeling are powerful tools for studying magnetic field-assisted processes. For high-performance plastic forming using magnetic field-assisted processes, multiscale coupled modeling is combined with digital twins and intelligent equipment to create a real-time simulation and monitoring platform for the forming process, realizing intelligent high-performance plastic forming manufacturing [108].

CRediT authorship contribution statement

Bo CHE: Formal analysis, Investigation, Methodology, Writing – Origin draft, Writing − Review & editing; **Liang HUANG:** Investigation, Conceptualization, Methodology, Funding acquisition, Supervision, Writing − Review & editing; **Bing-xin XIE:** Data curation, Formal analysis, Investigation, Methodology, Writing − Review & editing; **Wei ZHOU:** Formal analysis, Investigation, Methodology, Data curation.

Declaration of competing 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.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 52274382), and the National Key Research and Development Program of China (No. 2023YFB3407000).

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磁场辅助轻合金磁致塑性效应的研究进展

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摘 要：轻合金具有比强度高、质量轻等无可替代的优点，是航空航天、军事、海洋工程等前沿技术中不可缺少的工程结构材料。制备高强韧轻合金，使其在先进的工程应用中发挥更大作用，是一个持续的研究热点。磁场辅助工艺作为提高轻合金力学性能的新方法，可以产生磁致塑性效应。因此，本文综述了轻合金磁致塑性效应的研究进展，阐明了磁场对轻合金位错、晶粒细化、析出动力学、相变和力学性能的影响。磁场处理能使自由基对从基态转变为激发态，降低位错与障碍物之间的阻力，促进位错退钉扎。此外，磁场作用可促进晶粒细化和相变，促进析出动力学，并协同提高强度和伸长率。最后，对轻合金磁场辅助工艺的发展前景进行了展望。

关键词：轻合金；磁场；磁塑性效应；位错；析出动力学；力学性能

(Edited by Wei-ping CHEN)