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REVIEW

Research Progress on Microstructure and Mechanical Properties of Medical Rare-Earth Magnesium Alloys

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Abstract: Recently, magnesium alloys attract much more attention as the biomedical metallics. Unfortunately, due to their low strength, the implantation materials of Mg alloys are prone to collapse and fracture during the in-vivo/vitro service, which seriously endangers the life-safety of patients. Rare-earth micro-alloying is an effective method to enhance the mechanical properties of degradable Mg-based alloys, which cannot only eliminate the impurities and purify the melt, but also promote the dynamic recrystallization and form the long period stacking ordered phase structure. Therefore, based on the correlations between mechanical properties and microstructure transformation of Mg alloys, the research progress on the microstructure and mechanical properties of rare-earth Mg alloys was reviewed. The essential correlations among the rare-earth elements, the secondary phases, and the mechanical properties of Mg alloys were investigated. Additionally, the strengthening and toughening mechanisms of the continuous dynamic recrystallization of medical rare-earth Mg alloys were clarified. Besides, the effect of long-period stacking ordered structure induced by rare-earth elements on the mechanical properties of Mg alloys was comprehensively summarized. Finally, the development directions of medical rare-earth Mg alloys was proposed.

Key words: rare-earth elements; degradable magnesium alloys; microstructure; recrystallization mechanism; mechanical properties

As a new generation of biomedical metallics, magnesium-based alloys attract much attention due to their excellent biocompatibility, controllable spontaneous degradation, and unique elastic modulus which is suitable for human bones[1–14]. More importantly, magnesium-based alloys can minimize the stress-shielding effect and effectively stimulate and guide the bone-loading transmission[15–19]. Besides, they can avoid the secondary surgery for implant removal and reduce the medical cost and physical pain for the patients[20–26]. Thus, the medical Mg alloys show great application potential in the fields of large-size bone fixation and micro-scale cardiac vascular stents[27–31], as shown in Fig. 1[32–36]. However, the mechanical properties of Mg alloys are very poor, compared with those of other traditional inert metals, which may affect the accuracy of tissue reconstruction and healing effect[37–40]. Importantly, the prerequisite that the mechanical properties can satisfy the standards is an essential condition and reliable guarantee for the safe implantation of medical Mg implants. Normally, the implantation criteria for medical magnesium alloys as bone fixation and vascular stent materials are yield strength (YS)> 200 MPa, ultimate tensile strength (UTS) >300 MPa, elongation (EL) >15%, and corrosion rate<20 μm/a in simulated body fluid[41]. As a result, how to precisely control/ modify the microstructure characteristic and improve the mechanical properties of medical Mg alloys becomes an urgent issue.

Commonly, the heat-treatment, plastic-deformation, and alloying are effective ways to improve the service performance of Mg alloys[42–45]. The heat treatment can enhance the mechanical properties of magnesium alloys by changing their microstructures, but the optimal heat treatment can be hardly determined because of the phase transformation

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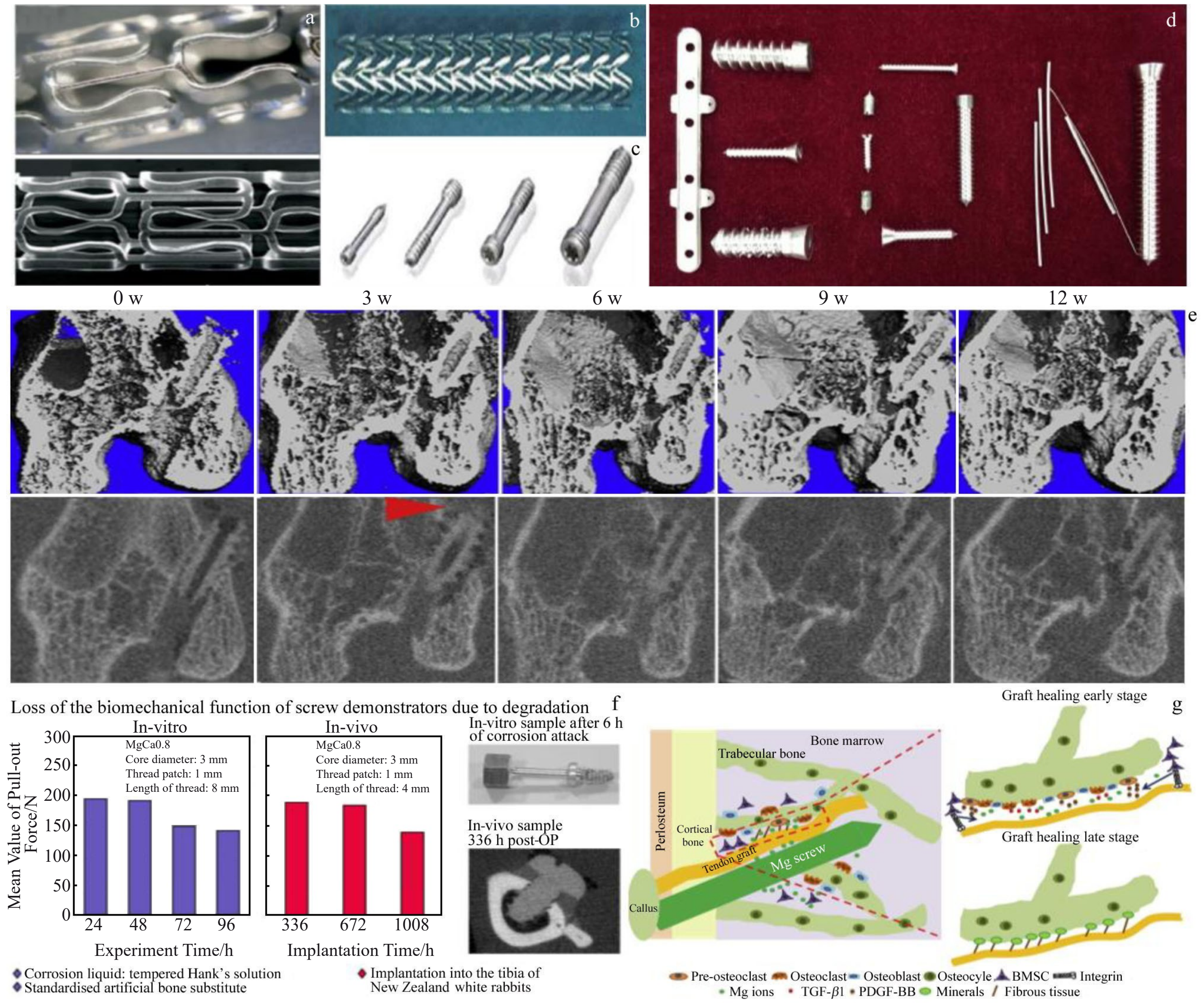

Fig.1 Various types of biodegradable Mg-based metal implants with clinical applications (a–d); in-vivo images of knee joint in rabbits after insertion of Mg interference screw (the periosteal reaction can be observed at the extra-articular exit in the Mg group, which is indicated by the red arrow head) (e); comparison of in-vivo and in-vitro biomechanical loss of functions (f); schematic diagrams of mechanism of Mg screw in tendon graft healing (g)[32–36]

temperature of the alloys[46–47]. Additionally, long period of heat treatment may lead to the abnormal grain growth and then deteriorate the service index of the raw Mg-based materials. Plastic deformation can cause/induce more sliding dislocations and lattice rotation, which refines the grain microstructures of Mg alloys, thus improving the plasticity and toughness of the Mg-based alloys[48–49]. Moreover, it is found that the rare earth (RE) micro-alloying is also a valid/effective way to adjust/optimize the phase features and improve the mechanical properties[50–57]. Firstly, these rare earth elements (REEs) can participate in the human metabolism reactions, such as Nd, Ce, La, Gd, Y, and Dy, thereby improving the biological safety of implanted magnesium alloys[58]. Secondly, most of these elements have pharmacological functions, such as anticoagulation, anti-tumor, anti-arteriosclerosis, anti-inflammatory, and bactericidal performance, which contributes to the better biocompatibility of Mg-based implantation materials. As for the enhancement in mechanical properties, REEs can exert the following effects. (1) REEs have high solid solubility and are easy to form the eutectic phases with magnesium alloys, which can further refine the interior-grains, form the high density grain boundary structures, and improve the mechanical properties of the alloys[59–62]. (2) The addition of REEs can form the long period stacking ordered (LPSO) structure, which can effectively block the movement of dislocations and increase the dislocation densities in the Mg-alloys matrix. (3) REEs can also react with some impurities in the Mg-based alloys to precipitate as the secondary phases, thereby purifying the melting-liquid phases[63–66]. In summary, the types/sizes of the precipitates can be controlled by micro-alloying with appropriate REE addition. Simultaneously, the addition of

REE solutes can change the *c*/*a* ratio of lattice structure in Mg-based alloys, form the LPSO structure, and promote the secondary-phase-induced recrystallization process, which can further impact the mechanical properties of Mg alloys.

Thus, based on the correlations between mechanical properties and microstructure transformation, the essential correlations among REEs, the secondary phases, and the mechanical strength of Mg-based alloys are summarized in this review. The strengthening and toughening mechanisms of the continuous dynamic recrystallization (CDRX) for the medical REE-containing Mg alloys were discussed. Meanwhile, the relationships between the mechanical properties and special structure/LPSO structure induced by REE addition of the Mg-based alloys were investigated. Finally, the development directions of the medical RE Mg alloys were proposed.

1 Influence Mechanism of Secondary Phases

1.1 Single RE Mg alloys

Single REE has been widely used in medical magnesium alloys, because REEs can react with the impurities in Mg alloys to facilitate the formation of the secondary phases with smaller size and to optimize the microstructure features. Meanwhile, REEs can also promote the component supercooling, which is beneficial to the formation of new nuclei sites. Additionally, REEs can be dissolved in the Mg-based alloys to achieve the intense solid-solution strengthening effect, therefore improving the mechanical performance. Jin et al[67] discussed the mechanical behavior of medical Mg-1.67Zn-0.52Zr-0.34Nd and Mg-1.62Zn-0.55Zr-0.38Y alloys. It is found that both alloys have the high mechanical properties (UTS=299, 312 MPa; YS=256, 276 MPa; EL=26.15%, 19.89%), which are much better than those of the pure Mg (YS =120 MPa, UTS=193 MPa, EL=16.83%). Nd can exert better secondary phase strengthening and grain refinement effects. Therefore, the atomic energy of Nd at solid solution state can diminish the energy changes and activate the non-substrate slip. Compared with that of Mg-Zn-Zr-Y alloys, the yield ratio of Mg-Zn-Zr-Nd alloys is 0.856, which is more suitable for medical materials. Subsequently, Peng et al[68] investigated the effects of Sn and Y on the microstructure characteristics and mechanical behavior of Mg-4.90Li-2.98Al-1.75Zn (LAZ532) alloys. It is reported that YS of LAZ532-0.8Sn-1.2Y alloy is approximately 166 MPa, UTS is 229 MPa, and EL is 15%. This is because the existence of Sn and Y can enhance the mechanical behavior of alloys through the grain refinement and the strengthening effect caused by the secondary precipitates of Mg$_2$Sn and Al$_2$Y. Similarly, Li et al[69] considered the effect of Dy addition on the mechanical behavior of Mg-2Zn-0.5Zr-*x*Dy alloys. It is reported that with increasing the Dy content to 1.5wt%, UTS, YS, and EL are 150 MPa, 89 MPa, and 9.2%, respectively. This is because the Dy addition reduces the grain size and forms the tiny (Mg, Dy)$_7$Zn$_3$ precipitates which have the body-centered cubic structure.

Additionally, Xie et al[70] investigated the mechanical properties of Mg-3Nd-*x*Gd-0.2Zn-0.5Zr alloy. It is found that with increasing the Gd content, the strength is improved. Besides, the alloys containing 4.5wt% Gd present the optimal comprehensive mechanical properties (YS=200±6 MPa, UTS= 343±3 MPa, EL=5.4%±0.6%). This is because the primary secondary precipitates change from Mg$_{12}$Nd to Mg$_3$Gd with increasing the Gd content. Moreover, the transformation from Gd into β'' precipitates can significantly improve the precipitation kinetics, thereby increasing the strength index.

1.2 Double RE Mg alloys

Compared with those of the single RE Mg alloys, the mechanical properties of magnesium alloys can be further enhanced by the addition of double REEs. For example, the mechanical properties of as-extruded Mg-7.53Gd-2.1Y-0.76Zn-5.38Li (wt%) are enhanced[71]: YS=202±2.6 MPa, UTS =243±2.1 MPa, and EL=10.7%±2.3%. This result is attributed to the formation of three Mg$_3$RE variants, including the bulk Mg$_3$RE phase, spot Mg$_3$RE phase, and spherical Mg$_3$RE phase. The spherical Mg$_3$RE and spot Mg$_3$RE phases cause the grain boundary pinning phenomenon, promoting the recrystallization β-Li refinement. Among these phases, the Mg$_3$RE phase with spherical-shape exerts the strongest dispersion-strengthening effect. Wang et al[72] found the microstructure characteristics and strength index of the as-cast Mg-2Zn-0.2Y-0.5Nd-0.4Zr alloy for medical applications. Interestingly, the maximum EL achieves 35% and UTS is 203 MPa. The as-cast dual RE alloys are basically composed of equiaxed and refined grain structures as well as a small number of the secondary phases (T phases). This is mainly because the precipitated T phase can reduce the grain size during the forming process, thus improving the mechanical strength. Meanwhile, during the deformation process, the $\{10\bar{1}2\}$ extension twins appear and the non-basal pyramidal structure slips, resulting in the good ductility. Jana et al[73] discussed the strength of Mg-1.3Gd-2.58Nd-0.48Zr-0.28Zn alloy after different heat treatments. The HV and UCS hardness of the Mg alloys is approximatively 529 and 240 MPa, respectively, which is better than that of pure-Mg (HV=392 MPa, UCS= 125 MPa). The heat treatments can further enhance the mechanical properties, reaching HV=588 MPa and UCS=260 MPa. This result is mainly caused by the existence of the uniform secondary phase in the alloys, which can effectively restrict the movement of grain boundaries, thereby hindering the grain growth. After heat treatment of 250 °C/12 h, the HV and UCS hardness of the Mg alloys is improved, which is attributed to the rearrangement of grains and the secondary phases, such as Mg$_3$Gd/Nd, Mg$_{12}$Gd/Nd, and Mg$_{41}$Nd$_5$.

Additionally, Zheng et al[74] discussed the mechanical behavior of as-cast Mg-9Gd-*x*Nd-0.5Zr (wt%) alloy. The results suggest that with increasing the Nd content, YS and UTS are increased from 47.8 and 114.3 MPa to 104.5 and 181.6 MPa, respectively. This mainly caused by the dynamic precipitation of nano-Mg$_5$(Gd, Nd) particles from Mg-9Gd-0.5Zr alloy after the Nd addition, as shown in Fig.2. The nucleation energy can be provided by preventing the consumption of deformation energy, thus improving the strength. On this basis, Wang et

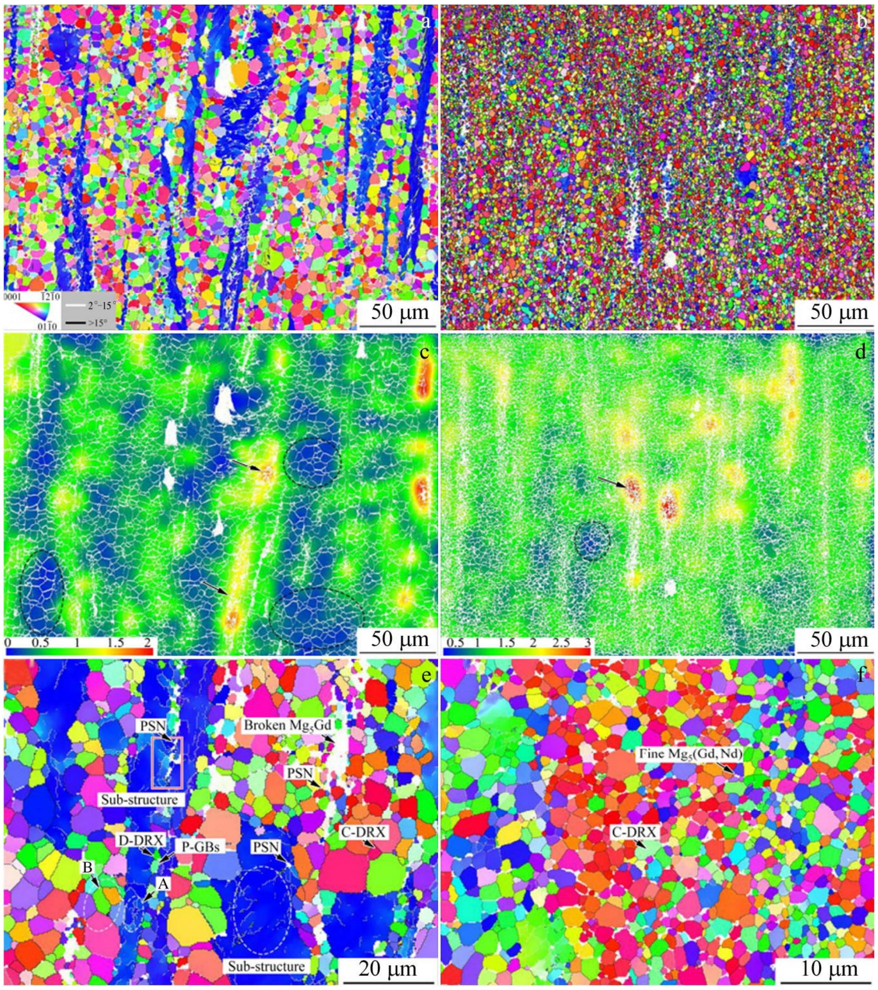

Fig.2 EBSD maps (a–b, e–f) and strain distribution maps (c–d) of Mg-9Gd-0.5Zr alloy (a, c, e) and Mg-9Gd-2Nd-0.5Zr alloy (b, d, f) after extrusion[74]

al[75] analyzed the influence of Nd on the microstructures and mechanical behavior of Mg-7Gd-0.5Zr alloy. It is indicated that the Mg-7Gd-2Nd-0.5Zr alloy achieves the maximum UTS of 294 MPa. The new $Mg_{41}Nd_5$ phase is formed after the Nd addition, which results in the heterogeneous nucleation, therefore achieving the fine grains. Meanwhile, Nd and Gd accelerate the generation of the major strengthening β' phase. In summary, compared with the addition of single RE Mg alloys, the addition of composite REEs in the medical-used Mg alloys is commonly used to enhance the mechanical properties. However, the mechanism between the microstructure and service performance of the new composite medical RE Mg alloy is rarely studied. Therefore, the fine-characterization and interfacial-relations at atomic scale should be further investigated.

2 Influence Mechanism of Dynamic Recrystallization

The recrystallization mechanism of Mg-based alloys is principally composed of CDRX and discontinuous dynamic recrystallization (DDRX). CDRX occurs in the process of dislocation accumulation and reconfiguration to form the subgrains and low angle grain boundaries (LAGBs). In addition, the continuous absorption in LAGBs results in the generation of high angle grain boundaries (HAGBs) and new dynamic recrystallization (DRX) grains. For DDRX, DRX grains nucleate at the serrated HAGBs under the continuous strain and then migrate and grow along the grain boundaries. DRX grains formed by CDRX have different sizes, whereas DDRX usually causes the fine DRX grains. Adding REEs, such as Y and Nd, can hinder DRX process, which improves the grain size and enhances the mechanical properties of medical-used magnesium alloys. Huang et al[76] investigated the influence of the existence form of Y (eutectic phase/solute state) on DRX and mechanical behavior of as-cast Mg-6Zn-1Y-0.5Zr alloys. The results indicate that YS, UTS, and EL of the as-cast alloys are 90 MPa, 200 MPa, and 11%, respectively. This is mainly because the Y presence can reduce the mobility of dislocations as well as grain boundaries and decrease the twinning activation, thereby facilitating the DRX process. Thus, the grain refinement caused by Y addition occurs, which enhances the strength and ductility of as-cast alloys. Du et al[77] discussed the microstructure characteristics and mechanical behavior of as-extruded Mg-4Zn-*x*Y-0.5Nd alloys with different Y contents. It is found that the mechanical properties of the alloy with 0.8wt% Y addition (YS =153 MPa, UTS=245.6 MPa) are better than those with 0.6wt% Y addition (YS=252.6 MPa, UTS=308.8 MPa). With increasing the Y content, DRX process and the growth of DRX grains are hindered, as shown in Fig.3. Moreover, Lv et al[78] discussed the strength of as-extruded Mg-6.0Zn-0.5Zr-1.5Nd alloy. It is reported that after Nd addition, YS and UTS are improved from 342 and 382 MPa to 408 and 424 MPa, respectively. The Nd addition significantly changes the presence of intermetallic phases, which can further refine the DRX grains and lead to the more uniform and denser microstructure.

Change in dislocation density can also affect the recrystallization driving force and then influence the mechanical performance of the alloys. Du et al[79] discussed the grain boundary densities and mechanical behavior of as-extruded Mg-4Zn-0.8Y-0.5Nd alloy. It is indicated that the YS, UTS, and EL of the as-cast alloys are approximately 112 MPa, 218 MPa, and 9.2%, respectively. YS, UTS, and EL of the alloys after extrusion of one pass are 252.6 MPa, 308.8 MPa, and 10.0%, respectively; whereas those after extrusion of two passes are 306.4 MPa, 325.2 MPa, and 18%, respectively. This result is caused by the continuous sliding of Mg-4Zn-0.8Y-0.5Nd alloy during extrusion process, which leads to the formation and segregation of many dislocations along the grain boundaries. At the same time, REEs promote DRX of alloys, and the larger extrusion pressure forms more dislocations during the second extrusion process. As a result, these equiaxed grains are continuously divided into smaller ones, therefore reducing the grain sizes and enhancing the strength. During the accumulative hot rolling process, Zhao et al[80] investigated the grain refinement of Mg-3Sn-1Mn-1La alloy with La addition. The grain refinement is primarily caused by the MgSnLa compound, whose shape is transformed form the plate into fine sphere in Mg-Sn-Mn-La alloys. The spherical MgSnLa phase can control the movements of dislocations, thus increasing the dislocation density. As a result, DRX driving force increases the formation of more twins and deformation bands, further improving the mechanical strengths. Ansari et al[81] studied the recrystallization and mechanical behavior of as-rolled Mg-5/10Y alloys. It is reported that the Mg-10Y alloy has better ductility and strength, compared with those of Mg-5Y alloy. The increase in Y content of Mg-10Y alloy effectively decreases the recrystallization kinetics by increasing the degree of dislocation pinning with the solute atoms. Thus, the Mg-10Y alloy shows finer grain size and better mechanical behavior. In conclusion, the dislocation density of medical Mg alloys can be increased by REE addition, which can produce remarkable pinning effect and promote DRX, therefore improving the comprehensive service performance of medical-used Mg-based alloys.

3 Influence Mechanism of LPSO Morphology and Structure

LPSO morphology and orientation are important factors for the mechanical properties of medical Mg-based alloys. The relationship between the orientation of LPSO phase and tensile direction can affect the initiation and propagation of the micro-cracks, thereby resulting in different fracture modes. Currently, the randomly oriented LPSO phase in

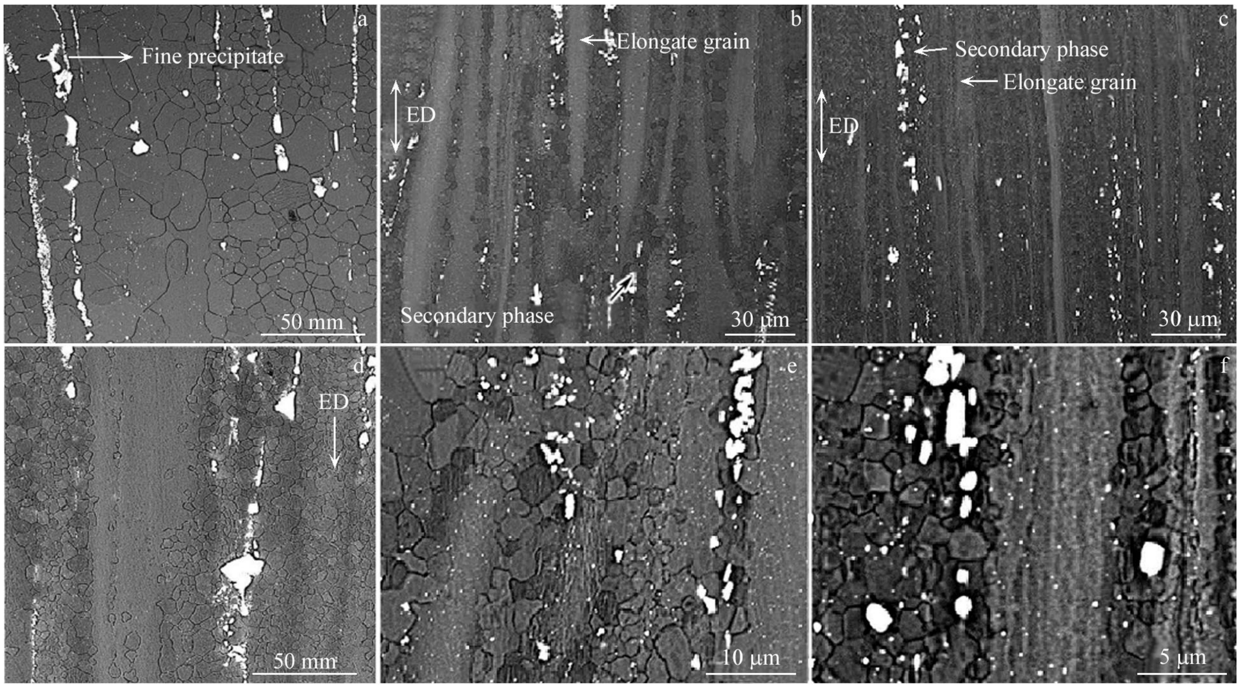

Fig.3 SEM images of Mg-4Zn-xY-0.5Nd alloys: (a) x=0.6 and (d) x=0.8; SEM images of Mg-Zn-Y-Nd alloys after extrusion of one pass (b, e) and two passes (c, f) [77]

magnesium alloys have better plastic anisotropy.

Somekawa et al[82] discussed the strength variation of caliber-rolled Mg-5Y-2.5Zn alloys. It is reported that after rolling of 6 passes, YS increases from 260 MPa to over 500 MPa, and the HV hardness increases from 882 MPa to 1264 MPa. After the rolling treatment of one or two passes, the α-Mg and LPSO phases with homogeneous distribution appear in the alloys. With further increasing the number of rolling passes, the size is gradually reduced. Besides, after rolling treatment, the dense dislocations appear in the grains and the interface between the LPSO and α-Mg phase also appears. Based on the high strength and high hardness, the largest bending angle of the alloys after rolling of 6 passes is 20.9° , which plays a crucial role in hindrance of the dislocation sliding. As shown in Fig. 4a, the formation of LPSO phase is closely related to the mechanical properties of magnesium alloys. Thus, the occurrence of deformation kink bands and dense dislocations induced by caliber rolling results in the excellent hardness and strength of alloys. Meanwhile, Wang et al[84] investigated the mechanical strength of the pre-aged Mg-9.2Gd-4.4Y-1.0Zn-0.8Mn alloy after extrusion. After extrusion, UTS is 455±5 MPa, YS is 382±5 MPa, and EL is 11.0%±0.4%, presenting the optimal combination of strength and ductility. On the one hand, the fine β-Mg_5(Gd, Y) grains are generated after extrusion, which results in the pinning effect on the secondary phase particles. On the other hand, the block LPSO phase and coarse β-Mg_5(Gd, Y) phase accelerate the recrystallization through particle-stimulated nucleation. Although the lamellar LPSO phase forms kink bands and alters the stress concentration, the combined effects still significantly improve the alloy strength. Liao et al[85] evaluated the LPSO morphology of as-cast Mg-xZn-Y-Gd (x=0.93, 1.80, at%) alloys after heat treatment. It is found that the alloys containing the block LPSO phases present the highest strength, followed by the alloy sheets containing lamellar LPSO phases, and the alloy film containing LPSO phase has the worst properties. Compared with the lamellar and block LPSO phases, the alloy film containing LPSO phases cannot effectively hinder the dislocation slip. The thickness of the block LPSO phase is the largest, which is difficult to kink by compression. Therefore, the strength of the block alloys is further increased when the dislocation slip is impeded. Moreover, the strength of as-cast alloy is better than that of the heat-treated alloy. This is because the as-cast alloy contains more lamellar and block LPSO phases.

Lu et al[86] discussed the influence of the morphologies of LPSO phase in Mg-9.1/9.2Y-xZn (x=1.0, 1.8, 3.1, wt%) alloys on the mechanical properties. It is demonstrated that when the Zn content is 1.0wt%, 1.8wt%, and 3.1wt%, UTS is 148±0.6, 153±4, and 185±4 MPa, and EL is 1.4%±0.1%, 2.6%±0.3%, and 5.3%±0.6%, respectively. This is because α-Mg, LPSO, and $Mg_{24}Y_5$ phases are the main phases in Mg-9.1Y-1Zn alloy. The eutectic $Mg_{24}Y_5$ phase clearly diminishes, and LPSO phase gradually forms a network structure in the Mg-9.1Y-1.8Zn alloy. The presence of continuous precipitation of fine lamellar LPSO phase leads to the secondary phase strengthening effect, resulting in the enhanced strength of Mg-9.2Y-3.1Zn alloy.

LPSO structure is formed based on Mg-REEs-X (X is a transition element) system during alloy solidification. The kink band appearing during the twist deformation can effectively hinder the movement of base dislocations, so the properties of Mg-based alloys are strengthened. Chen et al[87] discussed the impact of LPSO phase in DRX on the as-compressed Mg-Zn-Y alloys. It is found that the kinked LPSO phase region is conducive to the DRX occurrence. With the hot compression, the fragmentation of LPSO phase significantly improves DRX process through particle-simulated nucleation (PSN) mechanism. Hao et al[83] investigated the function of the 14H-LPSO phase on DRX process of as-extruded $Mg_{94}Zn_{2.5}Y_{2.5}Mn_1$ (at%) alloy. Fig. 4b displays the 14H-LPSO phase formation process. It can be seen that the extruded alloys without 14H-LPSO phase have YS and UTS of 228 and 368 MPa, whereas YS and UTS can increase to 315 and 406 MPa for the alloys with 14H-LPSO phase, respectively. This is primarily attributed to the large number of dislocations generated by 14H-LPSO phase, which increases the dislocation density of the alloys. Meanwhile, the alloy with 14H-LPSO phase has finer grain size, compared with the one without 14H-LPSO phase. Thus, the improvement in alloy strength is mainly due to the interplay of dislocation strengthening, grain refinement, and lamellar LPSO phase strengthening effects. Wang et al[88] investigated the microstructure evolution and mechanical properties of the as-extruded Mg-9.11Gd-3.12Y-0.68Zn-0.38Zr alloy. It is indicated that YS of the alloys reaches 385±5 and 320±4 MPa at 26 and 250 °C, respectively. This is mainly because the intermetallic phases are Mg_5RE, Mg_3RE, and 14H-type LPSO phase in the as-cast alloys. After extrusion, the large aggregation of 14H-LPSO phases occurs with the fine precipitated Mg_5RE phases which are uniformly distributed at the grain boundaries. Thus, the increase in alloy strength is caused by the grain boundary strengthening and LPSO phase strengthening effects. On this basis, Yuan et al[89] studied the mechanical strength variation of as-cast Mg-2.2Y-1.1Zn-0.4Mn alloys with LPSO phases after solution treatment and multi-pass equal-channel angular pressing (ECAP) process. UTS and EL of the alloys after solution treatment and ECAP process increase from 171.6 MPa and 11.9% to approximately 326.6 MPa and 14.5%, respectively. This is because the as-cast alloy primarily contains the large 18R-LPSO phases distributed at the grain boundaries. After solution treatment and deformation, due to the fracture of 18R stripes and 14H lamella, the interfaces of α-Mg/LPSO phases increase, resulting in much more denser dislocations in the crystals. The refined LPSO phases promote DRX behavior through ECAP process. Thus, the dislocation strengthening and grain refinement improve the mechanical behavior. Consequently, LPSO Mg alloys present excellent medical potential. As a result, the addition of REEs can form the LPSO structure in Mg-based alloys, which effectively hinders the dislocation movement and refines the α-Mg grains, therefore

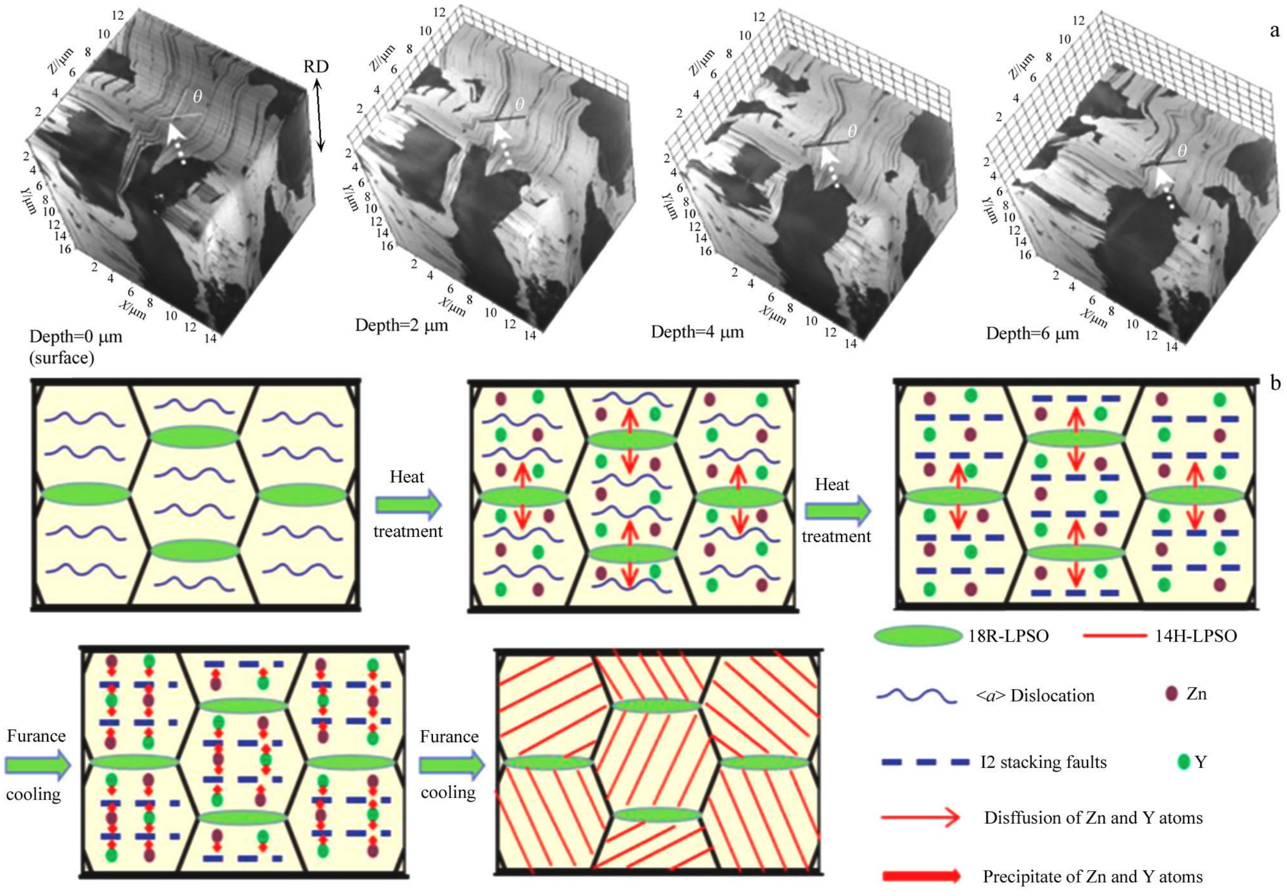

Fig.4 3D microstructures of alloys after rolling of 6 passes[82] (a); schematic diagrams of 14H-LPSO phase formation process[83] (b)

enhancing the mechanical properties of medical-used magnesium alloys.

Thus, the secondary phase, LPSO phase, and recrystallization in RE magnesium alloys are all closely related to the mechanical properties. Firstly, REEs can react with impurities in the alloys to facilitate the formation of the secondary phases with smaller sizes and to optimize/modify the microstructure. The precipitation of the secondary phases induces the pinning effect on the dislocations, thereby promoting the formation of a large number of subgrain boundaries and HAGBs, and increasing the density of grain boundaries. This effect can further promote the DRX process in the alloy, resulting in the grain refinement and strength enhancement. At the same time, the stress and strain increase, and the elongation also increases. Secondly, the morphology and structure of LPSO phase are significantly important factors affecting the microstructure and strength of medical-used Mg-based alloys. The kink band appearing during the twist deformation of LPSO phase can impede the movement of base dislocations, so the mechanical properties of Mg alloys can be further strengthened. Meanwhile, at the grain boundaries, the LPSO phase breaks, promoting DRX process through PSN mechanism, and thus refining the grain size. The secondary phase/LPSO phase can also directly affect the DRX behavior, thereby improving the mechanical properties. In addition, the existence form, state, and size of the secondary phase/LPSO phase are also closely related to their quantity. When the amount of secondary phase is trace, LPSO phase plays the dominant role; at the critical state, the combined action affects the alloy strength.

The composition design of medical-used RE magnesium alloys is based on the solid solubility, radius, electronegativity, the secondary phase melting point, and the relationship between the secondary phase and the α-Mg matrix interface, which cannot only improve the strength but also ensure the elongation. Appropriate medical magnesium alloys are designed according to the implantation requirements.

Although the formation mechanism of LPSO phase under different components is clarified to some extent, the mutual disturbance mechanism of LPSO structure under the condition of trace addition of multi-component REEs is barely explained. Fig.5 summarizes the mechanical properties of RE Mg alloys with different RE contents after different processes. Compared with those of the conventional medical Mg alloys, the mechanical properties of medical-used RE magnesium alloys are significantly improved. This is primarily caused by the grain refinement, dispersion distribution, the secondary phase crushing, and LPSO phase strengthening effect induced by RE elements, which significantly improves the service index of Mg alloys as implantation materials.

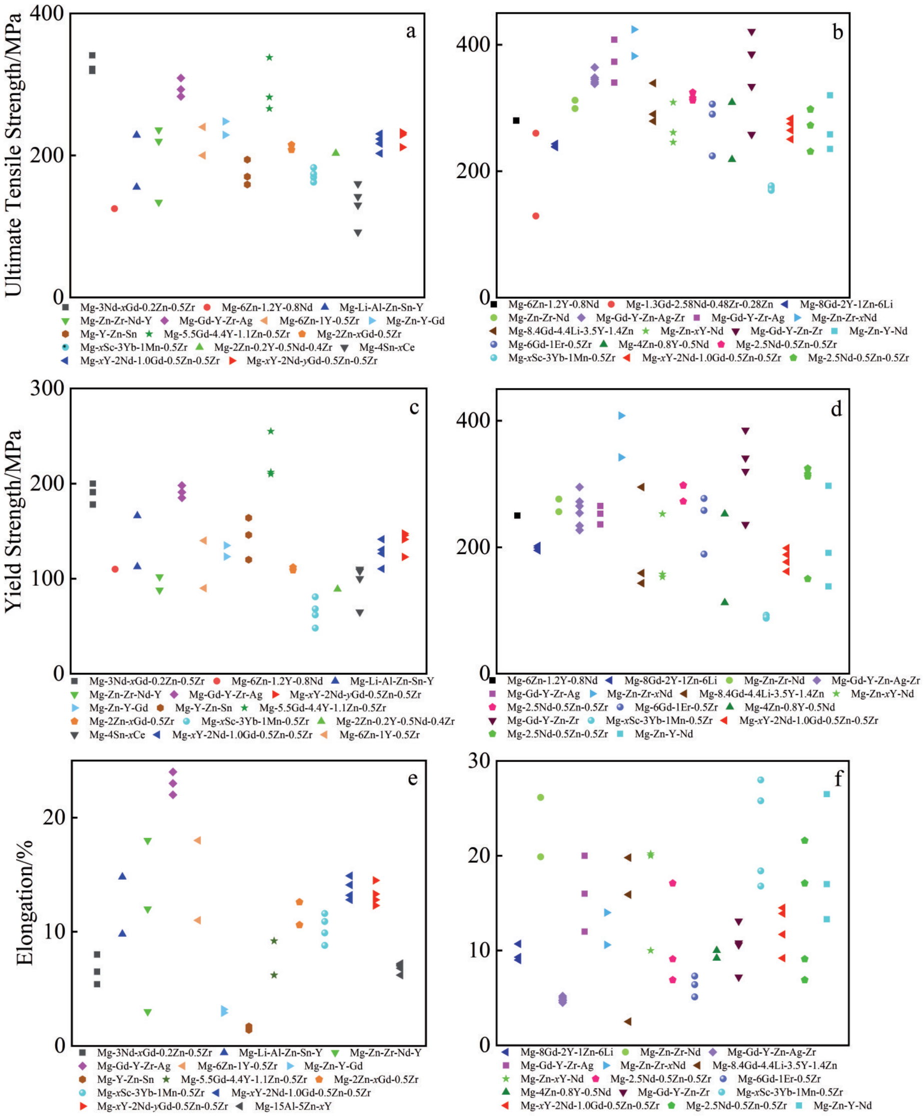

Fig.5 UTS (a–b), YS (c–d), and EL (e–f) of different as-cast (a, c, e) and as-deformed (b, d, f) RE magnesium alloys[67–68,70–73,76–79,84,90–105]

4 Summary and Prospective

Medical degradable magnesium alloys are one of the most valuable biodegradable materials, and their further development is restricted by the inferior mechanical properties. Consequently, it is crucial to improve the mechanical properties of medical-used magnesium materials through the single rare-earth/dual rare-earth micro-alloying to promote the extensive clinical application. Although the researches on the mechanical qualities of rare-earth Mg-based materials have been widely conducted, there are still many problems to be solved. Therefore, the medical development potential of rare-earth magnesium alloys should be further researched:

1) The structure determines the material properties. With denser magnesium alloy structures, smaller grain size, and more uniform distribution, the mechanical properties of magnesium alloys are better. The rare-earth elements (REEs) can further refine the grains, resulting in more uniform and compact structures. Thus, the relationship between REEs and the properties of magnesium alloys should be explored. Excellent service performance can be obtained by regulating the categories and contents of REEs.

2) The microstructure, the secondary phase precipitation, and mechanical properties of Mg alloys are mainly affected by the REE contents. However, it is difficult to obtain the accurate impact rule of REE contents on mechanical properties. Thus, the material genetic engineering and artificial intelligence technology can be used to explore the change rule of the influence of REE content on the mechanical properties.

3) The match between the degradation cycle and the fracture repair time is a major concern. However, the degradation rate of single rare earth magnesium alloy is difficult to meet the requirements of long-term in-vitro/vivo service. Thus, the methods of plastic deformation and surface modification can be further ameliorated to improve the corrosion resistance.

4) Currently, the physiological effects of REEs on human body are still divergent. On the one hand, REEs can play an

active role in anticoagulation and hypoglycemia. On the other hand, the REE enrichment in the human body can lead to the hemolysis. Particularly, the uneven distribution of REEs with body fluid flow after degradation has adverse effects to the human body. Thus, a large number of in-vivo and in-vitro degradation tests of rare-earth magnesium alloys should be conducted to further explore the biocompatibility in the practical service environment.

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医用稀土镁合金微观组织特征及力学行为研究进展

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摘　要：近年来，镁合金作为生物医用金属材料受到了广泛关注，但其较差的力学强度极易导致植入物在服役周期内崩塌断裂，严重危及患者生命安全。稀土微复合合金化作为当下提高可降解镁合金力学性能的有效措施，在消除镁合金杂质元素、净化熔体的同时，还可以起到促进动态再结晶、形成长周期堆垛有序相等作用。因此，本文从稀土镁合金微观结构转变及其与力学性能的基本关联出发，综述了近年来医用稀土镁合金组织特征及力学性能的研究进展，深入发掘了稀土元素、第二相及镁合金力学性能之间的本质关联，详细阐述了连续动态再结晶对稀土镁合金的强韧化机理，全面叙述了稀土元素诱导长周期堆垛有序结构对镁合金力学性能的影响规律。最后，本文对医用稀土镁合金未来的发展方向进行了展望。

关键词：稀土元素；可降解镁合金；微观组织；再结晶机制；力学性能

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