Study on microstructure and dynamic corrosion behavior of degradable Mg-Y-Zn-Zr alloy with different Sr contents

Zhengwei Zhang, Qinggong Jia, Xiaofeng Wu, Xin Cao, Chunxiang Xu*, Jinshan Zhang and Wenfu Yang

College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan, 030024, People’s Republic of China

E-mail: xuchunxiang2012@126.com

Keywords: magnesium alloy, Sr, W-phase, microstructure, corrosion performance

Abstract
Microstructure and corrosion behaviors of cast Mg-2Y-1Zn-0.4Zr-xSr alloys were investigated by using OM, SEM, immersion and electrochemical tests. The results show that the addition of Sr refines the grain, the grain size of Mg-2Y-1Zn-0.4Zr-0.3Sr alloy is the thinnest. The addition of Sr also changes the morphology and distribution of the second phase. The precipitation of W-phase at grain boundary decreases, while the precipitation of punctate W-phase and Mg_{0.97}Zn_{0.03} phase in the grain increased. In addition, both immersion and electrochemical tests illustrates Mg-2Y-1Zn-0.4Zr-0.3Sr alloy has the best corrosion performance among the four investigated alloys, and shows a relatively uniform corrosion morphology on the surface. Moreover, as the Sr content increases, the corrosion mode of the alloy changes from intergranular corrosion to intragranular corrosion.

1. Introduction
Owing to the excellent biodegradability, physical and mechanical properties, magnesium and its alloys have drawn more and more attention as biomedical implant [1]. The magnesium alloys can avoid the complications caused by stress shielding, and can reduce the risk of myocardial hyperplasia, restenosis and thrombosis in the stent [2, 3] compared with the traditional metal implant (such as stainless steel, cobalt-chromium alloy and titanium alloy). Whereas the excessive corrosion rate of magnesium alloys leads to premature loss of mechanical integrity, which limits the application of magnesium alloys [4]. In order to better apply magnesium alloys to medicine, it is necessary to develop new magnesium alloys with corrosion-resistant and uniform corrosion patterns.

Studies have shown that Mg–Zn–RE alloys have excellent castability and mechanical properties both at room temperature and high temperature [5, 6], among which Mg–Zn–Y alloys have attracted much attention due to their high strength [7, 8]. Anja et al [9] reported that Mg-2Y-1Zn-0.25Ca-0.15Mn (wt%) alloy has excellent mechanical properties and biocompatibility. Li et al [10] reported that the Mg-2Y-1Zn-0.4Zr (wt%) alloy has excellent cell compatibility properties. However, The corrosion performance of Mg–Zn–Y alloy is still too fast to meet the requirements of cardiovascular stents. Alloying is one of the effective methods to improve the corrosion resistance of alloys [11, 12]. Adding Sr element in magnesium alloys can refine grains, resulting to increasing the mechanical and corrosion properties [13, 14]. Aaron F Cipriano et al [15] studied the cytocompatibility and early inflammatory response of human endothelial cell scultured directly with Mg–Zn–Sr alloy, which provided an early basis for the application of Sr elements to the study of human cardiovascular stents. At present, many studies have shown that the addition of Sr in Mg–Zn–Sr [16], Mg–Zn–Zr–Sr [17], Mg–Zn–Ca–Sr [18] and other series of alloys can improve the mechanical and corrosion properties. However, there are not many reports about the effect of Sr on alloys in the Mg–Zn–Y alloy system. Therefore, the microstructure and corrosion properties of Mg-2Y-1Zn-0.4Zr-xSr alloys were investigated in this paper. Additionally, In order to simulate the human vascular environment, the dynamic corrosion test was carried out by weight loss method.
2. Experimental details

Mg-2Y-1Zn-0.4Zr-xSr (wt%) alloys is selected from high purity Mg (99.99%), Zn (99.99%), Y (99.99%), Mg-30wt%Zr and Mg-20wt%Sr master alloys. The alloys was smelted at 750 °C in a protective atmosphere of CO2 and SF6, and then the melts was poured into a iron mold preheated at 200 °C. The chemical compositions of the as-cast alloys are listed in table 1.

The immersion test was carried out in dynamic corrosion equipment. Dynamic corrosion test equipment (as shown in figure 1) is composed of thermostatic waterbath, peristaltic pump and rubber pipe. Before the immersion test, the specimens (Φ20 mm × 10 mm) were polished to 3000 # with abrasive paper. Then the samples immersed in SBF solution at 37 °C (To 1000 ml of deionized water as the standard: NaCl (8.00 g), KCl (0.40 g), CaCl2 (0.14 g), NaHCO3 (0.35 g), MgCl2•6H2O (0.10 g), MgSO4•7H2O (0.06 g), KH2PO4 (0.06 g), Na2HPO4•12H2O (0.06 g)) [19] for 14 day, the solution was refreshed every 24 h. After immersion test, the corrosion product on the surface of the sample was removed with a chromic acid solution (200 gl−1 CrO3 + 10 gl−1 AgNO3), and then the sample was washed with absolute ethanol and acetone. The average corrosion rate was calculated by the following formula:

\[
CR = \frac{8.76 \times 10^4 \cdot \Delta W}{A \cdot T \cdot D}
\]  

Where CR is the average corrosion rate (mm/a), ΔW is the difference in weight before and after soaking (g), A is the surface area (cm²) of the sample, T is the soaking time (h), and D is the alloy density (1.74 g cm⁻³).

The electrochemical test of the sample was carried out in simulated body fluid by electrochemical workstation (CS310). The three-electrode cell was composed of a saturated calomel electrode as a reference electrode, a platinum plate as a counter electrode, and a prepared sample having an exposed area of 1 cm² as a working electrode. The potentiodynamic polarization curve were conducted at a constant scan rate of 0.5 mV s⁻¹ initiated at −300 mV below the open-circuit potential. Electrochemical impedance spectroscopy (EIS) was tested at a scanning frequency of 0.01 Hz to 100 kHz and a scanning rate of 10 mV s⁻¹. Three sets of parallel tests were performed on each alloy to ensure data reproducibility.

The microstructure and surface corrosion morphology of the alloy were observed by optical microscope (OM) and scanning electron microscope (SEM) equipped with energy dispersive spectroscpe (EDS).

\[\text{Figure 1. Dynamic corrosion test equipment.}\]
3. Results and discussion

3.1. Microstructure characterization

The optical microscopy images of Mg-2Y-1Zn-0.4Zr-xSr alloys are shown in Figure 2. As can be seen, the as-cast microstructures of the four alloys are composed of equiaxed dendrites of different sizes. With the increase of Sr content, the continuous second phase at the grain boundary is gradually broken, and the second phase inside the grain gradually increases. Moreover, the addition of Sr refines the grain size of the alloy that the average grain size of the four alloys is about 75 μm, 68 μm, 60 μm, 90 μm, respectively. At present, there are many discussions about the refinement mechanism of Sr on magnesium alloys. From a thermodynamic point of view, it is considered that the addition of Sr increases the undercooling degree of the alloy to refine the grains. In addition, from the ‘surface-active element’ aspect, it is believed that the Sr adsorption film is formed at the grain growth interface, resulting in a decrease in grain growth rate and an increase in the nucleation rate to refine the grain [20, 21].

Figure 3 is an SEM image of as-cast Mg-2Y-1Zn-0.3Zr-xSr alloys. Figure 4 shows the EDS at each point in the SEM image of the as-cast Mg-2Y-1Zn-0.3Zr-xSr alloys. The second phase at grain boundary of alloy I is continuously distributed, and the enlarged view of the second phase at the angle (marked on figure 3(a)) is shown in the figure 3(e). According to the EDS result (figure 4(a)), the second phase at the angle may be Mg₃Zn₃Y₂ (W-phase) that looks like fish-bone, meanwhile there is trace small amount of punctate precipitates inside the grain. After the addition of 0.1 wt% Sr, the second phase at the grain boundary becomes discontinuous, and the precipitation of the peculiar phase inside the crystal grains increases. When the Sr element is increased to 0.3 wt%, the W-phase on the grain boundary of alloy III becomes further intermittent, the EDS results are shown in figure 4(b). The punctate precipitates in the grains are further increased and mainly divided into light and dark. A higher Y element is detected in the bright punctate phase, such as point C, and the second phase should be W-phase in combination with EDS results (figure 4(c)). However, The dark point-like phase that its Y element content is less should be Mg₀.₉₇Zn₀.₀₃ phase, as point D, the EDS results are shown in figure 4(d). After the addition of 0.5 wt% Sr, the grain growth of the alloy is obvious, and the point-like second phase inside the grain is significantly larger and thicker than before.

The surface energy on the front of the interface increases due to the enrichment and segregation of Sr at the front of the growth interface and a certain thickness of solute transition layer is formed, which affects the diffusion of the front edge of the solid-liquid interface of the Y atom. Moreover, the formation of the W-phase is slow, resulting in disconnection of the continuous second phase at the grain boundary, which also verifies the phenomenon observed before. Liu et al [14] found that when 0.9 wt% of Sr element was added to the
Mg-3Zn-1Y (wt%) alloy, Mg$_6$Zn$_2$Sr$_1$ (S-phase) appeared in the original W-phase areas. With the Sr element continued to be added, the W-phase at the grain boundary basically disappeared completely and the reticulated S-phase appeared. The appearance of the S-phase also indicates that the addition of the Sr element is not conducive to the precipitation of the W-phase at the grain boundary. According to the results of Cheng Renju’s research, the precipitation of the second phase has grain refinement effect on α-Mg$^{20}$. The addition of a trace amount of Sr has weaker growth inhibition on the growth of W-phase. However, when 0.5 wt% Sr is added to

---

**Figure 3.** SEM micrographs of as-cast Alloys: (a) Alloy I, (b) Alloy II, (c) Alloy III, (d) Alloy IV, higher magnification of (e) e area, (f) f area.
the alloy, the enrichment ability of Sr near the grain boundary is significantly enhanced, which hinders the precipitation of the W-phase at the grain boundary. It can be observed in figure 3(d) that the second phase of the addition of alloy IV grain boundary is severely broken compared with the former alloys, and the inhibition effect of W-phase on grain growth is weakened, which can not refine the grain well. Thus, the grain size of alloy IV becomes large.

3.2. Electrochemical measurements

Figure 5 shows the polarization curve of Mg-2Y-1Zn-0.4Zr-xSr alloys after soaking for 1 h in SBF. As can be seen, the electrochemical polarization curve of each alloy consists of anode polarization curve (right side) and cathode polarization curve (left side). Generally, the cathode branch is attributed to hydrogen evolution reaction \(2H_2O + 2e^- \rightarrow H_2 + 2OH^-\) and the anode branch is related to the dissolution of Mg substrate \(\text{Mg} \rightarrow \text{Mg}^{2+} + 2e^-\) [22]. Furthermore, plateaus are also observed in the polarization curves of all alloys, which shows that passive films are formed on the surfaces of these alloys in SBF. The free corrosion potential \(E_{\text{corr}}\) is the thermodynamic factor for corrosion of materials, reflecting the corrosion tendency of the alloy. It can be seen from table 2 that \(E_{\text{corr}}\) exhibited an increasing order as follows: alloy I < alloy IV < alloy II < alloy III. It is proved that the addition of Sr increases the Mg matrix potential. Hence, the Sr-containing alloy has a smaller tendency to corrode. The corrosion current density \(I_{\text{corr}}\) represents the kinetic factors of corrosion, which reflects the corrosion rate of the alloy. In general, the smaller the corrosion current density, the slower the corrosion rate, the better the corrosion resistance of the alloy [23]. Of course, the actual alloy corrosion performance is also affected by other factors, such as alloy microstructure, distribution of the second phase, corrosion products and the storage environment [24]. The current densities \(I_{\text{corr}}\) of samples were ranked in decreasing order: alloy I > alloy IV > alloy II > alloy III, which indicated that alloy III has the best corrosion resistance.

The relationship between corrosion rate \(P_i\) and corrosion current density \(I_{\text{corr}}\) can be expressed by the following formula [25]:

\[
P_i = 22.85I_{\text{corr}}\tag{2}\]

Based on the electrochemical parameters of the sample \((I_{\text{corr}}, \beta_{\alpha} \text{ and } \beta_{\beta})\), the polarization resistance \(R_{p}\) is calculated from the following formula [26]:

\[
\]
In the polarization test, alloy III had the lowest corrosion rate of 0.14 mm/a. The corrosion rate of the alloy decreased from 0.74 mm/a to 0.14 mm/a after adding Sr. The polarization resistance is inversely proportional to the corrosion rate. The larger the polarization resistance, the smaller the corrosion rate. The polarization resistance of alloy III is the largest (7.27 kΩ cm²) among the four alloys, which indicates alloy III has the best corrosion resistance. In addition, the polarization resistance of the Sr-containing alloy is significantly higher than that of the non-Sr-containing alloy, which indicates that the kinetic reaction of the Sr-containing alloy is more difficult than that of the non-Sr-containing, so the corrosion resistance of the alloy is improved.

Figure 6 is the EIS curve of the as-cast alloy after immersion in the SBF solution. It can be seen from the Nyquist plots (figure 6(a)) that the four alloys have two capacitive loops in both the high and medium frequency regions. The alloy containing Sr has a larger loop radius of high frequency capacitance than that of alloy I, which indicates the addition of Sr improves the corrosion resistance of the alloy I. Moreover, the radius of the medium frequency capacitor of Alloy III is the largest, indicating that the corrosion product film formed by Alloy III during the immersion process is relatively dense, which hinders the expansion of corrosion to a certain extent, so the corrosion rate is the lowest. It can also be seen from figure 6(b) (frequency versus impedance) that Alloy III has the highest impedance value. The two peaks in figure 6(c) (frequency versus degree) correspond to two time constants, and the relationship of phase angle at medium frequency is alloy III > alloy II > alloy IV > alloy I in a decreasing order, which shows that Alloy III has the best corrosion resistance. All EIS results are consistent with the polarization curve results.

In order to further explain the corrosion phenomenon of the as-cast alloys, the EIS results were fitted and the equivalent circuit is shown in figure 6(d). Table 3 shows the fitting results. In this circuit, \( R_s \), \( R_{ct} \), and \( R_f \) are solution resistance, charge transfer resistance, and surface film resistance, respectively. Generally, the higher the value of \( R_{ct} \) or \( R_f \), the better the corrosion resistance. It can be seen from table 2 that the values of \( R_{ct} \) and \( R_f \) of alloy III are the largest, indicating that the corrosion of alloy III is the slowest. In addition, \( CPE_{dl} \) represents the constant phase angle element of the double layer, and the minimum \( CPE_{dl} \) value of alloy III implies that the effective area of the metal exposed to solution during corrosion is the smallest. \( CPE_{f} \) is the constant phase angle element of surface film. The lowest \( CPE_{f} \) value of alloy III indicates that the corrosion product film formed by the metal is the most compact. In summary, the alloy containing Sr forms a dense product film, which improves the corrosion resistance of the alloy. The alloy III has the best corrosion resistance.

\[
R_p = \frac{\beta_a \beta_b}{2.3(\beta_a + \beta_b)I_{corr}}
\]
3.3. Immersion tests

Figure 7 shows the average weight loss rate of Mg-2Y-1Zn-0.4Zr-xSr alloys after immersing in SBF solution for 14 days. The average weight loss rate of the four alloys were $1.08 \pm 0.048$ (mm/a), $0.65 \pm 0.038$ (mm/a), $0.54 \pm 0.022$ (mm/a) and $0.73 \pm 0.029$ (mm/a), respectively. It can be seen that the corrosion rate of the alloy decreases significantly after the addition of Sr, and the corrosion rate of alloy III is about half lower than that of alloy III. Alloy III has the best corrosion resistance, which can be analyzed from the following aspects: On the one hand, the addition of Sr to the alloy increases the matrix potential, thereby weakening the tendency of galvanic corrosion; On the other hand, alloy III has the smallest grain size. According to Aung and Zhou research [27], grain boundaries can act as a barrier during the corrosion process. The smaller the grain size, the more the grain boundaries, the better the effect of preventing the solution from etching the substrate, and the better the corrosion resistance. In addition, the second phase distribution of alloy III is relatively uniform and the corrosion type is uniform corrosion. Therefore, alloy III has the best corrosion resistance.

Figure 8 shows the corrosion morphologies of alloys after immersion in SBF solution for 12 h after removing the corrosion products. The corrosion of the four alloys is significantly different under the same immersion time. As shown in figure 8(a), the corrosion of alloy I is serious that many continuous corrosion trenches are formed at the grain boundary and severe pitting pits were formed locally in the alloy, alloy I dominated by grain boundary corrosion. In the case of alloy II, the continuous grain boundary can still be seen after the corrosion of the alloy, and there are many pitting pits at the grain boundary, which is still dominated by grain boundary corrosion. While for alloy III, there is no pitting pit at the grain boundary, but there are many small pitting pits.
inside the grain, and the corrosion is relatively uniform. In contrast, the corrosion degree of alloy IV is serious. Although grain boundaries can be observed, there are many continuous pitting pits in the grains of the alloy, the corrosion is mainly intragranular corrosion.

Figure 9 shows the surface morphologies of alloys before removal of corrosion product formed during immersion in SBF for 48 h. A large number of cracks can be observed, which results from dehydration when samples were removed from the solution. The surface of alloy I has been covered by white lamellar and granular...
corrosion products. EDS analysis (figure 9(b)) of the granular corrosion products shows that the main element is Ca (13.7%), P (10.7%), O (41.7%), C (24.5%), Mg (9.3%), the presence of C element may be CO2 adsorbed during immersion, while Ca:P = 13:10, which is close to the ratio of Ca and P elements in CaHPO4 (HA), it can

Figure 9. SEM and EDS of the surface of as-cast alloys after 48 h of immersion in the SBF: (a) Alloy I, (b) A point, (c) Alloy II, (d) B point, (e) Alloy III, (f) C point, (g) Alloy IV, (h) D point.
be inferred that HA is produced in alloy I during immersion. A large number of white lamellar corrosion products were observed on the surface of alloy II. Combined with EDS analysis (figure 9(d)), the lamellar corrosion products were mainly Mg(OH)$_2$ and a trace amount of HA. The surface of the alloy III is covered by white granular corrosion products, and the granular corrosion products are dispersed so that the grain boundaries are not easily observed. The corrosion products are mainly Mg(OH)$_2$ by EDS analysis (figure 9(f)). Obvious grain boundaries and some white flake corrosion products concentrated in the interior of the alloy IV were observed on the surface. During the immersion process, a thin film of Mg(OH)$_2$ is first produced on the surface of the alloy. Due to the difference in structure, the corrosion near the second phase is faster, and a large amount of lamellar corrosion products are generated on the surface of the alloy, which protects the Mg matrix to a certain extent. Besides, the potential difference between corrosion pit and Mg matrix also aggravates the corrosion, and as the corrosion progresses, some spherical HA corrosion products appear on the surface of the alloy. According to the number of products on the corrosion surface, it can be judged that the alloy III has the best corrosion resistance.

Figure 10 shows the schematic illustration of initial corrosion mechanism for as-cast alloys. It is known from the previous analysis that the W-phase is mainly distributed at the grain boundary. W-phase acts as the cathode and the Mg matrix acts as the anode, it is easy to form a large number of micro-galvanic couples. Therefore, the corrosion first occurs near the second phase of the grain boundary. Due to the different sequence of corrosion, there are different etch pits in the dendrite grain boundaries and inside the grains. For the alloy I, the corrosion...
process is as shown in figures 10(a)–(c). Due to the uneven surface structure of the alloy, some locations first corrode. As the corrosion process progresses, the potential difference between the corroded and non-corroded areas occurs, the corrosion region propagates along the second phase and the crystal, and a severe corrosion pit is gradually formed. In addition, due to the continuous W-phase at the grain boundary of the alloy, more corrosion galvanic cells and larger corrosion currents are formed, continuous corrosion gullies are formed along the grain boundary. Then serious corrosion deep pits are formed. The corrosion morphology is the same as shown in figure 8(a). Since there are fewer second phases in the grain, it can be regarded as no corrosion. Therefore, the initial corrosion of alloy I is mainly grain boundary corrosion. The corrosion process of alloy III is shown in figures 10(d)–(f). On the one hand, with the addition of Sr, the continuous W-phase at the grain boundary is disconnected and reduced. The reduction of the W-phase of the grain boundary decreases the degree of grain boundary corrosion, thus the obvious grain boundaries can be observed. On the other hand, the addition of Sr also promotes the precipitation of fine W-phase and Mg0.97Zn0.03 phase in the grain, these two phases will form galvanic cells. Since the amount of precipitated second phase is small, so is the number of galvanic cells. Therefore, a small amount of pitting corrosion pits can be observed in the grain. The corrosion morphology is shown in figure 8(c). The corrosion of alloy III is relatively uniform. The corrosion mechanism of alloy II is between alloy I and III, it is mainly based on grain boundary corrosion. No further analysis is carried out here. When the content of Sr is added to 0.5 wt%, the corrosion process is as shown in figures 10(g)–(i), and the corrosion of the alloy is further aggravated. This is because the large grain boundary can not effectively prevent the corrosion process, a substantial number of second phases are precipitated inside the grains, forming more micro-galvanic couples. The corrosion changes from the grain boundary to the intragranular corrosion to the intragranular corrosion, there are many corrosion pits inside the grain. Therefore, the continued addition of the Sr element can not protect the alloy matrix, but the corrosion is intensified.

4. Conclusion

(1) The addition of Sr refines the microstructure of the alloy. The grain size of Mg-2Y-1Zn-0.4Zr-0.3Sr alloy is the thinnest, and the average grain size is 60 μm. In addition, as the Sr content increases, the W-phase at the grain boundary is gradually disconnected, and the precipitation of W-phase and Mg0.97Zn0.03 phase in the grain increases.

(2) According to the weight loss experiment and electrochemical corrosion test, the corrosion resistance of the alloy with the addition of Sr is significantly improved, and the Mg-2Y-1Zn-0.4Zr-0.3Sr alloy has the best corrosion resistance.

(3) According to the corrosion morphology, the corrosion of alloy I, II and III is mainly concentrated at the grain boundary, and the corrosion of alloy IV is mainly in the crystal. The corrosion of Alloy IV is relatively uniform.

Acknowledgments

The authors would like to thank the National Natural Science Foundation of China (No. 51574175, 51474153) for financial support.

ORCID iDs

Chunxiang Xu @ https://orcid.org/0000-0002-9668-1466

References

[1] Staiger M P et al 2006 Magnesium and its alloys as orthopedic biomaterials Biomaterials 27 1728–34
[2] Song G 2007 Control of biodegradation of biocompatible magnesium alloys Corros. Sci. 49 1696–701
[3] Zhou Y L et al 2015 Microstructures, mechanical and corrosion properties and biocompatibility of as extruded Mg–Mn–Zn–Nd alloys for biomedical applications Mater. Sci. Eng., C 49 93–100
[4] Sanchez A H M et al 2015 Mg and Mg alloys: how comparable are in vitro and in vivo corrosion rates? A review Acta Biomater. 13 16–31
[5] Kawamura Y et al 2006 Elevated temperature Mg97Y2Cu1 alloy with long period ordered structure Scr. Mater. 55 453–6
[6] He S M et al 2007 Microstructure and strengthening mechanism of high strength Mg–10Gd–2Y–0.5Zr alloy J. Alloys Compd. 427 0–323
[7] Chaman-Ara M, Ebrahim G R and Ezatpour, H R 2018 Deformation behavior and processing maps of Mg–Zn–Y alloy containing I phase at elevated temperatures Transactions of Nonferrous Metals Society of China 28 629–41
[8] Zhu J et al 2017 High strength Mg–Zn–Y alloys reinforced synergistically by Mg12ZnY phase and Mg3Zn3Y2 particle J. Alloys Compd. 703 508–16
[9] Hänzi A C et al 2009 Design strategy for new biodegradable Mg-Y-Zn alloys for medical applications International Journal of Materials Research 100 1127–36
[10] Li F et al 2019 A novel magnesium alloy with enhanced mechanical property, degradation behavior and cytocompatibility. Mater. Lett. 244 70–3
[11] Lu Y et al 2015 Effects of secondary phase and grain size on the corrosion of biodegradable Mg–Zn–Ca alloys Materials Science and Engineering C 48 480–6
[12] Atrens A et al 2015 Review of Recent Developments in the Field of Magnesium Corrosion Adv. Eng. Mater. 17 400–53
[13] Chen Y et al 2014 Recent advances on the development of magnesium alloys for biodegradable implants Acta Biomater. 10 4561–73
[14] Liu J et al 2015 Effect of Sr addition on microstructure and elevated temperature mechanical properties of Mg–3Zn–1Y alloy Materials Science and Engineering A 655 (S1) 331–8
[15] Cipriano A F et al 2017 Cytocompatibility and early inflammatory response of human endothelial cells in direct culture with Mg–Zn–Sr alloys Acta Biomater. 48 499–520
[16] Cheng M et al 2017 Effects of minor Sr addition on microstructure, mechanical and bio-corrosion properties of the Mg–5Zn based alloy system J. Alloys Compd. 691 95–102
[17] Li Z et al 2017 The synergistic effect of trace Sr and Zr on the microstructure and properties of a biodegradable Mg–Zn–Zr–Sr alloy J. Alloys Compd. 702 290–302
[18] Li H et al 2015 Biodegradable Mg–Zn–Ca–Sr bulk metallic glasses with enhanced corrosion performance for biomedical applications Mater. Des. 67 9–19
[19] Kokubo T and Takadama H 2006 How useful is SBF in predicting in vivo bone bioactivity? Biomaterials 27 2907–15
[20] Cheng R J et al 2008 Effects of various Mg–Sr master alloys on microstructural refinement of ZK60 magnesium alloy Transactions of Nonferrous Metals Society of China 18 50–4
[21] Ali Y et al 2015 Current research progress in grain refinement of cast magnesium alloys: a review article J. Alloys Compd. 619 639–51
[22] Esmaily M et al 2017 Fundamentals and advances in magnesium alloy corrosion Prog. Mater Sci. 89 92–193
[23] Zhang J S et al 2012 Corrosion behavior of Mg–Zn–Y alloy with long-period stacking ordered structures Journal of Materials Science & Technology 28 1157–62
[24] Bao L et al 2017 Corrosion behavior and mechanism of Mg–Y–Zn–Zr alloys with various Y/Zn mole ratios J. Alloys Compd. 712 15–23
[25] Shi Z, Liu M and Atrens A 2010 Measurement of the corrosion rate of magnesium alloys using Tafel extrapolation Corros. Sci. 52 579–88
[26] Argade G R et al 2012 Corrosion behavior of a friction stir processed rare-earth added magnesium alloy Corros. Sci. 58 321–6
[27] Aung N N and Zhou W 2010 Effect of grain size and twins on corrosion behaviour of AZ31B magnesium alloy Corros. Sci. 52 589–92