Effect of rolling deformation on microstructure and mechanical properties of Mg-6Sn-3Al-1Zn alloy

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Abstract
The Mg-6Sn-3Al-1Zn alloys treated with the solid solution were induced 25%, 45%, 65% and 85% rolling deformation at 400 °C, respectively. The microstructures of as-rolled magnesium alloys were analyzed by XRD, OM, SEM and TEM, the mechanical properties were also measured. The results revealed that the rolled Mg-6Sn-3Al-1Zn alloys were composed of α-Mg matrix phase and Mg2Sn second phase, Mg2Sn distributed at the grain boundaries and intra-grains. With the increasing of the rolling deformation, the volume fraction of Mg2Sn phase distributed at the grain boundaries firstly decreased and then stabilized, the average size of Mg2Sn phase firstly increased and then decreased, the Mg2Sn phase distributed inside the grains gradually transformed from a rod shape to a spherical shape, the volume fraction of the recrystallized grains gradually increased and the average size of the recrystallized grains early decreased and eventually almost unchanged. When the rolling deformation exceeded 25%, the value of tensile strength and Vickers hardness of the Mg-6Sn-3Al-1Zn alloys increased with the rolling deformation. However, when the rolling deformation exceeded 65%, the elongation of the magnesium alloys diminished, however, the strength of as-rolled magnesium alloys did not increase significantly when the amount of rolling deformation increased from 65% to 85%. The mechanical properties were the best when the amount of rolling deformation reached 65%. Meanwhile, the volume fraction and area of Mg2Sn phase distributed on the grain boundaries were 2.9%, 105.5 μm², the volume fraction and average grain size of recrystallized grains were 87% and 2.2 μm, respectively. In addition, it was worth noting that the Mg2Sn phase distributed inside the grains was radically converted into a spherical shape, and the tensile strength, elongation, hardness of the alloy were 317 MPa, 13% and 77.52 HV, respectively.

1. Introduction
Magnesium alloys have been and continue to be the most widely used in many fields, from daily necessities to aerospace, due to their low density, high specific strength and excellent electromagnetic shielding capability [1–3]. However, low strength and the extremely poor plasticity at room temperature have directly limited the applications of the magnesium alloys in many fields [4, 5]. In recent years, many series of magnesium alloys have been reported. For example, magnesium alloys with different rare earth elements [6, 7], magnesium alloys with different elements (such as Al, Zn, Sn, Mn, and Li) have exhibited excellent properties [8–10]. The mechanical properties of the magnesium alloys can be strengthened by plastic deformation processing such as extrusion or rolling [11, 12]. Magnesium alloys are popularly used in many fields by strengthening the low strength and poor elongation at room temperature. For further application, there is a necessity to control costs in the business which leads to the inability to upgrade the mechanical properties of magnesium alloys through adding more precious metals. Among the majority of magnesium alloys, Mg-Al alloys are low in cost, easy to cast, and have excellent mechanical properties, which make such magnesium alloys have a higher specific gravity[13]. The Zn
element could effectively intensify the creep strength of solid solution alloys at higher temperatures because of inhibiting non-basal slip [14]. The addition of Sn element can suppress the eutectic transformation and refine the eutectic phase. The addition of a small amount of Sn element can facilitate the formation of dispersed short rod-shaped Mg2Sn particles and enhance the strength of the Mg-6Sn-3Al-1Zn alloy at room temperature and high temperature [15]. In order to obtain a lower cost magnesium alloy, we should reasonably control the ratio of Al, Zn, and Sn in the magnesium alloy.

In recent years, a large number of studies have reported on Mg-Sn-Al-Zn system [16–18]. However, few works have pointed out the effect of rolling deformation on the mechanical properties of Mg-6Sn-3Al-1Zn alloy. Herein, we have explored the effects of rolling deformation amount on microstructure and mechanical properties of Mg-6Sn-3Al-1Zn alloy. The desired properties have been achieved successfully by controlling grain size and second phase distribution. In addition, the microstructure and composition of the samples are characterized by scanning electron microscope (SEM) and transmission electron microscope (TEM). The discrepancy in mechanical properties of magnesium alloys with different rolling deformation amount is explained by the microstructure, the volume fraction, size, shape and distribution of the second phase particles, the volume fraction and grain size of the recrystallized grains. The present researches have considerable value for the applications of Mg-6Sn-3Al-1Zn alloy and guiding significance for the development of magnesium alloys in the future.

2. Experimental

2.1. Fabricated of cast Mg-6Sn-3Al-1Zn alloy
Herein, the alloy used in the experiment is Mg-3Al-6Sn-1Zn. Firstly, the raw materials of the alloy were weighted by analytical balance according to weight ratio of the alloying elements, 1620 g of pure Mg, 54 g of pure Al, 108 g of pure Sn and 18 g of pure Zn. Secondly, the mold was heated by high temperature box resistance furnace in order to make the alloy smoothly fill the cavity during the casting process. Thirdly, the SG-3-10 type smelting furnace temperature was heated to 750 °C and a mixture protective gas of SF6 and Ar with a volume ratio of 99:1 was introduced into the crucible, and then the pure magnesium bulk was heated to complete melting. After removing the upper scum of the magnesium liquid, the Sn, Zn, and Al metal blocks were respectively added to the magnesium liquid successively. After the metal blocks completely melted, mechanical agitation was performed on the melt for thoroughly mix uniformly, and then the upper layer impurities were removed. Fourthly, when the temperature of the melt increased to 730 °C, about 36 g of the refining agent was added to the melt and subsequent stirring will ensure homogeneous mixing. Fifthly, the melt was heated to 750 °C and held for 20 min, then naturally cooled to 730 °C and casted into a pre-prepared mold. After the mold was cooled for a while, the mold was finally opened to obtain the desired billet.

2.2. Preparation as-rolled Mg-3Al-6Sn-1Zn alloy samples
The as-cast Mg-3Al-6Sn-1Zn alloy was immediately performed water quenching after the solid treatment at 450 °C for 8 h. Subsequently, the sample was machined by wire cutting to 30 mm × 50 mm × 5 mm. The mill roll temperature was heated to 200 °C and the resistance furnace nearest from the mill roll was heated to 400 °C. The rolling reduction in the first rolling pass was 1 mm, and the subsequent rolling pass reduction was 0.3 mm. A series of rolled magnesium alloys with various rolling deformation, 25%, 45%, 65%, and 85%, were acquired.

2.3. Microstructure characterization of rolled Mg-3Al-6Sn-1Zn alloy
2.3.1. Optical microscope (OM) microstructure characterization
The rolled alloys were firstly cut into 10 mm × 10 mm and rhythmically ground by 400#, 800#, 1200#, 1500#, and 2000# sandpapers, respectively. Subsequently, all alloys slices were polished with the polishing machine at 900 r min⁻¹. The polished samples were etched by the metallographic etch liquid (10 ml CH3COOH, 10 ml H2O, 4.2 g picric acid, 70 ml CH3CH2OH) for 40 s and were cleaned with distilled water, and dried by a blower. Lastly, the OM microstructures were observed by a Leica DMI3000I microscope.

2.3.2. Scanning electronic microscope (SEM) microstructure characterization
The samples were explored to microstructure by the ZEISS MERLIN COMPACT type SEM after were observed by OM characterization, operated at 20 kV and 10 µA.

2.3.3. X-ray diffraction (XRD) phase characterization
The rolled samples were cut to 10 mm × 10 mm and ground by 400# and 800# sandpapers, successively. The processed samples were measured by the D8-advanced XRD operated at 40 kV and 40 mA. The scanning range and step size was 20°–90° and 0.02°, respectively.
2.3.4 Transmission electron microscope (TEM) microstructure characterization

The rolled sample was cut by wire cutting machine. The sample fixed on a glass sheet and was grounded by 400# sandpaper until reducing half thickness of the sample. Meanwhile, the surface of sample was sufficiently smooth. Then, the thin slice was experienced a multiple polish by 800#, 1200#, 1500#, and 2000# sandpaper. Identical method was applied to the other surface. Finally, the sample was grounded to 40 μm thicknesses. And then the sample was thinned by a twin-jet electropolishing device at 40 μm for 2 min, electrolyte solution was 4 vol.% perchlorate alcohol solution, after that the sample thickness was further reduced by precision ion polishing system (PIPS), at this time, sample preparation was completed. Lastly, the sample was observed by JEOL2010F TEM operated at 200 kV and 103 μA.

2.4. Mechanical properties test

2.4.1 Vickers hardness test

The square sample (10 mm × 10 mm) was made by wire cutting and underwent a hardness test at 0.2 kgf loading force and dwelling time of 10 s by a Vickers hardness tester (WILSON VH1102). Each sample was tested 5 times and the average value was as the finally hardness value.

2.4.2 Tensile property test

The standard sample form was mechanized by wire cutting and shown in figure 1. The accurate parameters were captured by a vernier caliper after reduced the surface oxide layer from the sample. Tensile properties were tested on an Instron 5982 universal testing machine with a cross-head speed of 0.2 mm min⁻¹ and repeated three times, final value was an average value of the three times.

3. Results

3.1. Microstructural characterization

Figure 2 shows the XRD patterns of various rolling deformation magnesium alloys. As can be seen from figure 2, magnesium alloys include the α-Mg matrix phase and Mg2Sn second phase. Besides, the inferior diffraction peak (2θ = 34°) intensity increases significantly as the amount of rolling deformation increasing. However, when the rolling deformation achieves to 85%, the diffraction peak intensity decreases slightly.

The OM images of the Mg-6Sn-3Al-1Zn alloys are shown in figure 3. As can be seen from figure 3, the coarse black Mg2Sn second phase of the solid solution sample is uniformly distributed at the grain boundaries of the gray coarse crystal. The rolled alloy with 25% deformation appears abundant twins, which are observed in the figure 3(b). When the rolling deformation exceed 25%, with the increasing of the rolling deformation, the number of twins is gradually declining until such phenomenon disappears. When the rolling deformation attains 65%, the majority of the regions have transformed into fine grains by dynamic recrystallization, and the number of twins reduces radically. When the rolling deformation enhances to 85%, the sample almost composes of small crystal grains, which indicate that the dynamic recrystallization process has been completed. In addition, the Mg2Sn phase is broken down and distributes more uniformly as the rolling deformation increasing.

Figure 4 shows the EBSD images, misorientation angle distribution diagrams and twin distribution diagrams of the rolled Mg-6Sn-3Al-1Zn alloys with different rolling deformation. As shown in figure 4(a), after the sample is rolled by 25% deformation, the grain boundaries are clear, grain orientation shows anisotropism, the microstructure is based on big deformation grains, and few small recrystallized grains are formed at trigeminal...
Figure 2. The XRD patterns of magnesium alloys with various rolling deformations.

Figure 3. OM pictures of magnesium alloys with different rolling deformation. (a) Solid solution, (b) 25% rolling deformation, (c) 45% rolling deformation, (d) 65% rolling deformation, (e) 85% rolling deformation.
grain boundaries of big deformation grains. As shown in figure 4(b), when the amount of deformation of alloy increases to 45%, the number of recrystallized grains increases dramatically and the average grain size further decreases. From figures 4(c) and (d), the average misorientation angle increases with increasing of the rolling deformation, which indicate that the proportion of high angle grain boundaries increases because of increasing of the number of recrystallize grains [19]. Otherwise, it’s worth noting that only a few of misorientation angle concentrate on near high-angle boundaries (figures 4(c) and (d)), which indicate that few \{10\text{–}12\} extension twinning and \{10\text{–}11\} contraction twinning exist in deformed alloy. Related studies have reported that these twins have a special orientation relationship with the parent crystal (\{10\text{–}12\} twin 86.1° and \{10\text{–}11\} twin 56°) [19, 20]. Thereby, in order to observe twinning boundaries distribution visually, we used EBSD technology to index twinning boundaries (figures 4(e) and (f)), the red and blue lines represent extension twinning boundaries and contraction twinning boundaries, respectively. The volume fraction of the twinning boundaries is the volume fraction of the extension twinning boundaries add the volume fraction of the contraction twinning boundaries. It can be clearly seen from partial enlarged image, the volume fraction of the twinning boundaries decrease with the increasing of deformation, the volume fraction of the twinning boundaries of the rolled alloy with 25% deformation is 1.29% (figure 4(e)), after the sample is rolled with 45% deformation, the volume fraction of the twinning boundaries decrease to 0.26% (figure 4(f)). These indicate that with the increasing of the
rolling deformation, the number of twins is gradually declining, these results are consistent with the results of the OM analysis.

Figure 5 shows the SEM images of solid solution magnesium alloys and the EDS mapping of Mg, Sn, Al, and Zn elements. According to the EDS mapping, the gray region is the matrix α-Mg phase, and the dendritic white phase is the Mg2Sn second phase, which is consistent with the phase results of the XRD analysis. Both Al and Zn elements are distributed uniformly in the microstructure.

The curves of volume fraction and area of the Mg2Sn phase, the average grain size of the recrystallized grains, and the volume fraction of the recrystallized grains with the rolling deformation are shown in figure 6. As can be seen from figure 6(a), with rolling deformation increasing, the volume fraction of the Mg2Sn phase primordially decreases and then stabilizes, the volume fraction of the Mg2Sn phase in the samples with 25% and 45% rolling deformation decreases from 6.7% of solid solution magnesium alloy to 4.3% and 2.9%, respectively. When the rolling deformation exceeds 45%, the volume fraction of the Mg2Sn phase remains a constant. Figure 6(b) shows that the sample at 25% rolling deformation possesses a larger average size of the Mg2Sn phase than that of the sample at solid solution, when the rolling deformation exceeds 25%, the size of the Mg2Sn phase decreases with the rolling deformation. Figure 6(c) reveals the volume fraction of the recrystallized grains gradually increases as the rolling deformation. As shown in figure 6(d), the average grain size of the solid solution magnesium alloy is 125μm and the recrystallized grains appear in the alloy with 25% rolling deformation. It is worth noting that the

![Figure 5](image-url)
average grain size of recrystallized grains gradually diminishes from 9.6 μm at the 25% rolling deformation to 3 μm at the 45% rolling deformation. When the rolling deformation oversteps 45%, the value holds a steady state.

The SEM images of the magnesium alloys with different rolling deformation are shown in figure 7. As can be seen from the figure 7, the inside of the magnesium alloys are discovered small size particles. Interestingly, as the rolling deformation increasing, these fine particles reform from a rod shape to a spherical shape. When the rolling deformation attains to the 65%, the rod phase has been reformed to spherical phase completely. In addition, the spherical phase clearly increases after the alloy experiences 85% rolling deformation.

The HADDF (high angle annular dark field probe) bright field image and the corresponding EDS picture of the sample with a rolling deformation of 85% are shown in figure 8. As can be seen from figure 8(a), the plentiful granular phase on the matrix α-Mg phase, which is analyzed by the EDS characterization and the result is shown in figure 8(b). Clearly, the plentiful granular phase is Mg2Sn, it is because that the atomic percent of the Mg and Sn elements (Mg: Sn = 22.3: 76.3) is approximately 1:3. However, according to Mg-Sn binary diagram [21], the major phases of Mg-6Sn-3Al-1Zn alloy are α-Mg and Mg2Sn phase after rolling at 400 °C. From the above analysis, the granular phase in the TEM image is Mg2Sn phase.

3.2. Mechanical properties of the Mg-6Sn-3Al-1Zn alloys with and without rolling at different deformation
The tensile stress-strain curves, the variation of tensile strength and elongation with rolling deformation are shown in figure 9. As can be seen from figure 9(b), the tensile strength of the sample with 25% rolling deformation decreases to 164 MPa from 203 MPa of solid solution. Subsequently, the tensile strength gradually increases with the rolling deformation increasing, when the rolling deformation reaches up 85%, the tensile strength increases to 352.5 MPa. Figure 9(c) shows that the solid solution magnesium alloy has the largest elongation, for the sample with 25% rolling deformation, the elongation decrease from 16.3% of solid solution magnesium alloy to 4.4%. However, after that the elongation of alloys increase with the rolling deformation increasing, when the rolling deformation increases to 65%, the elongation achieves an extremum value of 13%. However, while the rolling deformation attains 85%, the elongation immediately reduces to 9.8%.

The Vickers hardness of the magnesium alloys are listed in table 1. The hardness of the magnesium alloys continue to increase with increasing rolling deformation.
4. Discussion

4.1. Effect of rolling deformation on texture

The increases of the rolling deformation leads to the grains in the magnesium alloys showing a preferred orientation, and the number of preferred orientation grains increases with the degree of plastic deformation. Rolling pass increases with rolling deformation. And after a rolling pass, the preferred direction further increases. When the rolling deformation is 65%, the preferred direction of alloy reaches up to the maxima value. When the rolling deformation achieves 85%, the preferred orientation of grains part eliminate because of recrystallization. Meanwhile, this will slightly weaken the intensity of diffraction peak compare to the sample with 65% rolling deformation.

4.2. Effect of rolling deformation on recrystallized grains

The grain boundaries are mainly recrystallized nucleation region for magnesium alloys during the rolling process. Meanwhile, the twins region becomes the subordinate recrystallized nucleation region. The volume fraction of recrystallized grains of magnesium alloys increase with increasing of the rolling deformation, such a result is caused by the tedious recrystallized process, because of rolling pass increase with rolling deformation and need heat preservation after rolled each pass, recrystallization take place every time heat preservation. The sample with 25% rolling deformation possesses 9.6 μm recrystallized grains. However, the average recrystallized

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Figure 7. The SEM micrographs of the magnesium alloys with various rolling deformation, (a) 25%, (b) 45%, (c) 65%, (d) 85%.

Figure 8. (a) The HADDF bright field and (b) the corresponding EDS picture of the red region in (a) of 85% rolling deformation sample.
4.3. Effect of rolling deformation on mechanical properties

4.3.1. Effect of rolling deformation on the tensile strength
The volume fraction and phase size of the Mg-Sn phase are respectively decrease and increase with the increasing of deformation, which is an important reason for the reducing of the tensile strength of the sample with 25% rolling deformation. Although the twins can be found in the sample with 25% rolling deformation, which can hinder dislocation motion and pile-up at the twin boundaries lead to the strength increase [22], the volume fraction of twins are 1.29%, the effect of twins on strength very little.

The tensile strength is gradually enhancement as the rolling deformation improvement. The dislocation density increases with the increasing of the rolling deformation, leads to the strength of alloy increases [23]. The 45% rolling deformation alloy possesses the outstanding tensile strength than that of the alloy with 25% rolling deformation. The phenomenon is caused by the more volume fraction and small average grain size of...
recrystallized grains, which leads to fine grain reinforcing. In addition, fragmentation and uniform distribution of the rod Mg$_2$Sn phase plays a role of dispersion strengthening. When the rolling deformation exceeds 45%, the fine crystal reinforcing turn into the main reason for the tensile strength of alloys increase gradually, fine crystal reinforcing including the reduce Mg$_2$Sn phase size and the increase volume fraction of the recrystallized grains. Besides, the rod Mg$_2$Sn phase constantly breaks down to spherical phase with the rolling deformation increasing, after rolled with 65% thickness reduction, the rod Mg$_2$Sn phase completely turns into small spherical phase with 100 nm in diameter. The number of spherical phase increases after rolled with 85% thickness reduction, which plays a role of dispersion strengthening.

4.3.2. Effect of rolling deformation on the elongation
For the plasticity of wrought magnesium alloys, the solid solution alloy possesses the excellent elongation achieves 16.3%, due to the large grain size of the solid solution. There are recrystallized grains and the salient twins appear in the 25% rolling deformation alloy which induce the 4.4% elongation, these results consistent with the reference [24]. The elongation rate increases gradually during the rolling deformation from 25% to 65%, because the fine grain strengthening plays a leading role. The fine crystal reinforcing not only improves the strength, but also enhances the plasticity of alloy. However, after rolled with 85% thickness reduction, the elongation decreases because of the Mg$_2$Sn hard brittle phase increases in the microstructure which enhance the strength of the alloy, but degrades the plasticity of the alloy.

4.3.3. Effect of rolling deformation on the Vicker hardness
There are four factors leading to increases of the Vicker hardness with the increasing of rolling deformation. Firstly, the hard brittle phase of Mg$_2$Sn gradually turns to the spherical phase and the dispersion strengthening constantly enhances with the increasing of rolling deformation. Subsequently, the number of recrystallized grains constantly increases with the rolling deformation. The effect of fine crystal reinforcing is obvious. Thirdly, the strain strengthening effect increases with the increasing of rolling deformation. Finally, the formation of twins lead to the Vicker hardness of alloy increase [25].

5. Conclusions
The Mg-6Sn-3Al-1Zn alloys without and with different thickness reductions are composed of $\alpha$-Mg matrix phase and Mg$_2$Sn second phase. The larger Mg$_2$Sn phase distributed on the grain boundaries, and the smaller Mg$_2$Sn phase distributed in the grains. Both Al and Zn elements distributed evenly in the microstructure. With the enhancement of rolling deformation, the volume fraction of Mg$_2$Sn phase distributed on the grain boundaries firstly decreased and then stabilized and the average size of Mg$_2$Sn phase firstly increased and then decreased. The volume fraction of the recrystallized grains monotonously increased and the average grain size of recrystallized grains firstly decreased and then stabilized. Besides, the shape of Mg$_2$Sn phase distributed inside the grains gradually transformed from the rod-like shape to the spherical shape. When the rolling deformation overstepped 25%, the tensile strength, and Vickers hardness of the Mg-6Sn-3Al-1Zn alloys increased as the rolling deformation increasing. However, when the rolling deformation exceeded 65%, the elongation of the magnesium alloy was diminished obviously, and the alloy was not significantly superior in strength. In summary, when the deformation of magnesium alloy was 65%, the mechanical properties were the best. The tensile strength, elongation, and hardness of the alloy with 65% rolling deformation were 317 MPa, 13%, 77.52 HV, respectively.

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References
[1] Somekawa H, Singh A, Sahara R and Inoue T 2018 Excellent room temperature deformability in high strain rate regimes of magnesium alloy Sci. Rep. 8 656
[2] Zhao X, Chen H, Wilson N, Liu Q and Nie J F 2019 Direct observation and impact of co-segregated atoms in magnesium having multiple alloying elements Nat. Commun. 10 3243
[3] Chen C, Chen J, Yan H, Su B, Song M and Zhu S 2016 Dynamic precipitation, microstructure and mechanical properties of Mg-5Zn-1Mn alloy sheets prepared by high strain-rate rolling Mater. Des. 100 58–66
[4] Zheng R, Bhattacharjee T, Gao S, Gong W, Shibata A, Sasaki T, Hono K and Tsuji N 2019 Change of deformation mechanisms leading to high strength and large ductility in Mg-Zn-Zr-Ca Alloy with fully recrystallized ultrafine grained microstructures Sci. Rep. 9 11702
[5] Yin S, Zhang Z, Yu J, Zhao Z, Liu M, Bao L, Jia Z, Cui J and Wang P 2019 Achieving excellent superplasticity of Mg-7Zn-5Gd-0.6Zr alloy at low temperature regime Sci. Rep. 9 4365
[6] Imandoust A, Barrett C D, Oppedal A L, Whittington W R, Paudel Y and El Kadiri H 2017 Nucleation and preferential growth mechanism of recrystallization texture in high purity binary magnesium-rare earth alloys Acta Mater. 138 27–41
[7] Al-Samman T and Li X 2011 Sheet texture modification in magnesium-based alloys by selective rare earth alloying Materials Science and Engineering: A 528 3809–22
[8] Jandaghif M R and Pouriakbar H 2017 Study on the effect of post-annealing on the microstructural evolutions and mechanical properties of rolled CGPed aluminum-manganese-silicon alloy Materials Science and Engineering: A 679 493–503
[9] Tang S, Xin T, Xu W, Miskovic D, Sha G, Quadir Z, Kiringer S, Nomoto K, Birbilis N and Ferry M 2019 Precipitation strengthening in an ultralight magnesium alloy Nat. Commun. 10 1003
[10] Li C Q, Xu D K, Wang B J, Sheng L Y, Qiao Y X and Han E H 2017 Natural ageing responses of duplex structured Mg-Li based alloys Sci. Rep. 7 40079
[11] Wang L, Zhao Y Q, Chen H M, Zhang J, Liu Y D and Wang Y N 2017 Improvement of mechanical properties of magnesium alloy ZK60 by asymmetric reduction rolling Acta Metall. Sinica 31 63–70
[12] Li Z, Liu F, Yuan A, Duan B, Li Y and Li X 2017 Effect of rolling deformation on microstructure and texture of spray-deposited magnesium alloy containing Mg-Nd-Zn typed LPSO Journal of Materials Science & Technology 33 630–6
[13] Dahle A, Lee Y, Nave M, Schaffer P and Stlohn D 2001 Development of the as-cast microstructure in magnesium–aluminium alloys J. Light Met. 1 61–72
[14] Suzuki M, Kimura T, Koike J and Maruyama K 2003 Strengthening effect of Zn in heat resistant Mg–Y–Zn solid solution alloys Scr. Mater. 48 997–1002
[15] Chen J, Chen Z, Yan H, Zhang F and Liao K 2008 Effects of Sn addition on microstructure and mechanical properties of Mg–Zn–Al alloys J. Alloys Compd. 461 209–15
[16] Wang B, Pan F, Chen X, Guo W and Mao J 2016 Microstructure and mechanical properties of as-extruded and as-aged Mg–Zn–Al–Sn alloys Materials Science and Engineering: A 665 165–73
[17] Park S H, Kim S H, Kim H S, Yoon J and You B S 2016 High-speed indirect extrusion of Mg–Sn–Al–Zn alloy and its influence on microstructure and mechanical properties J. Alloys Compd. 667 170–7
[18] Cheng W, Tian L, Wang H, Bian L and Yu H 2017 Improved tensile properties of an equal channel angular pressed (ECAPed) Mg-8Sn-6Zn-2Al alloy by prior aging treatment Materials Science and Engineering: A 687 146–54
[19] Li X Q, Cheng C L, Le Q C, Zhou X, Liao Q Y, Chen X R, Jia Y H and Wang P 2019 Ex-situ EBSD analysis of yield asymmetry, texture and twinning development in Mg–5Li–3Al–2Zn alloy during tensile and compressive deformation J. Alloys Compd. 805 947–56
[20] Park S H, Hong S G, Lee J H and Lee C S 2012 Multiple twinning modes in rolled Mg-3Al-1Zn alloy and their selection mechanism Materials Science and Engineering: A 532 401–6
[21] Liu C M, Zhu X R and Zhou H T 2006 Phase Diagram Collection of Magnesium Alloy (Changsha, China: Central South University Press) 9787811053227
[22] Han K, Xin Y and Ishmaku A 2003 Strain hardening by formation of nanoplatelets Pro. Conf Nanomaterials by Severe Plastic Deformation 1, 95–100
[23] Ishmaku A and Han K 2004 Deformation induced nanostructure and texture in MP35N alloys J. Mater. Sci. 39 5417–20
[24] Cai S, Barrow A T W, Yang R and Kay E L 2013 Effect of cold work and aging on a Cobalt-Nickel based alloy Biomaterials Science: Processing, Properties and Applications III: Ceramic Trans. 242 (Wiley)
[25] Sorensen D, Li B Q, Gerberich W W and Mkhoyan K A 2014 Investigation of secondary hardening in Co–35Ni–20Cr–10Mo alloy using analytical scanning transmission electron microscopy Acta Mater. 63 63–72