Effect of extrusion speed on microstructure and mechanical properties of Mg-Al-Ca-Sn alloy

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Abstract

Low-temperature and high-speed extrusion of wrought magnesium alloy is an urgent problem. Mg-2.5Al-2Ca-1Sn alloys were extruded at 260 °C with different ram speeds (2.0, 4.0 and 6.0 mm s⁻¹). The effects of extrusion speed on the microstructure and mechanical properties of the alloys were systematically investigated. It’s worth noting that all the three extruded alloys were fully dynamic recrystallized (DRXed). With the increase of extrusion speed from 2 mm s⁻¹ to 6 mm s⁻¹, the DRXed grain size are increased from 1.25 μm to 1.94 μm, average second phase particles are augmented from 0.79 μm to 0.89 μm and the volume fraction of second phase increases from 6.4% to 18.6%. All the three extruded samples show excellent comprehensive mechanical properties because of fine grain size, fully recrystallization and homogeneously dispersed second phase particles. The tensile yield strength (TYS) and ultimate tensile strength (UTS) decreased from 285 MPa, 304 MPa to 217 MPa, 264 MPa while the elongation increased from 11.4% to 20% when the ram speed rose from 2.0 mm s⁻¹ to 6.0 mm s⁻¹.

1. Introduction

Magnesium alloy possesses some excellent mechanical properties including high specific strength, high specific stiffness and low density, etc [1–4]. These advantages endow magnesium alloy with great prospect in practical applications, such as aviation, aerospace, automobile and other transportation fields. Compared with high-strength aluminum alloy, however, the defects in magnesium alloy will strictly limit its practical applications, which is characterized by its low absolute strength, unsatisfied creep resistance at high temperature, poor plasticity, etc [5, 6]. Although high-strength rare earth (RE) magnesium alloys with good comprehensive mechanical properties have been investigated in some previous literature over the past few years [7–9], the addition of large quantities of RE elements will make these alloys very expensive. Therefore, it is necessary to develop a new strategy to synthesize rare-earth-free magnesium alloy with the optimal high strength and low cost [10–12].

The traditional cast magnesium alloy has low strength and poor plasticity, which is difficult to meet the requirements of modern structural materials, and limits the development and application of magnesium alloys. The deformation process of wrought magnesium alloy can greatly reduce the grain size, increase dislocation density, and have high strength and ductility, which greatly expands the application range of the material, and brings good news to the magnesium alloy. Common deformation methods include extrusion, rolling, forging, etc, among which the extrusion magnesium alloy has the largest deformation, the highest strength, and the best comprehensive performance, which has attracted a lot of attention. There are many factors affecting the effect of extrusion, such as extrusion temperature, extrusion speed, the extrusion ratio and so on [13–16]. Many people [9, 17–20] have prepared the high-strength magnesium alloys by extrusion, but most of them adopted the high temperature and high-speed extrusion or low temperature and slow speed, and even high temperature and slow...
speed, which greatly reduces the production efficiency and increases the cost, and is not conducive to the
development of magnesium alloys. There are two main reasons why it is difficult to achieve low-temperature and
high-speed extrusion: (i) Magnesium alloy is HCP structure, which is difficult to slide at low temperature and
easy to crack during extrusion. (ii) In the process of high-speed extrusion, severe deformation will produce a
large amount of deformation heat instantly, which greatly affects the properties of magnesium alloy, and even
melt the second phase with low melting point in the extrusion process, directly leading to cracking. Mg-Al alloy
can be used as the main component of commercial magnesium alloy because of its high strength and plasticity,
excellent castability, low price and good corrosion resistance [21]. Ca is a promising element with low density
and price in magnesium alloys, which can improve its high-temperature performance, creep resistance and
refine grain size [22–26]. In the Mg-Al-Ca ternary alloy, with the difference of Ca/Al, Laves phases (Mg, Al)$_2$Ca
(C36), Al$_2$Ca and Mg$_2$Ca (C14) with high temperature stability will be produced at grain boundaries [27]. These
eutectics will not melt in the extrusion process and have significant effects on the strength of extruded
magnesium alloy [18, 28]. The addition of Sn element into Mg-Al alloy can reduce the stacking fault energy of
the alloy and improve its ductility [29]. Thus, the cracking tendency during hot working process can be
obviously reduced, which is conducive to extrusion forming.

Mg-Al-Ca alloys have great potential in high-speed extrusion and some studies have been carried out to
explore the high-speed extrusion of Mg-Al-Ca alloys, but with high extrusion temperature [30, 31], most
researchers tended to focus on the extrusion temperature and the influence of phase composition on extrusion
alloys [16, 18, 28, 32], the related reports on high-speed extrusion magnesium alloys at low temperatures are
actually deficient. Therefore, the development of low temperature and high-speed extrusion magnesium alloy is
a problem that must be solved of extrusion magnesium alloy, and it is of far-reaching significance to study the
impact of extrusion speed on its effect.

This work provides a facile strategy for synthesis of Mg-Al-Ca alloy with a small amount of dopped Sn
element at a relatively low temperature to achieve high-speed extrusion, which represents a fundamental
breakthrough in the development of magnesium alloy extruded at low temperature and high speed. The change
of microstructure and mechanical properties is also explored with the further increase of extrusion speed.

2. Experimental

The alloy of ACT221 (Mg–2.5 wt%Al–2 wt%Ca–1 wt%Sn) in this study was prepared by melting commercial
pure Mg, Al, Sn and Mg–25wt%Ca master alloy in a cylinder steel crucible under flowing inert protective
atmosphere (SF$_6$ + CO$_2$) through direct chill casting. The alloy melt was kept at 760 °C for 30 min before
pouring into a steel mold that preheated at 260 °C to obtain cast billet, which was subsequently wire cut into ingots with a height of 20 mm and a diameter of 25 mm. These obtained ingots were then homogenized with graphite covering at 400 °C for 24 h followed by water quenching and then preheated to 260 °C for 30 min before extrusion. Subsequently, direct extrusion was carried out at 260 °C at different ram speeds of 2.0, 4.0 and 6.0 mm s$^{-1}$ (corresponding die-exit speeds of 3.0, 6.0, 9.0 m min$^{-1}$, respectively), and extrusion ratio of 25:1. The mixture of graphite and animal fat is employed as lubricant to effectively reduce friction between the extrusion cylinder and the ingot. The obtained extruded rods with radius of 2.5 mm by the above steps were finally air cooled to room temperature.

The morphology of synthesized ACT221 alloys was studied and analyzed by scanning electron microscopy (SEM Hitachi REGULUSS 8230) equipped with an energy dispersive x-ray spectrometer analysis system. The samples for SEM observation were grounded and mechanically polished before being etched in acetic picral. The phases of ACT221 alloys were studied by SEM-EDS analysis. The texture and average DRXed grain size were examined by an EDAX-TSL electron back-scattered diffraction (EBSD) system, and the data were further analyzed by AZtec Crystal The fraction, size of second phase particles, and average grain size were measured by using Image-pro Plus software. The tensile dog-bone-shaped specimens with a gauge length of 25 mm and a diameter of 2.5 mm, were machined parallel to the extrusion direction at a crosshead speed of 0.42 mm min$^{-1}$ at room temperature using an Instron 5569 universal test machine.

3. Results and discussion

3.1. Microstructure of the As-homogenized alloy

Figure 1(a) shows the SEM image of as-homogenized alloy, from which it can be seen that the microstructure of the as-homogenized alloy is mainly composed of a large number of netlike second phases distributed along grain boundary as shown by the red arrow, a few feathery phases, several dendritic phases and α-Mg phase. The grain size and the volume fraction of the second phases were measured by Image-Pro Plus software. The measured averaged grain size of as-homogenized is approximately 40–60 μm and the volume fraction of second phase is about 22.96%. In addition, many tiny second phase precipitates dispersed in the matrix grains. In order to identify the elementary composition of these different morphology of the second phase compounds, the EDS elemental mapping images are given in figures 1(b)–(d). It shows that these netlike second phase are enriched with Al and Ca, feathery and dendritic phase are enriched with Ca and Sn. Figure 2(a) shows SEM image of these second phases and figures 2(b)–(d) presents its detailed magnified SEM image and table 1 displays its related EDS analysis of these second phases. The EDS results and SEM images of these second phase particles of point A and point E are consistent with reported literatures $^{[25, 27]}$, which is related to (Mg,Al)$_2$Ca phase. Point B, C, D, and
F are all CaMgSn phase with a small amount of Al solid solution, in which point F is typical feather-like, point B and C are discontinuous dendritic, point D is rod-like, which is consistent with these literature \[28, 30, 32, 33\]. These second phases distributed along grain boundaries can effectively refine grains.

3.2. Microstructure of the As-extruded alloys

Broken fine second phases uniformly dispersed along the extrusion direction as shown by the red arrow can be seen in all the three kinds of as-extruded alloys with different extrusion speed from figures 3(a)–(c). Image-Pro Plus software was used for statistics and the results show these broken fine particles increases distinctly with the increase of extrusion speed from 2 mm s\(^{-1}\) to 6 mm s\(^{-1}\), and their volume fraction are 6.4%, 12.9%, 18.6%, respectively. However, the particle size of the second phase did not change significantly, and the average particle diameters were 0.79, 0.85 and 0.89 \(\mu\)m, respectively. For comparison with the as-homogenized alloys, EDS mapping images of as-extruded alloy of 2 mm s\(^{-1}\) and 4 mm s\(^{-1}\) are shown in figures 3(a)–(b). The majority of broken second phase particles are enriched with Al and Ca, few are composed of Sn and a large number of tiny uniformly distributed precipitates were observed. Combined with EDS results of 6 mm s\(^{-1}\) in table 2, these broken particles after extrusion remain the same as the as-homogenized alloy.

Table 1. EDS results of the second phases in the as-homogenized alloy in figure 2 (at%).

| Position | Mg   | Al   | Ca   | Sn   | Possible second phases |
|----------|------|------|------|------|------------------------|
| A        | 59.64| 28.84| 11.52| 0.00 | (Mg, Al)\(_2\)Ca       |
| B        | 84.99| 1.08 | 6.34 | 7.59 | CaMgSn                 |
| C        | 88.28| 1.74 | 4.14 | 5.84 | CaMgSn                 |
| D        | 77.20| 1.72 | 10.11| 11.79| CaMgSn                 |
| E        | 66.72| 23.94| 8.36 | 0.98 | (Mg, Al)\(_2\)Ca       |
| F        | 89.33| 1.28 | 3.51 | 5.87 | CaMgSn                 |

Figure 3. SEM image and EDS mapping of the vary extrusion speed alloys: (a) 2 mm s\(^{-1}\), (b) 4 mm s\(^{-1}\), and SEM image of 6 mm s\(^{-1}\)(c).
Inverse pole figure (IPF) maps and corresponding grain size distribution graphs obtained from the three extruded samples are shown in figures 4(a)–(f). It is obvious that unDRXed regions are not found in all the three samples, which means that all the three extruded alloys with different extrusion speed show almost fully dynamic recrystallized structure. One important parameter to identify DRXed grains is grain orientation spread (GOS) in °. According to A. Hadadzadeh et al [34], GOS ≤5° is a proper threshold value to recognize all DRXed grains. Figures 5(a)–(c) show GOS value of the three samples of 2, 4, 6 mm s⁻¹. Obviously, the GOS values of all the three extruded samples are ≤5°. We can further confirm that all samples have almost complete recrystallization. As shown in figures 5(d)–(e), the average diameters of 2 mm s⁻¹, 4 mm s⁻¹ and 6 mm s⁻¹ are about 1.25, 1.74 and 1.94 μm respectively. With the increase of extrusion speed, average grain size increases and the grain of 2 mm s⁻¹ distributed more uniform than other extruded alloys. Several abnormally grown large

Table 2. EDS results of second phases formed in the as-extruded alloy of 6 mm s⁻¹ (at%).

| Position | Elements |
|----------|----------|
|          | Mg       | Al       | Ca   | Sn   |
| A        | 89.61    | 8.23     | 2.16 | 0.00 |
| B        | 83.89    | 11.71    | 3.95 | 0.45 |
| C        | 89.98    | 7.81     | 2.22 | 0.00 |
| D        | 97.97    | 1.28     | 0.75 | 0.00 |
| E        | 85.68    | 2.93     | 1.46 | 9.93 |
| F        | 88.94    | 2.25     | 3.11 | 5.69 |
| G        | 98.6     | 0.95     | 0.34 | 0.11 |

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grains are found in the extruded alloy of 4 mm s\(^{-1}\) and 6 mm s\(^{-1}\) due to the large amount of deformation heat generated by high-speed deformation. A string of fine broken second phase particles dispersed along the extrusion direction (ED) also can be seen. These second phase particles play a crucial role in the formation of nucleus of DRXed grain and may effectively restrict the growth of DRXed grains, which finally lead to near fully DRXed and fine DRXed particles.

When the grain size of magnesium alloy is refined to about micron, grain boundary sliding and new rheological processes will occur at room temperature, which can greatly improve the plasticity of magnesium alloy (the effect of grain size on plasticity).

The main factors affecting dynamic recrystallization of magnesium alloy are deformation temperature, deformation speed, deformation degree and original grain size.

In this paper, the Mg-Al-Ca-Sn alloy system was hot extruded at 260 °C with different extrusion speeds. The EBSD results show that the three alloys have undergone complete recrystallization. Mabuchi M et al [35] found that the dynamic recrystallization grain size was related to \(Z\) parameter:

\[
d' \propto Z^{-p}
\]

\(d'\) is the DRX grain size, \(Z\) is the \(Z\)-parameter, \(p\) is the grain size exponent.

Equation (1) shows that the larger the \(Z\) parameter is, the smaller the dynamic recrystallization grain size will be, and the \(Z\) parameter conforms to the following formula:

\[
Z = \dot{\varepsilon} \exp(Q/RT)
\]

\(\dot{\varepsilon}\) is the strain rate, \(Q\) is the activation energy for dominant diffusion, which is assumed to be similar to that for self-diffusion in magnesium (135 kJ mol\(^{-1}\)), \(T\) is the absolute temperature, \(R\) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)).

As can be seen from equation (2), \(Z\) parameter is affected by strain rate and strain temperature. With the continuous increase of extrusion speed, the strain rate gradually increases, which is conducive to the nucleation of new grains and leads to the decrease of dynamic recrystallization grains. However, due to the large amount of deformation heat generated by rapid extrusion deformation, the temperature of the die rises rapidly. Furthermore, the dynamic recrystallization and grain growth are further promoted. A small number of abnormally grown grains appear in the sample of 4 mm s\(^{-1}\), which is due to the medium \(Z\) value caused by the temperature of medium extrusion speed and deformation, leading to a small number of abnormally grown grains. In addition, some studies have shown that the original grain size also has a great effect on the dynamic recrystallization grain size [36]. The \((\text{Mg, Al})_2\text{Ca}\) phase distributed along grain boundaries and the \(\text{CaMgSn}\) phase can inhibit the grain growth of the original as-cast alloy. After homogenization, the grain size does not change significantly. As described in section 3.1, the grain size is 40–60 \(\mu\)m. It is important to note that these second phases distributed along grain boundaries are broken into particles after extrusion deformation, which greatly promotes the nucleation of dynamic recrystallization [37].

The occurrence of dynamic recrystallization is not only related to the deformation temperature, velocity, magnitude of deformation and grain size [38], but also affected by the properties of the material itself, especially the magnitude of stacking fault energy. Low stacking fault energy, wide extension of dislocation, makes it difficult to be free from node and dislocation network, so as to offset unlike dislocation through the cross-slip and climbing and leads to slow dynamic response process, high dislocation density in substructure. The rest of the energy storage is enough to cause recrystallization. The stacking fault energy of magnesium is very low, thus,

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**Figure 6.** Pole figures from the as-extruded alloys with different extrusion speeds: 2 mm s\(^{-1}\), 4 mm s\(^{-1}\), 6 mm s\(^{-1}\).
the thermal deformation process of dynamic recrystallization can happen easily. It has been shown in the literature [29] that the addition of Sn in the magnesium alloy is beneficial to reduce the stacking fault energy. So, the extruded magnesium alloy studied in this paper is very prone to dynamic recrystallization in the extrusion deformation process.

To sum up, the combined influence of the original grain size, deformation velocity, deformation temperature, second phase particles and the stacking fault energy of the material itself eventually led to fully dynamic recrystallization of all three as-extruded alloys, which plays an important role in grain refinement, texture weakening and comprehensive mechanical properties [39, 40].

3.3. Texture evolution
Figure 6 shows the pole figures of (0001), and \langle 10\rangle \langle 11\rangle \langle 20\rangle of the three samples. It can be seen from the figure that the samples with three extrusion speeds all have faint texture of (0001) and weaker texture of (0001) with increasing extrusion speed. And all the three extrudates show random distribution due to PSN effect of fine second phase particles and dynamic recrystallization [41, 42]. Similarly, the orientation of the three samples in the direction of \langle 10\rangle \langle 10\rangle and \langle 11\rangle \langle 20\rangle is also very random. Weaker texture accounts for the decrease in strength and the increase in ductility, which is consistent with literature [43]. It is worth noting that, with the increase of extrusion speed, the local texture strength appears higher, which may be due to the increase of extrusion speed and strain rate, and the random orientation caused by recrystallization cannot make up for the preferred orientation caused by deformation.

Deformation orientation is one of the characteristics of dynamic recrystallization, especially when using high Z parameter (high strain rate or low strain temperature) [34] of the deformation conditions, this paper adopted the extrusion speed 2, 4 and 6 mm s\(^{-1}\), respectively, and at relatively low temperature (260 °C) by extruding, have created favorable conditions for the deformation orientation, as shown in figure 4, even if dynamic recrystallization is complete, there will still be preferred orientation with certain strength.

3.4. Mechanical properties
Figure 7 illustrates the tensile stress-strain curves of extruded samples with varying speeds. It is shown that all the extruded alloys occupy excellent mechanical properties, with maximum yield strength (YS) of 285 MPa, ultimate tensile strength (UTS) of 302 MPa and maximum elongation (EL) of 20%. The yield strength and tensile strength are almost linearly proportional to the extrusion speed and the elongation is almost linearly inversely
dislocation movement is. Therefore, the strength decreases with the increase of extrusion speed. The more the second phase particles are, the more obvious the effect of impediment to movement of inner-grain dislocations, and then improve the strength of the alloy. With the increase of extrusion speed, solution hardening decreases, according with strength decrease with increasing extrusion speed.

Magnesium alloy has high strength increases with the decrease of grain size. It is higher for HCP metals than for FCC and BCC metals. The average size of second phase particles and its volume fraction increases, and the dislocation lines are entangled, which effectively hinders slip. The strength increases with increasing extrusion speed. It is known that, grain coarsening will lead to weak grain boundary strengthening because of inverse relationship between grain size and yield strength. Besides, For most crystalline materials, dislocation density increases greatly after plastic deformation and this dislocation density decreases with increasing deformation temperature. High speed extrusion lead to higher deformation temperature and lower dislocation density. Therefore, the reduction in strength at higher extrusion speed is mainly due to larger grain size and lower dislocation density.

In this experiment, the comprehensive mechanical properties of the three extruded alloys are affected by the following factors: (i) fine grain strengthening mechanism. According to section 3.2, complete recrystallization occurred in all three samples, and with the increase of extrusion speed, the grain sizes were 1.25, 1.74 and 1.94 μm, respectively.

According to the Hall-Petch relationship [44]:

\[ \sigma_y = \sigma_0 + K_y d^{-\frac{1}{2}} \]

\( \sigma_y \) is the yield strength, \( K_y \) is material constant, the value of \( K_y \) depends on the number of slip systems, the strength increases with the decrease of grain size. It is higher for HCP metals than for FCC and BCC metals. Magnesium alloy has high \( K_y \) value, so its fine grain strengthening effect is obvious. (ii) grain boundary strengthening mechanism. In all the three extruded alloys, there are a large number of fine evenly distributed second phase particles. In the process of tensile deformation, the grain boundary does not participate in the deformation, but the fine second phase particles dispersed along the grain boundary can effectively hinder the movement of inner-grain dislocations, and then improve the strength of the alloy. With the increase of extrusion speed, although the overall volume fraction of the second phase increases, the number of the second phase particles decreases. The more the second phase particles are, the more obvious the effect of impediment to dislocation movement is. Therefore, the strength decreases with the increase of extrusion speed. (iii) dislocation strengthening mechanism. After extrusion deformation of as-homogenized alloy, the dislocation density increases, and the dislocation lines are entangled, which effectively hinders slip. (iii) solid solution strengthening mechanism. As mentioned in section 3.2, the average size of second phase particles and its volume fraction increases with increasing extrusion speed, which means solid solution atoms in α-Mg becomes less. Thus, solid solution hardening decreases, according with strength decrease with increasing extrusion speed.

4. Conclusions

In this study, Mg-2.5Al-2Ca-1Sn alloys extruded at 260 °C with different ram speeds (2.0, 4.0 and 6.0 mm s\(^{-1}\)) were fabricated and the effects of extrusion speed on the microstructure and mechanical properties of the extruded alloys were systematically investigated. Conclusions are drawn as follows:

• Mg-Al-Ca-Sn alloy was successfully extruded at low temperature and high speed for the first time.

• A large number of netlike second phases distributed along grain boundary which may well be C36-(Mg, Al)\(_2\)Ca and a few feathery, dendritic CaMgSn phases were also observed in the as-homogenized alloys. These second phases were fragmented into fine particles, which is beneficial to facilitate recrystallization after extrusion. And These eutectics have high temperature stability without melting in the process of extrusion, which ensure high-speed extrusion.

• The second phase of extruded alloys did not change compared to as-homogenized alloys and all the three alloys were fully recrystallized (DRXed) after extruded at different speeds. With the increase of extrusion speed, the DRXed grain size are 1.25 μm, 1.74 μm and 1.94 μm respectively, and volume fraction of second phase particles are 6.4%, 12.9%, 18.6%, besides the deformation orientation becomes more random.

| Extrusion Speed (mm s\(^{-1}\)) | Vf\(_{DRXed}\) | AGS (μm) | Vf\(_i\) (%) | YS (MPa) | UTS (MPa) | E (%) |
|-------------------------------|----------------|----------|--------------|---------|----------|-----|
| 2.0                           | Near fully     | 1.25     | 6.4          | 285     | 302      | 11.4|
| 4.0                           | fully          | 1.74     | 12.9         | 246     | 280      | 16.5|
| 6.0                           | fully          | 1.94     | 18.6         | 217     | 264      | 20  |
• All the three extruded alloys exhibit excellent comprehensive mechanical properties because of relatively fine grain size, fully recrystallization and homogeneously dispersed second phase particles. With the increase of extrusion speed, the yield strength (YS) decrease from 285 MPa to 217 MPa, while the ductility improved greatly from 11.4% to 20%.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

All authors contributed to the study conception and design. Maochao Zhang: experimental design and operation, data analysis, writing-original draft, investigation. Chao Yang and Zhenshuai Li: scientific discussion, writing revision and provided guidance, Shuai Bao and Peiran Ye: material preparation, experimental design and scientific discussion, Yungui Chen: project administration, supervision, writing-review, conceptualization, formal analysis, methodology. All authors have reviewed the paper.

Conflicts of 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.

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References

[1] Ali Y, Qiu D, Jiang B, Pan F and Zhang M – X 2015 Current research progress in grain refinement of cast magnesium alloys: a review J. Alloys Compd. 619 639–51
[2] Yeganeh M and Mohammadi N 2018 Superhydrophobic surface of Mg alloys: a review Journal of Magnesium and Alloys 6 59–70
[3] Qin G W, Ren Y, Huang W, Li S and Pei W 2010 Grain refining mechanism of Al-containing Mg alloys with the addition of Mn–Al alloys J. Alloys Compd. 507 410–3
[4] Yang Q, Jiang R, Pan H, Song B, Jiang Z, Dai J, Wang L and Pan F 2014 Influence of different extrusion processes on mechanical properties of magnesium alloy Journal of Magnesium and Alloys 2 220–4
[5] Park K C, Kim B H, Kimura H, Park Y H and Park I M 2010 Microstructure and Corrosion Properties of Mg–xSn–5Al–1Zn (x = 0, 1, 5 and 9 mass%) Alloys Mater. Trans. 51 472–6
[6] Kondori B and Mahmudi R 2009 Impression creep characteristics of a cast Mg Alloy Metallurgical and Materials Transactions A 40 2007–15
[7] Homma T, Kunito N and Kamado S 2009 Fabrication of extraordinary high-strength magnesium alloy by hot extrusion Scr. Mater. 61 644–7
[8] Yamasaki M, Anan T, Yoshimoto S and Kawamura Y 2005 Mechanical properties of warm-extruded Mg–Zn–Gd alloy with coherent 14H long periodic stacking ordered structure precipitate Scr. Mater. 53 799–803
[9] Xu C, Zheng M Y, Xu S W, Wu K, Wang E D, Kamado S, Wang G J and Lv X Y 2012 Ultra high-strength Mg–Gd–Y–Zn–Zr alloy sheets processed by large-strain hot rolling and ageing Mater. Sci. Eng. A 547 93–8
[10] Yang Q, Jiang R, Li X, Dong H, Liu W and Pan F 2014 Microstructure and mechanical behavior of the Mg–Mn–Ce magnesium alloy sheets Journal of Magnesium and Alloys 2 8–12
[11] Salami B, Afsar A and Mazaheri A 2014 The effect of sodium silicate concentration on microstructure and corrosion properties of MAO-coated magnesium alloy AZ31 in simulated body fluid Journal of Magnesium and Alloys 2 72–7
[12] Zhu T, Fu P, Peng L, Hu X, Zhu S and Ding W 2014 Effects of Mn addition on the microstructure and mechanical properties of cast Mg–9Al–2Sn (wt%) alloy Journal of Magnesium and Alloys 2 27–35
[13] Shahzad M and Wagner L 2009 Influence of extrusion parameters on microstructure and texture developments, and their effects on mechanical properties of the magnesium alloy AZ80 Materials Science and Engineering: A 506 141–7
[14] Chen Y, Wang Q, Peng J, Zhai C and Ding W 2007 Effects of extrusion ratio on the microstructure and mechanical properties of AZ31 Mg alloy J. Mater. Process. Technol. 182 281–5
[15] Yu H, Hu K, Park S, Sun You B, Min Kim Y, Shu Y-H and Soo Park S 2013 Effects of extrusion speed on the microstructure and mechanical properties of ZK60 alloys with and without 1 wt% cerium addition Mater. Sci. Eng. A 583 25–35
[16] Su K, Deng K K, Xu F J, Nie K B, Zhang L, Zhang X and Li W J 2015 Effect of extrusion temperature on the microstructure and mechanical properties of Mg–5Al–2Ca Alloy Acta Metallurgica Sinica (English Letters) 28 1015–23
[17] Zhang A 2019 A new rare-earth-free Mg-Sn-Ca-Mn wrought alloy with ultra-high strength and good ductility Materials Science and Engineering A 754 269–74
[18] Li Z T, Qiao X G, Xu C, Kamado S, Zheng M Y and Luo A A 2019 Ultrahigh strength Mg-Al-Ca-Mn extrusion alloys with various aluminum contents J. Alloys Compd. 792 130–41
[19] Xu S W, Oh-ishi K, Kamado S, Uchida F, Homma T and Hono K 2011 High-strength extruded Mg–Al–Ca–Mn alloy Scr. Mater. 65 269–72
[20] Sasaki TT, Yamamoto K, Homma T, Kamado S and Hono K 2008 A high-strength Mg–Sn–Zn–Al alloy extruded at low temperature Scr. Mater. 59 1111–4
[21] Mahmudi R, Kabirian F and Nematollahi Z 2011 Microstructural stability and high-temperature mechanical properties of AZ91 and AZ91 + 2RE magnesium alloys Mater. Des. 32 2383–9
[22] Zhang B, Hou Y, Wang X, Wang Y and Geng L 2011 Mechanical properties, degradation performance and cytotoxicity of Mg–Zn–Ca biomedical alloys with different compositions Mater. Sci. Eng. C 31 1667–73
[23] Kim Y M, Yun C D and You B S 2011 Effect of the Ca content on the microstructural evolution of Ca-containing AZ31 cast alloys Met. Mater. Int. 17 583–6
[24] Han L, Hu H and Northwood D O H 2008 Effect of Ca additions on microstructure and microhardness of an as-cast Mg–5.0 wt% Al alloy Mater. Lett. 62 381–4
[25] Suzuki A, Suddock N, Jones J and Pollock T 2004 Structure and transition of eutectic (Mg, Al)Ca Laves phase in a die-cast Mg–Al–Ca base alloy Scr. Mater. 51 1005–10
[26] Zhang B, Wang Y, Geng L and Lu C 2012 Effects of calcium on texture and mechanical properties of hot-extruded Mg–Zn–Ca alloys Mater. Sci. Eng. A 539 56–60
[27] Suzuki A, Suddock N D, Jones J W and Pollock T M 2005 Solidification paths and eutectic intermetallic phases in Mg–Al–Ca ternary alloys Acta Mater. 53 2823–34
[28] Jiang Z, Jiang B, Yang H, Yang Q, Dai J and Pan F 2015 Influence of the Al/Ca phase on microstructure and mechanical properties of Mg–Al–Ca alloys J. Alloys Compd. 614 357–63
[29] Wang H-Y, Zhang N, Wang C and Jiang Q-C 2011 First-principles study of the generalized stacking fault energy in Mg–3Al–3Sn alloy Scr. Mater. 65 723–6
[30] Nakata T, Mezaki T, Ajima R, Xu C, Oh-ishi K, Shimizu K, Hanaki S, Sasaki T T, Hono K and Kamado S 2015 High-speed extrusion of heat-treatable Mg–Al–Ca–Mn dilute alloy Scr. Mater. 101 28–31
[31] Nakata T, Xu C, Matsumoto Y, Shimizu K, Sasaki T T, Hono K and Kamado S 2016 Optimization of Mn content for high strengths in high-speed extruded Mg–0.3Al–0.3Ca (wt%) dilute alloy Mater. Sci. Eng. A 673 443–9
[32] Zhang L, Deng K-K, Nie K-B, Xu F-J, Su K and Liang W 2015 Microstructures and mechanical properties of Mg–Al–Ca alloys affected by Ca/Al ratio, Materials Science and Engineering: A 636 279–88
[33] Suresh K, Rao K P, Prasad Y V R K, Hort N and Kainer K U 2013 Microstructure and mechanical properties of as-cast Mg–Sn–Ca alloys and effect of alloying elements Transactions of Nonferrous Metals Society of China 23 3604–10
[34] Hadadzadeh A, Mokdad F, Wells M A and Chen D L 2018 A new grain orientation spread approach to analyze the dynamic recrystallization behavior of a cast-homogenized Mg-Zn-Zr alloy using electron backscattered diffraction Mater. Sci. Eng. A 709 285–9
[35] Mamoru M, Kubota K and Kenji H 1995 New recycling process by extrusion for machined chips of AZ91 magnesium and mechanical properties of extruded bars Mater. Trans., JIM 36 1249
[36] Wang F, Zheng R, Chen J, Lyu S, Li Y, Xiao W and Ma C 2019 Significant improvement in the strength of Mg-Al-Zn-Ca–Mn extruded alloy by tailoring the initial microstructure Vacuum 161 429–33
[37] Robson J D, Henry D T and Davis B 2009 Particle effects on recrystallization in magnesium–manganese alloys: Particle-stimulated nucleation Acta Mater. 57 2739–47
[38] Barnett M R, Beer A G, Atwell D and Oudin A 2004 Influence of grain size on hot working stresses and microstructures in Mg–3Al–1Zn Mater. Des. 51 19–24
[39] Chen W, Wang X, Hu L and Wang E 2012 Fabrication of ZK60 magnesium alloy thin sheets with improved ductility by cold rolling and annealing treatment Mater. Des. 40 319–23
[40] Sanjari M, Kabir A S H, Farzadfar A, Utsunomiya H, Petrov R, Kestens L and Yue S 2013 Promotion of texture weakening in magnesium by alloying and thermomechanical processing I: rolling speed, Journal of Materials Science 49 1426–36
[41] Bhatat Singh P, Sabat R K, Kumaran S and Suwas S 2018 Effect of aluminum addition on the evolution of microstructure, crystallographic texture and mechanical properties of single phase hexagonal close packed Mg–Li alloys J. Mater. Eng. Perform. 27 864–74
[42] Panda D, Sabat R K, Suwas S, Hiwarkar V D and Sahoo S K 2019 Texture weakening in pure magnesium during grain growth Philos. Mag. 99 1362–85
[43] Qin D H, Wang M J, Sun C Y, Su Z X, Qian L Y and Sun Z H 2020 Interaction between texture evolution and dynamic recrystallization of extruded AZ80 magnesium alloy during hot deformation Mater. Sci. Eng. A 788
[44] Hall E 1951 Proc. Phys. Soc. Sect. B 64 747