Effects of semi-solid treatment by electro-magnetic induction on micro-structure evolution and mechanical properties of the Mg-2.4Y-4Nd-0.5Zr-1Ni alloys

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Abstract

The semi-solid billets of Mg-2.4Y-4Nd-0.5Zr-1Ni (WE34-1Ni) alloys are fabricated by electromagnetic induction heating semi-solid treatment at 2.05 kW and 4.10 kW from 580 °C to 625 °C. In this work, the microstructure evolution and mechanical properties of WE34-1Ni alloys are investigated, and the results reveal that with increasing semi-solid temperatures, the average grain size of the solid globules and liquid fraction at the grain boundary gradually increase while the shape factor fluctuates slightly. Compared with 2.05 kW power, the semi-solid billet with 4.10 kW power at 625 °C has more fine homogeneous grains, the lower average size of the solid globules, more liquid fraction. The semi-solid billet with 4.10 kW at 625 °C obtains ideal semi-solid spheroid structure with the solid grains surrounded by a small amount of liquid pools and the best mechanical properties of the semi-solid process parameters. Besides, the elongation as-extruded of WE34-1Ni alloys increased from 21.4 ± 0.7% to 33.2 ± 0.3% at 4.10 kW power and 625 °C via electro-magnetic induction heating semi-solid treatment.

1. Introduction

Nowadays, unconventional energy resources known as shale gas in the world are abundant but have not been fully utilized. The fundamental reason is that one of the most critical components—dissolvable fracturing balls fail to meet their requirements [1, 2]. Currently, dissolvable fracturing balls manufactured by polymer composite materials or aluminum (Al) alloys have been proved not the best choice because of the high cost and too low dissolution rate [1–4], the main reason that the fabrication materials of dissolvable fracturing balls can’t meet the requirements of the development of staged fracturing is the low degradation rate in horizontal wells [4].

Magnesium (Mg) and its alloys have a faster dissolution rate than polymer composite materials and Al alloys, and excellent mechanical properties, so it is extraordinarily possible to manufacture dissolvable fracturing balls [3]. In general, the mechanical strength of the dissolvable fracturing balls should be enough to ensure the regular operation in the whole fracturing process. And compression strength (UCS), elongation and microhardness (HV) for the dissolvable fracturing balls should exceed 360 MPa, 20% and 60 HV, respectively [2, 6, 7]. Moreover, WE series alloys balancing magnesium (Mg), yttrium (Y), neodymium (Nd), and zirconium (Zr) have excellent mechanical properties [8–11]. The values of UCS, elongation and HV of Mg-4Y-3Nd-0.5Zr (WE43) after T5 heat treatment are 490 MPa, 18% and 70 HV, respectively [12, 13]. According to relevant studies [3, 14–17] adding Ni in magnesium and its alloy not only improves the mechanical properties but also greatly promotes the dissolution rate. Tsai et al [14] considered that Mg2Ni and MgNi2 formed in Mg-Ni binary diffusion system, but MgNi2 was unstable and easy to decompose. Song et al [15] and Oh et al [16] proposed that the nickel (Ni) element at the grain boundary formed the network structure that Mg2Ni improved the dissolution rate for magnesium and its alloy. Hou et al [17] showed that the values of UCS for Mg-Al-Ni alloys by

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powder metallurgy increased with the increase of Ni element at 150 °C. Niu et al [3] held that the values of UCS and HV for Mg-4Zn-xNi alloys increased with the growth of Ni element and the second phase (Mg2Ni).

At present, the dissolvable fracturing balls are mainly manufactured by powder metallurgy for metal and extrusion granulation for polymer composite materials. Their disadvantages on above two processing methods are complicated preparation process and high cost [17–19]. Besides, the dissolvable fracturing balls manufactured by extruding with Mg-xNi alloys have many problems, such as low elongation and low service time. There are a large amount fiber tissues in as-extruded Mg-xNi alloys [7]. However, the fiber tissues can transform into spheroid solid grains entrapped with a little amount of liquid pool via the semi-solid treatment [20]. In contemporary, semi-solid treatments mainly adopt isothermal heating and electro-magnetic induction heating to manufacture Mg alloys semi-solid billets [21–23]. The semi-solid temperatures and holding time play an enormously important role in forming process and mechanical properties of semi-solid billet [24]. Liu et al [25] believed with the increase of the semi-solid temperatures and the holding time, the grain size of the solid globules, liquid fraction and shape factor enhanced when Mg-2Zn-0.5Y alloys were manufactured the semi-solid billets by isothermal treatment. Sun et al [26] considered that the AZ80-0.2Y alloys were manufactured semi-solid billets by electromagnetic induction heating with tiny and uniform solid particles. Nowadays, most of semi-solid billets for Mg alloys are studies about the microstructure evolution of AZ series magnesium alloys by isothermal treatment [24–26]. However, there are few semi-solid studies on microstructure evolution and mechanical properties of rare earth Mg alloys by electro-magnetic induction heating.

Yu et al [27] believed that adding 1% Nd in Mg-11.5Gd-4.5Y-0.3Zr could promote the second phase precipitation and grain refinement to improve the mechanical properties. Zhang et al [28] deemed that the elongation of in AM60 via adding 0.9% Nd increased by 250% compared with that of AM60. The elongation of WE43 alloys couldn’t meet the mechanical properties of the dissolvable fracturing balls. While Nd and Ni elements could improve the compression strength and elongation of Mg alloy according to relevant studies [17, 27, 28]. Therefore, the quick-solution Mg-2.4Y-4Nd-0.5Zr-1Ni (WE34-1Ni) alloys are employed in this work. The semi-solid billets of WE34-1Ni alloys are manufactured semi-solid billets by electromagnetic induction heating under different powers (2.05 kW and 4.10 kW) and different semi-solid temperatures (from 580 °C to 625 °C) to explore the microstructure evolution and mechanical properties of rare earth Mg alloys.

### 2. Experimental

#### 2.1. Raw materials

WE34-1Ni alloys provided by Litmat Technology Chengdu Co., Ltd. in this work was extruded into a rod with a diameter of 160 mm and a length of 1000 mm. Actual compositions of WE34-1Ni alloys were tested by an inductively coupled plasma-atomic emission spectrometer (ICP-AES) as shown in table 1.

#### 2.2. Thermal analysis

WE34-1Ni alloys were machined into a thin slice with a diameter of 5 mm and a thickness of 0.3 mm (approximately 20 mg). Then differential scanning calorimetry (DSC) was used to estimate the semi-solid temperatures of WE34–1Ni alloys. It was put into a crucible and heated to 650 °C at a speed of 10 °C min⁻¹ under the protection of argon.

#### 2.3. Electro-magnetic induction heating process

The as-extruded WE34-1Ni alloys were machined into many samples with a diameter of 30 mm and a height of 33 mm. Furthermore, the hole with a diameter of 6 mm and a height of 10 mm in the center of the sample was used to accurately measure temperature by thermocouple. The schematic diagram of electro-magnetic induction heating equipment (SWS-65A) shown in figure 1 was used to heat the samples. The experimental parameters were at 2.05 kW and 4.10 kW powers with the heating rate of 3 °C s⁻¹ and 7 °C s⁻¹, respectively. The information on semi-solid temperatures and heating time at different powers were shown in table 2.
2.4. Microstructure characterization

The as-extruded WE34-1Ni samples after electro-magnetic induction heating were ground with 400#, 800#, 1000#, 1500#, 2000# and 2500# waterproof abrasive paper, mechanically polished and etched with 4 vol% acid-picric reagent (4.2 g picric acid, 100 ml alcohol, 10 ml acetic acid and 10 ml deionized water) for 4–8 s. The microstructure and the phase compositions of the WE34–1Ni alloys were observed by optical metallographic (OM) and x-ray diffraction (XRD) analysis, respectively. The WE34–Ni samples without erosion were observed to survey the microstructure and analyze the chemical composition of the micro-area by scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS), respectively.

The average grain size of solid particles, the liquid fraction and the shape factor were measured by Image-Pro Plus 6.0 software by taking 200 times OM images with different powers and different semi-solid temperatures. The samples at the same semi-solid state was measured for at least three times, and the average value was taken as the experimental result. The liquid fraction was measured mainly by the liquid films between solid particles by the metallographic method. In this work, the average grain size ($D_{eq}$) of solid particles and the shape factor ($SF$) were calculated by the following equations:\cite{29–31}

\[
D_{eq} = \frac{1}{n} \sum_{i=1}^{n} \sqrt{4A_{n}/\pi}
\]

\[
SF = \frac{1}{n} \sum_{i=1}^{n} \frac{4A_{n} \pi}{P_{n}^{2}}
\]

where $n$, $A_{n}$ and $P_{n}$ are the amounts, area, and perimeter of solid particles, respectively.

2.5. Mechanical properties

The WE34-1Ni alloys after electro-magnetic induction heating were machined into 5 mm in diameter and 7.5 mm in length. In order to explore the compression strength at different conditions, the compression tests were carried out on a universal testing machine (MTS-CMT5105) with the crosshead speed of 0.45 mm min$^{-1}$. The

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**Figure 1.** Schematic diagram of electromagnetic induction treatment equipment Among them: 1. cooling tank; 2. baffle board; 3. heating coil; 4. sample; 5. thermocouple temperature bulb point; 6. temperature probe.

**Table 2.** Semi-solid temperatures and heating time at different powers.

| Powers/kW | Sample numbers | Semi-solid temperatures/°C | Time/s |
|-----------|----------------|----------------------------|--------|
| 2.05      | 1              | 580                        | 165    |
|           | 2              | 595                        | 174    |
|           | 3              | 610                        | 189    |
|           | 4              | 625                        | 201    |
| 4.10      | 5              | 580                        | 65     |
|           | 6              | 595                        | 70     |
|           | 7              | 610                        | 79     |
|           | 8              | 625                        | 90     |
The microhardness of WE34-1Ni alloys at different conditions was tested by Vickers hardness tester (HBRV-187.5) at a load of 200 g with a dwell time of 15 s. Thus, seven microhardness (HV) values were measured for every sample, but the highest and latest values were removed to reduce the error. The average value of the five microhardness values was taken as the final micro-hardness value.

3. Results and discussion

3.1. The microstructure of as-extruded material

Figure 2 shows the optical micrograph of as-extruded WE34-1Ni alloys. It is observed that the as-extruded WE34-1Ni alloys mainly composed of small, irregular \( \alpha \)-Mg grains with discontinuously rod-shaped eutectics at grain boundaries and a small number of circular second phases inside the grain [12]. The initial average grain size of as-extruded WE34-1Ni alloys is measured as about 8 \( \pm \) 1.05 \( \mu \)m. The phases of as-extruded WE34-1Ni alloys mainly consists of Mg\(_2\)Ni, \( \alpha \)-Zr, Mg\(_{12}\)Nd, and Mg\(_{24}\)Y\(_5\), as shown in figure 7.

3.2. Calorimetric results analysis

Figure 3 reveals the DSC curve of as-extruded WE34-1Ni alloys. It indicates that the melting temperatures of the second phase, the solidus and liquidus temperatures of the \( \alpha \)-Mg grains are 516 \( ^\circ \)C, 592 \( ^\circ \)C and 631 \( ^\circ \)C, respectively. The semi-solid temperatures are determined as 580 \( ^\circ \)C, 595 \( ^\circ \)C, 610 \( ^\circ \)C and 625 \( ^\circ \)C at 2.05 kW and 4.10 kW to manufacture semi-solid billets.

Figure 2. OM image of as-extruded WE34-1Ni alloys.

Figure 3. DSC curve of as-extruded WE34-1Ni alloys.
3.3. The evolution of semi-solid microstructure

Figures 4 and 5 demonstrate the evolution of the semi-solid microstructure for as-extruded WE34-1Ni alloys via electro-magnetic induction semi-solid treatment. With the increase of semi-solid temperatures, the irregular $\alpha$-Mg grains are replaced by homogeneous and spherical solid particles. Moreover, there is a very common phenomenon that a small number of large grains surrounded by some small grains. The reason on phenomenon is that the Ostwald ripening mechanism plays an essential role and promotes the growth of some small grains after electro-magnetic induction semi-solid treatment \[19–21\]. When recrystallizing, there were many large and small grains at the grain boundary. The tiny particles would gradually dissolve and reprecipitate on the surface of the larger particles due to the more significant curvature and higher energy. While the large particles further grew up. Hence, there are the big grains surrounded by some small grains due to inadequate heating.

Figure 4a represents the microstructure of as-extruded WE34-1Ni alloys heated 580 °C at 2.05 kW through electro-magnetic induction treatment. Most of the $\alpha$-Mg grains stick together and form only a small amount of liquid films. Besides, it can be seen that solid grains are heterogeneous and coarsened compared with that of as-extruded WE34-1Ni alloys. With the semi-solid temperature rising to 595 °C, there are a few liquid droplets inside the grain as shown in figure 4b. It may be that a small amount of low melting second phases including Ni element inside the $\alpha$-Mg grains precipitated \[32–34\]. As could be seen similar results that Haghdadi et al\[33\] considered in A356 alloy, the original liquid phase derived from the melting of low melting point phases at grain boundaries. Figure 4c shows a large number of liquid droplets distribute evenly inside the grain at 610 °C, and the average grain size of solid grains grows up to 22.9 ± 0.11 \(\mu\)m. The $\alpha$-Mg grains are almost homogeneous and low globular degree in figure 4d. In the meantime, adjacent grains are segregated by liquid films at the grain boundary.

When the as-extruded WE34-1Ni sample heats to 580 °C at 4.10 kW. It costs 65 s that heating efficiency increased by 153.8% compared with that of 2.05 kW in table 2. But, the average size grains of the solid particle at 580 °C (4.10 kW) are smaller about 16.8%. It may be that the solute elements can’t enough time to disperse as a result of the high heating rate. The similar conclusion could be got that the average grain size of solid particle at higher power was smaller and more uniform in AZ80-0.2Y alloy by electro-magnetic induction treatment \[26\]. When the semi-solid temperature increases to 595 °C (figure 5b) and 610 °C (figure 5c), the average grain size of solid particle rises and liquid films thicken compared with that of 2.05 kW power in figures 4c and (d). It’s a surprise finding that the phenomenon of figure 5b corresponds to figures 4c and 5c corresponds to figure 4d. The reason on phenomenon may be that higher power leads to the advance of microstructure evolution. While
the liquid fraction and the average grain size solid particle augment by 2.3% and 9.3% at 4.10 kW (610 °C) compared with that of 2.05 kW. Continuing to increase semi-solid temperature to 625 °C (figure 5d), it can be seen that many solid grains are isolated by a large number of liquid films or pools, and a few droplets appear inside the solid grains. What’s more, the liquid fraction reaches the peak about 0.296. This is because with the higher semi-solid temperatures, more and more the second phases including Y, Ni, and Nd elements melt and form the liquid films, which results in rising the length and width of the liquid pools [34, 35].

Toward a detailed survey on microstructure evolution, relationship between the average grain sizes and the semi-solid temperatures from 580 °C to 625 °C at 2.05 kW and 4.10 kW powers is shown in figure 6a. The average sizes of solid grains gradually increase with the increase of semi-solid temperatures. The similar results could be found that increasing the isothermal temperatures led to larger grain size of the solid particle in the Mg-Y-RE-Zr alloys on the basis of Moradjoy et al’s report [36]. It is clearly that at the same semisolid temperatures the average grain sizes of solid grains at 4.10 kW power is smaller than that of 2.05 kW power. Besides, solid grains at 4.10 kW power is more homogeneous according to figures 4 and 5. The minimum and the maximum average grain size of solid grains are 16 ± 0.02 μm at 4.10 kW power and 28 ± 0.11 μm at 2.05 kW, respectively. Further, it could be seen that the grain sizes of solid grains slightly changed in the work via electro-magnetic induction treatment. While, the result is opposite compared with the other results through isothermal treatment. Fan et al [21] considered that the grain sizes of solid grains massively varied from 49 ± 1 μm to 102 ± 2 μm at 570 °C–590 °C with isothermal time 10–60 min for AZ80-0.2Y-0.15Ca alloys. The reason why the average grain sizes of semi-solid billet by isothermal treatment is bigger is that the slow heating speed and long holding time lead to grains growth. On the contrary, the main reason that the grain sizes of solid grains slightly changed by electro-magnetic induction is that grain growth is difficult due to the high heating efficiency.

Figure 6b demonstrates the relationship between the liquid fraction and the semi-solid temperatures at different powers from 580 °C to 625 °C. In general, the effects of holding time and the semi-solid temperatures were significant to improve the liquid fraction in isothermal treatment according to the results of Fan et al [21] and Moradjoy et al [36]. However, the semi-solid temperatures played a more distinctly role in the liquid fraction via the electro-magnetic induction treatment. As figure 6b is described, the liquid fraction slowly varies from 0.233 to 0.276 at 2.05 kW and from 0.259 to 0.296 at 4.10 kW, respectively. It is extraordinary obvious that higher heating rate (higher power) has more liquid fraction. At 2.05 kW power, the liquid fraction slowly
increases with the semi-solid temperatures from 580 °C to 595 °C and rapidly boosts from 595 °C to 625 °C. While at 4.10 kW power, the liquid fraction increases slowly from 580 to 610 °C and rapidly adds from 610 °C to 625 °C. The tendency of liquid fraction in the present work was similar finds for AZ80–0.2Y alloys [26].

Figure 6c exhibits the relationship between the shape factor and the semi-solid temperatures at different powers. The shape factor gently varies from 0.738 to 0.763 at different powers and semi-solid temperatures. The higher semi-solid temperatures result in the increase of shape factor. However, it’s difficult for the elements to diffuse due to low heating time via electro-magnetic induction treatment. The shape factor of α-Mg grains slowly decreases from 580 °C to 595 °C at 4.10 kW. The grain growth and coarsening mechanism play a major
role. Several small grains merge into a large irregular grain at 595 °C. Hence, the shape factor comes out a rapid downward trend. With the semi-solid temperatures continuing from 695 °C to 625 °C at 4.10 kW, the shape factor gradually increases. It may be that the spheroidizing mechanism and the number of continuous liquid film play a vital role in forming globular grains. So, the shape factor of grains increases, and the largest shape factor is obtained about 0.763 at 4.10 kW with semi-solid temperatures of 625 °C.

There are three indexes to evaluate the forming performance of semi-solid billet: the average grain size, the liquid fraction and the shape factor. The liquid fraction is mainly controlled by the semi-solid temperatures, while the average grain size and shape factor are mainly related to the pretreatment, semi-solid temperatures and holding time. The average grain size, liquid fraction and shape factor of WE34-1Ni alloys are shown in Table 3. The smaller grain size and the higher liquid fraction is obtained at 4.10 kW compared with that of 2.05 kW power. The semi-solid billet of WE34-1Ni alloys at 4.10 kW and 625 °C has better semi-solid forming performance via electro-magnetic induction treatment. Besides, the average grain size, liquid fraction and shape factor of WE34-Ni are 23 ± 1.29 μm, 0.296 and 0.763, respectively. The smaller solid particles, more liquid phase and more round grains are beneficial to improving thixo-forming properties.

3.4. Semi-solid microstructure analysis

Figure 7 shows the phases composition of WE34-1Ni alloys in extrusion (RT), at 2.05 kW and 4.10 kW power with the semi-solid temperature 625 °C. WE34-1Ni alloys mainly consists of Mg2Ni, α-Zr, Mg12Nd, and Mg24Y5. However, the content of Mg24Y5, Mg12Nd and Mg2Ni at 2.05 kW and 4.10 kW power with the semi-solid temperature 625 °C increases compared with that of RT. It may be Y, Ni and Nd elements heated via electro-magnetic induction treatment melt and precipitate at the grain boundary. It’s an interesting phenomenon that at the same semi-solid temperature, the content of the second phase at 4.10 kW power increases more than that at 2.05 kW power. More liquid films include more second phases at 4.10 kW power than that of 2.05 kW power. Therefore, the content of the second phase at 4.10 power is the highest than that of 2.05 kW and RT.

To further verify element distribution after electro-magnetic induction treatment, figures 8 and 9 demonstrate the second phase morphologies and element distributions characterized of WE34-1Ni alloys at 4.10 kW with the semi-solid temperature of 625 °C. The liquid films are located at the fine and homogeneous α-
Figure 8. (a), (b) SEM images of WE34-1Ni alloy after electromagnetic induction heating at 4.10 kW power and 625 °C, and (c), (d), (e), (f), (g) EDS mapping of Mg, Nd, Y, Ni and Zr, respectively.
Mg grain boundary, but small droplets gather in one place inside the grain in figure 8a. What’s more, the white block at the grain boundary mainly contains Nd and Y elements, while the gray area contains Ni elements in figure 8b. Figure 9a represents that the eutectic phase at grain boundary primarily contains Mg and Y with a small amount of Nd. What’s more, the Mg/Y ratio of the second bulk phase is 69.07:26.63 in figure 9b. In ‘solution-treated WE43’ that was solution-treated at 525 °C for 8 h, followed by water quenching and ‘peak-aged WE43’ that was placed into an oil bath at 250 °C for 16 h to reach the peak hardness, Chu et al. [38] believed the rectangular shape particles were Mg24Y5. Y element forms mainly Mg24Y5 in magnesium alloy in figure 7. Hence, the eutectic phase is Mg24Y5 in this work. In figure 9c, the microscopic region shows that Mg mainly distributes inside the grain. However, the main solute elements including Y, Nd and Ni gather at the grain boundary. The same result on Y, Nd and Ni elements distribution could be obtained in figure 8. It was consistent that Ni mainly forms Mg2Ni at grain boundary according to the results of Song et al. [15] and Oh et al. [16] The main solute elements including Y and Nd melt and gradually spread to the grain boundary. While, parts of the elements inside the grain form many fine and uniform droplets in the center of the grain. What’s more, the Zr element is not found due to the low content of Zr and the appearance of α-Zr [10].

3.5. Mechanical property analysis
The values of yield strength (YS), elongations, uniaxial compressive strength (UCS) and microhardness (HV) of the WE34-1Ni alloys, and the relationship between yield strength (YS) and average grain size are shown in figure 10 and table 4. Compared with that of the as-extruded WE34-1Ni alloys, both of the yield strength and ultimate strength of the semi-solid billets are reduced, while the elongation is significantly enhanced after the electro-magnetic induction treatment. Besides, the semi-solid billets processed with higher power (4.10 kW) possessed higher YS and UCS at each semi-solid temperature. At 2.05 kW power, the elongations of WE34-1Ni alloys originally decrease, then increase from 580 °C to 625 °C, reaching the minimum value 30.2 ± 0.2% at 595 °C. However, at 4.10 power the elongations slightly float in the mean value of 32.8% from 580 °C to 625 °C, reaching the minimum value 30.4 ± 0.5% at 610 °C. The average elongations of WE34-1Ni alloys boost from 31.8% at 2.05 kW to 32.8% at 4.10 kW via electro-magnetic induction treatment. The values of yield strength (YS) and uniaxial compressive strength (UCS) present a trend of slow decline at 2.05 kW from 580 °C to 625 °C in the figures 10 (c) and (e). However, at 4.10 kW power, the values of yield strength (YS) remain almost at 146 MPa, and the values of uniaxial compressive strength (UCS) in the beginning decreases, then increases from 580 °C to 625 °C with the minimum value about 399 ± 6.5 at 610 °C. At 2.05 kW and 4.10 kW power, the values of microhardness (HV) present stable condition in figure 10f. However, it is undoubtedly apparent that not only
Figure 10. The yield strength (YS), uniaxial compressive strength (UCS), elongation and micro-hardness (HV) of WE34-1Ni alloys at different powers and temperatures: (a) engineering tensile stress-strain curves at 2.05 kW power and (b) at 4.10 kW power; (c) yield strength (YS) values and (d) relationship between yield strength (YS) and average grain size, $d^{-1/2}/(\mu m)^{-1/2}$; (e) uniaxial compressive strength (UCS) values and (f) micro-hardness (HV) values.

Table 4. Mechanical properties at different powers and semi-solid temperatures.

| Powers (kW) | Semi-solid temperatures (°C) | YS (MPa) ± SD | UTS (MPa) ± SD | Elongation (%) ± SD | Microhardness (HV) ± SD |
|------------|------------------------------|---------------|----------------|---------------------|------------------------|
| Unprocessed| /                            | 240 ± 4.5     | 473 ± 9.2      | 21.4 ± 0.7          | 89 ± 3.20              |
| 2.05       | 580                          | 145 ± 3.5     | 412 ± 6.8      | 31.2 ± 0.5          | 62 ± 0.61              |
|            | 595                          | 143 ± 2.4     | 408 ± 6.5      | 30.2 ± 0.2          | 61 ± 0.96              |
|            | 610                          | 138 ± 3.6     | 395 ± 4.6      | 32.8 ± 0.2          | 61 ± 2.59              |
|            | 625                          | 133 ± 4.2     | 386 ± 8.1      | 32.9 ± 0.7          | 60 ± 1.35              |
| 4.10       | 580                          | 150 ± 4.4     | 415 ± 7.2      | 33.1 ± 0.6          | 67 ± 0.62              |
|            | 595                          | 148 ± 5.1     | 412 ± 9.5      | 34.6 ± 0.8          | 65 ± 2.01              |
|            | 610                          | 142 ± 4.6     | 399 ± 6.5      | 30.4 ± 0.5          | 64 ± 1.41              |
|            | 625                          | 144 ± 3.5     | 409 ± 3.8      | 33.2 ± 0.3          | 64 ± 2.25              |
the values of uniaxial compressive strength (UCS) at 4.10 kW power is greater than that of 2.05 kW power, but also the microhardness (HV) presents the same situation.

Yu et al [39] considered that the average grain size played a great influence on the yield strength (YS) of materials according to the Hall-Petch equation:

$$\sigma_y = \sigma_0 + k d^{1/2}$$  \hspace{1cm} (3)

where $\sigma_y$ was the yield strength, $d$ was the average grain size, $\sigma_0$ and $k$ are constants relating to the material. From figure 10d, curves for YS of the semi-solid billets processed at different power as a function of grain size were fitted to the experimental values, indicating that average grain size of these billets could significantly affect their YS. Thus, the materials with smaller average grain size has higher yield strength (YS). In the semi-solid compression test of AZ80M alloy, Tang et al [40] believed that the deformation of solid particles played a leading role at 400 °C (the semi-solid temperature was not reached) with high uniaxial compressive strength (UCS) and low elongation. However, the liquid phase increased the movement of solid particles (it reached the semi-solid temperature) with low uniaxial compressive strength (UCS) and high elongation at 470 °C. Therefore, as-extruded WE34-1Ni alloys have high compression strength and the poor elongation, which is mainly plastic deformation of solid particles as a result of irregular $\alpha$-Mg grains in figure 2. In this work, the liquid fraction and shape factor of solid particles enhance the filling ability of solid particles after electro-magnetic induction treatment. WE34-1Ni alloys via electro-magnetic induction treatment has lower uniaxial compressive strength (UCS) and higher elongation compared with that of as-extruded WE34-1Ni alloys.

According to other studies [2, 6, 7], the mechanical properties of the dissolvable fracturing balls are generally as follows: the values of UCS, elongation and HV are 360 MPa, 20% and 60 HV, respectively. What’s more, the optimization of the mechanical properties of WE34-1Ni by electro-magnetic induction is obtained at 4.10 kW power with the semi-solid temperatures 625 °C. The uniaxial compressive strength (UCS), elongation and microhardness (HV) are $144 \pm 3.5$ MPa, $409 \pm 5.8$ MPa, $33.2 \pm 0.4\%$ and $64 \pm 5.8$ HV, respectively. Therefore, it’s also satisfied the mechanical properties of the dissolvable fracturing balls.

4. Conclusion

(1) With the increase of semi-solid temperatures at the same power, liquid fraction, the average grain size and shape factor of solid particles gradually increase after electro-magnetic induction treatment. Compared with that of 2.05 kW, liquid fraction, the average grain size and shape factor of solid particles are higher at 4.10 kW. The appropriate semi-solid process parameter is at 4.10 kW with the semi-solid temperature 625 °C.

(2) The phases composition of WE34-1Ni alloys are $\text{Mg}_2\text{Ni}$, $\text{Mg}_{12}\text{Nd}$ and $\text{Mg}_{24}\text{Y}_5$, and $\alpha$-Zr. The content of phases for $\text{Mg}_2\text{Y}_5$, $\text{Mg}_{12}\text{Nd}$, and $\text{Mg}_2\text{Ni}$ increases after electro-magnetic induction treatment.

(3) The optimized mechanical properties of the WE34-1Ni alloys by electro-magnetic induction treatment is obtained at 4.10 kW with the semi-solid temperatures of 625 °C. And the values of the yield strength (YS), the uniaxial compressive strength (UCS), elongation and microhardness (HV) are $144 \pm 3.5$ MPa, $409 \pm 5.8$ MPa, $33.2 \pm 0.4\%$ and $64 \pm 5.8$ HV, respectively.

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