

Article

The Effect of Y Content on the Strength and Toughness of Mg-Y-Zn Alloys

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Abstract

The microstructure and properties of Mg-Y-Zn as-cast alloys with the Y/Zn ratio of approximately 1.3 (wt%) and different Y contents were studied, including an analysis of the main factors and mechanisms affecting their toughness and ductility, such as dendritic morphology, mass fraction of different compound phases, and degree of solid solution. The results showed that the alloys with Y contents ranging from 3.5% to 5% exhibit high toughness. The 4.4% alloy has the best comprehensive mechanical properties with the UTS, YS, EL, and tensile deformation work of 188.9 MPa, 124.4 MPa, 5.9%, and 0.50 MJ/m², respectively. It is beneficial for achieving higher strength and toughness by maintaining the content of the W phase and the combined content of the W phase and LPSO phase at approximately 5.8 wt% and 28.8 wt%, respectively.

Keywords: Mg-Y-Zn alloy; Strength; Toughness; Y/Zn; W phase; LPSO phase



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1. Introduction

Magnesium alloys have a wide range of application scenarios in aerospace, 3C products, and transportation fields. Mg-Y-Zn alloys and their modified alloys have become the first choice for the composition design of high-strength magnesium alloys due to their abundance of reinforcing phases [1–3]. In the first study on Mg-Y-Zn alloy, carried out in 1982, Padezhnova et al. [4] found that there are three equilibrium phases in Mg-Y-Zn alloys: Mg₃YZn₆ (icosahedral quasi-crystalline structure I phase), Mg₃Y₂Zn₃ (face-centered cubic structure W phase), and Mg₁₂YZn (long-periodic stacking-ordered structure LPSO phase). With the gradual increase in the Y/Zn ratio, the I phase, W phase, and LPSO phase will appear, in turn, in Mg-Y-Zn alloys. By experiments and ternary phase diagram calculation, Luo et al. [5] found that the combination type of the second phase is determined by the Y/Zn atomic ratio; both the W phase and LPSO phase coexist when the Y/Zn atomic ratio is 0.33–1.32, while only the LPSO phase exists when the ratio is greater than 1.32. Convert the atomic ratio to the mass ratio. The critical values corresponding to the W phase and LPSO phase coexist, and the W phase disappears at 0.44 and 1.79, respectively. More studies have shown that the quasicrystalline phase (I phase) has a better co-lattice relationship with the Mg matrix, which can improve the toughness of the alloys; the W phase has a non-co-lattice relationship with the matrix, which is mainly distributed at grain boundaries and is unfavorable to the mechanical properties when its volume fraction is too high, while the LPSO can be used as a reinforcing phase of the alloy to improve the toughness of the

alloy, due to the fact that its hardness is significantly higher than that of the Mg matrix [6–9]. When the LPSO phase and the W phase coexist, the LPSO phase improves the strength by fine-grain strengthening, grain refinement, and torsion strengthening, while the W phase acts as the second phase to hinder dislocation movement, but the W phase will offset the contribution of the LPSO phase to the toughness [10,11]. Hu et al. [12] kept the total mass of Y and Zn alloying elements, added and regulated the Y/Zn ratio, and found the strengthening effect of the second-phase combination rank: $W + LPSO > LPSO > I + W > I$; the as-cast alloy has more strength and toughness advantages when a small amount of the W phase coexists with a larger amount of LPSO phases, and the Mg-Y-Zn alloy with 4.8Y + 2.6Zn (wt%) was the best in terms of toughness. Numerous studies have shown [13–16] that the Y/Zn mass ratio of 1–2 can obtain a stronger toughness advantage alloy with a small amount of W phases and a dominant proportion of LPSO phases. However, there are few studies on the effects of toughness under changes to the total mass percentage of the two phases, while maintaining a certain mass ratio of the W phase and the LPSO phase. In this paper, the effect of Y content on the total mass fraction of the Y-containing phase, the phase structure, phase distribution, strength and toughness, and the effect mechanism will be studied for the Mg-Y-Zn as-cast alloys with a Y/Zn ratio of 1.3 or so.

2. Materials and Methods

Pure Mg (99.97% wt%), pure Zn (99.98% wt%), and Mg-30Y (wt%) intermediate alloys were used as raw materials to prepare 9 kinds of Mg-Y-Zn as-cast alloys with different Y contents and an expected Y/Zn mass ratio of 1.3, and the designed chemical compositions are shown in Table 1. The melting experiments were carried out in a well-type resistance furnace with a low-carbon steel crucible, in which pure Zn and pure Mg were placed and then heated and melted in a mixed protective gas atmosphere of 99% CO₂ and 1% SF₆. The melt was heated up to 720 °C and slagged, then heated up to 750 °C and held for 10 min, and then the Mg-30Y master alloy was introduced and stirred thoroughly. The melt was heated up to 780 °C and the refining agent (MgCl₂: 45%; KCl: 31%; NaCl: 16%; BaCl₂: 8%) for purifying was added, stirred, and held for 20 min, and then it was cooled down to 720 °C and held for 10 min, and then it was slagged and cast with a casting temperature that was ensured to be above 710 °C.

Table 1. The actual measured composition.

Number	Samples	Y/wt%	Zn/wt%	Y/Zn
1	1.50Y-1.15Zn	2.02	1.47	1.37
2	2.50Y-1.92Zn	2.99	2.41	1.24
3	3.50Y-2.69Zn	3.54	2.65	1.33
4	4.50Y-3.46Zn	4.38	3.39	1.29
5	5.50Y-4.23 Zn	5.54	4.67	1.18
6	6.50Y-5Zn	6.41	5.14	1.25
7	8.0Y-6.15Zn	7.96	5.60	1.42
8	9.5Y-7.31Zn	9.11	6.72	1.36
9	11.0Y-8.46Zn	10.66	7.69	1.39

The chemical compositional tests were carried out by ICP-OES (SPECTRO FD564, SPECTRO Analytical Instruments GmbH, Kleve, Germany), with the actual measured compositions shown in Table 1. The phases present in the alloys were identified using a D/MAX-2500PC (Rigaku, Kyoto, Japan) X-ray diffractometer (XRD) with a scanning speed of 4°/min and a scanning angle of 10°–90°. Microstructural characterization and analysis were performed using a ZEISS-Axiolab 5 (Carl Zeiss AG, Auerkheim, Germany) optical microscope, JEOL JSM-7800F FEG SEM (Japan Electron Optics Laboratory, Tokyo,

Japan) electron microscope, and FEI Talos F200X (Thermo Fisher, Waltham, MA, USA) transmission electron microscope. The mechanical properties were tested by a New Sansi CMT-5105 (New Sansi Enterprise Development Co., Ltd., Shanghai, China) testing machine at a tensile speed of 1 mm/min at room temperature.

3. Results and Discussion

3.1. Mechanical Properties of Alloys

The tensile mechanical properties of various cast alloys were obtained from three specimens, as shown in Table 2 and Figure 1. The alloys were renamed according to the measured compositional values, and the Y/Zn mass ratio of different alloys in Table 1 was basically maintained at about 1.3.

Table 2. Mechanical properties of each alloy.

Number	Alloy	UTS (MPa)	YS (MPa)	EL (%)
1	2Y	151.7	92.4	5.8
2	3Y	158.3	112.3	4.3
3	3.5Y	173.3	118.8	5.4
4	4.4Y	188.9	124.4	5.9
5	5.5Y	183.2	130.0	4.5
6	6.4Y	189.3	134.5	4.2
7	8Y	183.6	136.1	3.1
8	9.1Y	162.4	135.5	2.0
9	10.7Y	163.8	132.9	1.9

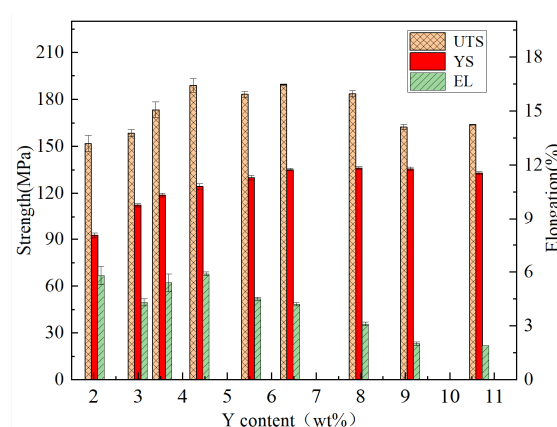


Figure 1. Mechanical properties of the alloys with different Y contents and Y/Zn of 1.3.

The trend of the mechanical properties of alloys with a Y/Zn mass ratio of around 1.3, varying with the Y mass percentage, is shown in Figure 1. The UTS slightly increases when the Y content is at a low level of 2 wt% to 3 wt%, and the increase in UTS is significant when the Y content ranges from 3 wt% to 4.4 wt%, while the UTS remains at a relatively stable level without further increase when the Y content reaches above 6.5 wt% and decreases markedly when it is over 8 wt%. The YS of the alloys gradually increased as the Y mass fraction increased from 2% to 6.5%, and stabilized at a high level of value beyond 6.5 wt% without further increase. The EL (elongation before tensile breaking) of the alloys is 5.8% at 2% Y, decreasing to 4.3% at 3 wt% Y. Thereafter, as the Y content increases to 4.4 wt%, the EL gradually increases to 5.9%, reaching the level of the 2Y alloys. After the Y content is greater than 4.4 wt%, continuing to increase the Y content will result in the EL decreasing progressively until it drops to 1.9% at 10.7 wt% Y. The overall mechanical properties of 4.4Y

alloy reach the optimized combination with UTS, YS, and EL of 188.9 MPa, 124.4 MPa, and 5.9%, respectively.

In order to characterize the toughness of the alloy, the integral value of the flow stress during the tensile deformation process, named tensile deformation work, is introduced, as shown in Figure 2. The tensile deformation work values of alloys with different Y content were shown in Figure 3. The average value of deformation work of the three samples is close to 0.34 MJ/m² at 2 wt% Y content, and decreases to 0.27 MJ/m² at 3 wt% Y. Thereafter, the deformation work gradually increases with the increase in Y content, and reaches a maximum value of 0.50 MJ/m² at 4.4% Y. The deformation work continues to decrease with the increase in Y content, and stays at the level of 0.09 MJ/m² until Y content exceeds 9.1 wt% Y.

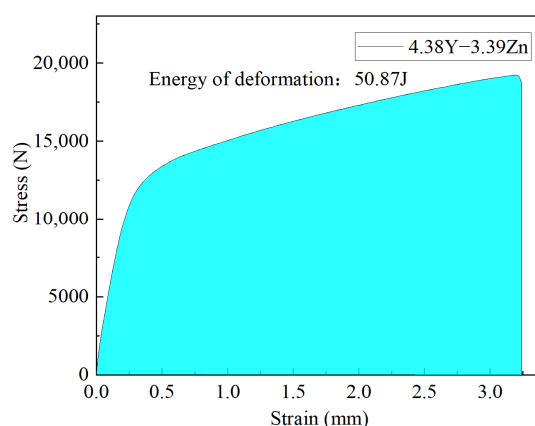


Figure 2. Deformation work during stretching of 4.4Y alloy.

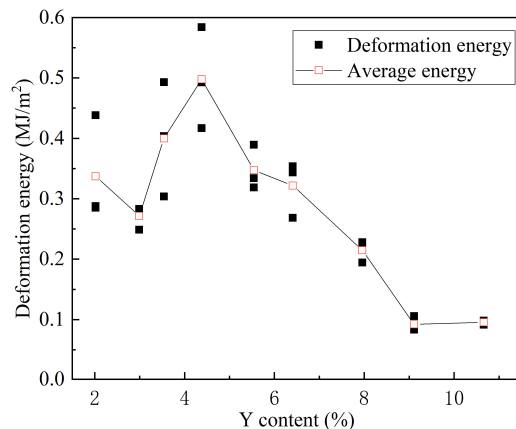


Figure 3. Tensile Deformation Work changes with Y content (wt%).

3.2. Microstructural Analysis

The metallographic structure of the dendritic structure of the alloy with different Y contents and a Y/Zn ratio of 1.3 is shown in Figure 4. The as-cast alloy mainly consists of the α -Mg matrix in the dendritic structure and the second phase of the inter-dendritic compound particles. As is well known to all, the spacing of secondary dendrites is an important factor affecting the strength of cast alloys. When the Y content is as low as 2 wt%, the dendritic structure is undeveloped and the compound phase is distributed uniformly with fine particles. The primary dendritic arms in the 3% Y alloy have a large difference in size, and the secondary dendrites are undeveloped. When the Y content increases to 3.5 wt%, the secondary dendrites of the alloy are more developed, and the compounds mainly exist in the interspaces of the secondary dendrites and are thus more uniformly distributed. For the 4.4% Y alloy, the spacing of the secondary dendrites is further reduced,

resulting in a more diffuse distribution of the compounds in the interspaces of the secondary dendrites. With the further increase in Y content, the degree of the further reduction in the secondary dendrite spacing is limited, and the more and more second-phase particles appear outside the secondary dendrite spacing; their particle sizes are mainly distributed in the range of 2–10 μm , and second-phase particles with a size larger than 20 μm appear when the Y content exceeds 9.1%. However, the development degree of secondary dendrites in the alloys does not change regularly with the Y content increase, and 4.4Y alloy with well-developed secondary dendrites and small inter-dendritic spacings is beneficial for enhancing the mechanical properties.

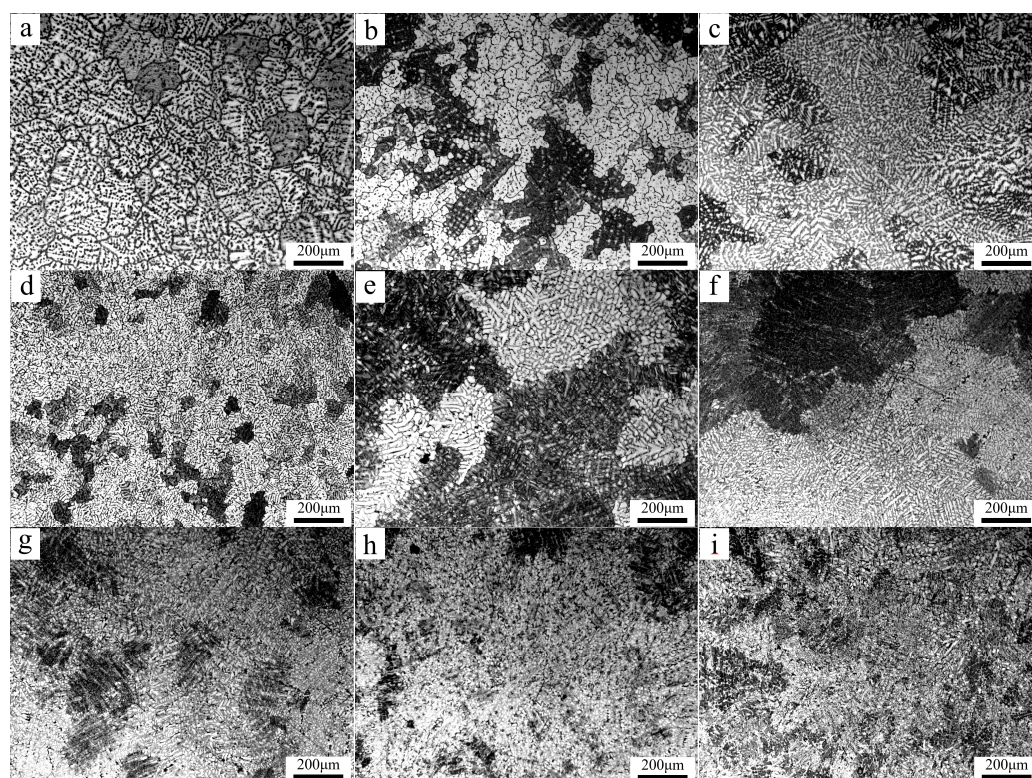


Figure 4. Metallographic microstructures of alloys with different Y contents: (a) 2Y, (b) 3Y, (c) 3.5Y, (d) 4.4Y, (e) 5.5Y, (f) 6.4Y, (g) 8Y, (h) 9.1Y, and (i) 10.7Y.

The morphology of the dendritic structure of the alloy with different Y contents and a Y/Zn ratio of 1.3 observed by polarized light microscopy is shown in Figure 5. The observation surface is the spatial cross-section cut through the alloy, and the area with the same color represents the α -Mg phase with the same orientation. That allows us to understand the shape of the dendrite unit, the abundance of primary dendrites, and the thickness of dendritic arms, while also grasping the refining degree of the as-cast structure to a certain extent.

Quantitative statistics on the size of different dendritic units were used to compare the refinement degree of as-cast structures, as shown in Figure 6. With the change in Y content, the size distribution of the dendritic units of each alloy has no obvious rule, but their respective distribution characteristics, combined with other factors, can be used to analyze the difference in mechanical properties.

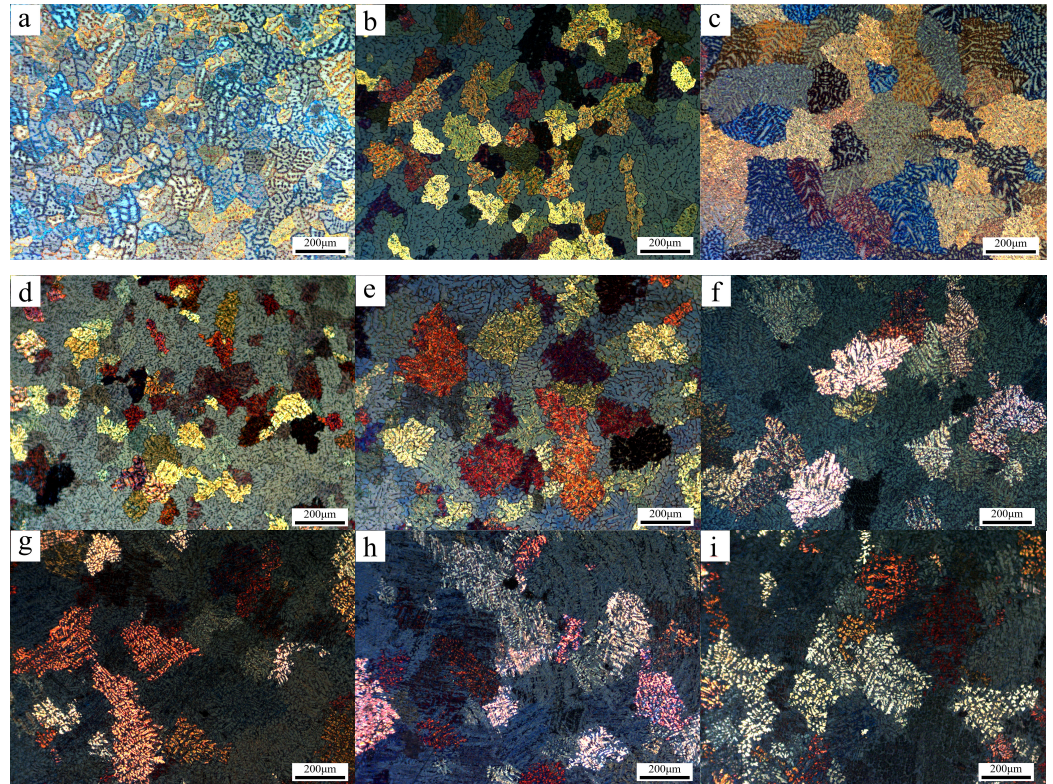


Figure 5. Polarized light microstructure of alloys with different Y contents: (a) 2Y, (b) 3Y, (c) 3.5Y, (d) 4.4Y, (e) 5.5Y, (f) 6.4Y, (g) 8Y, (h) 9.1Y, and (i) 10.7Y.

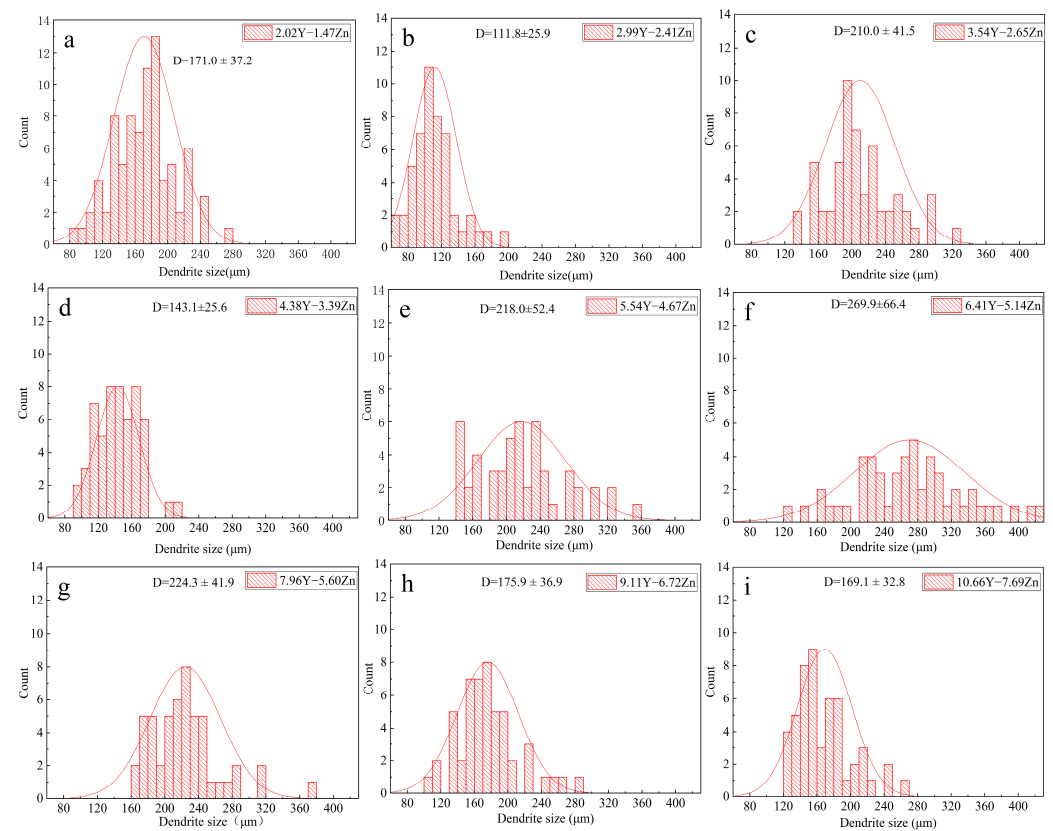


Figure 6. Distribution of dendritic unit size of different alloys: (a) 2Y, (b) 3Y, (c) 3.5Y, (d) 4.4Y, (e) 5.5Y, (f) 6.4Y, (g) 8Y, (h) 9.1Y, and (i) 10.7Y.

3.3. Compound Phases in Alloys

The XRD patterns of the alloys with different Y content and a Y/Zn ratio of 1.3 are shown in Figure 7. The main phases in the alloy include α -Mg, W phase, and LPSO phase. Within the experimentally designed Y/Zn ratio near 1.3 and the overall Y-containing compound mass fraction variation, the main phase components in the alloy remain unchanged.

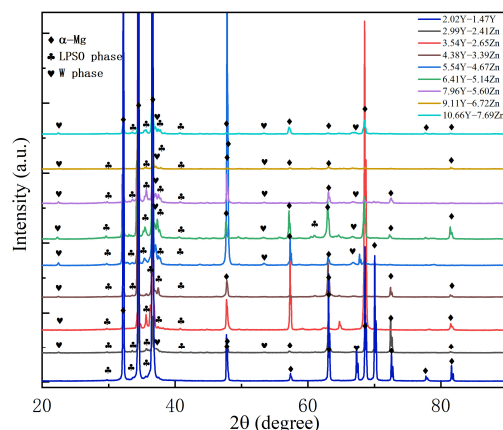


Figure 7. XRD diffraction patterns of alloys with different Y content.

The SEM morphology and energy spectrum analysis of the alloys with different Y contents and Y/Zn ratios of 1.3 are shown in Figure 8 and Table 3. The LPSO phase is gray in color and elongated or lamellar in shape, while the W phase is bright white, coral-like, or elongated. In addition to that, there were also a very small number of Y-rich particles in the form of small bright-white particles. The coral-like W phase is formed near the elongated and massive LPSO phase, and the elongated W phase is formed near the lamellar LPSO phase. A previous study [17] showed that the melting points of the W phase and the LPSO phase are 531 °C and 555 °C, respectively. During the alloy solidification process, the sequence of solidification and phase formation is α -Mg, LPSO phase, and W phase. Therefore, the W phase is usually located near the LPSO phase. When the Y content is from 2wt% to 8wt%, the second phase of the alloy mainly consists of the W phase and the LPSO phase, and when the Y content is above 9.1 wt%, a very small number of Y-rich particles, presumed to be MgY, appear. When the Y content is low, the second phase mainly contains elongated bars, lamellae, and granules, but, with the increase in the Y content, the granular second phase decreases gradually, and the elongated bars and lamellae gradually increase to form a continuous reticulum structure. As the Y content was further increased, the network structure became more complete and denser, with the width of the elongated stripes that form the network structure continuing to increase. With the proportional increase in alloying elements, the quantity and size of the two-second phases significantly increase. During the growth process, the morphology of the LPSO phase shows minimal changes, but the W phase transformed from being small and granular to large and coral-like, which was not conducive to plastic deformation.

The mass fractions of W phases and LPSO phases in the alloys with different Y contents and a Y/Zn ratio of 1.3 were obtained by volume fraction conversion, based on the densities of 4.58 g/cm³ and 2.26 g/cm³ for W and LPSO phases, respectively, while the phase densities were computed by JMATPRO v13.2 software and the volume fraction conversion of the second phase was statistically analyzed by the ImagePro software. The statistical data are shown in Table 3.

The volume and mass fraction of the second phase of the alloys with different Y contents and a Y/Zn ratio of 1.3 are shown in Figure 9. The total volume fraction of the second phase of the alloy increases continuously with the increase in Y and Zn additions, with the LPSO phase always dominating. When the Y content is between 2 and 3 wt%, the W-phase volume fraction increases slightly from 1.0% to 1.1%. When the Y content is between 3 and 5.5 wt%, the growth rate of W-phase volume fraction accelerates with the increase in Y content, and the W-phase volume fraction at 5.5 wt% Y is 3.3%. When the Y content is between 5.5 and 8 wt%, the W-phase volume fraction decreases gradually from 3.3% to 2.1% as the Y content increases. When the Y content increases from 8 to 9.1 wt%, the volume fraction of the W phase increases to 6.3%, and when the Y content continues to increase to 10.7 wt%, the volume fraction of the W phase continues to increase to 7.6%, and the growth rate slows down. The change in amplitude of the LPSO-phase volume fraction with increasing Y content varies greatly within different ranges of Y content. From 2Y to 3Y, the LPSO phase increases by 5.6% per 1 wt% increase. From 3.5Y to 4.4Y, the LPSO phase increased by 9.2% for each 1 wt% Y increase. Changing from 6.4Y to 8Y, the LPSO phase increases by 7.7% for each 1 wt% Y increase. From 9.1Y to 10.7Y, the LPSO phase increased by 10.8% for each 1 wt% Y increase. The growth rate of LPSO-phase volume fraction for all other Y variation ranges does not exceed 3.2%.

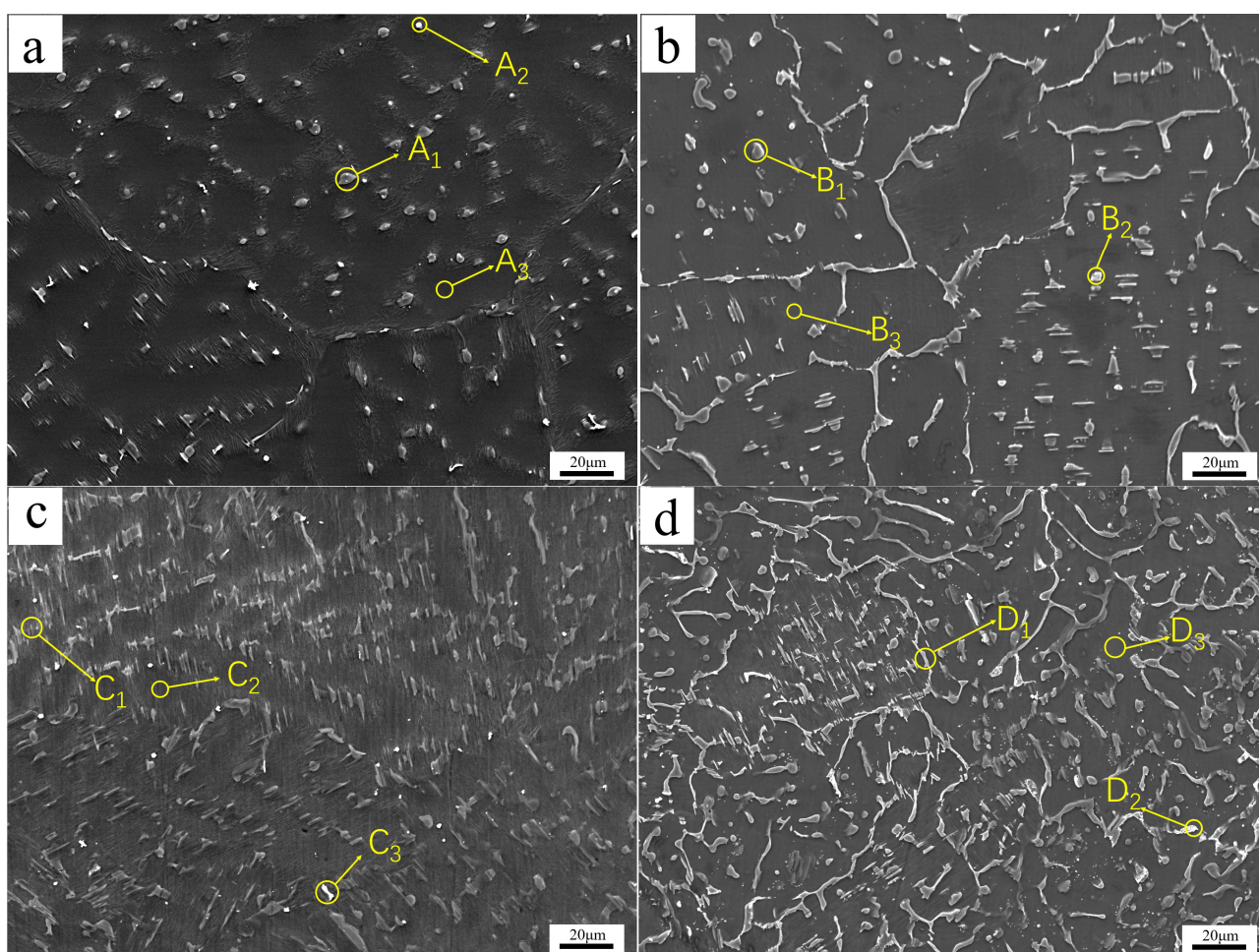


Figure 8. Cont.

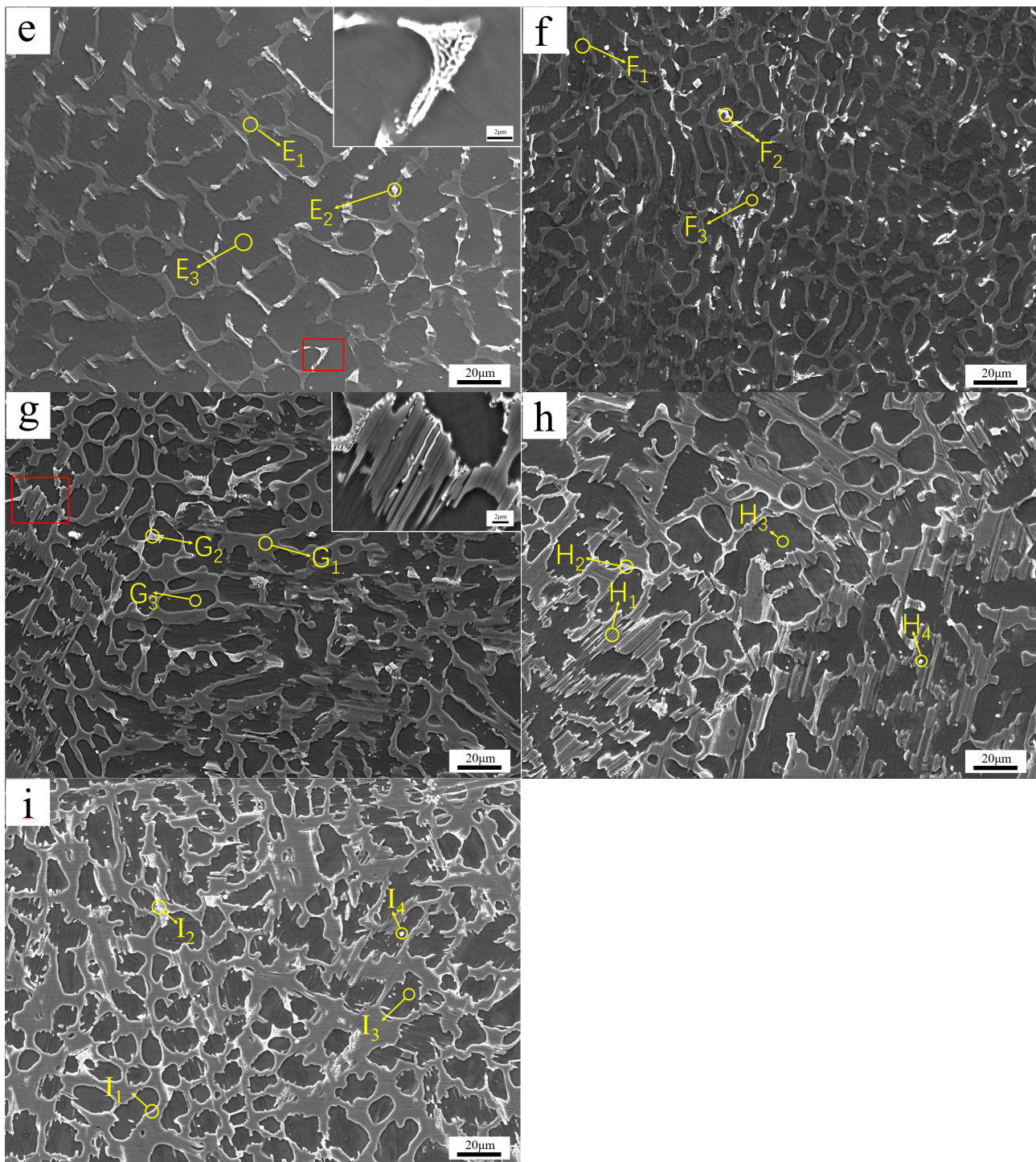
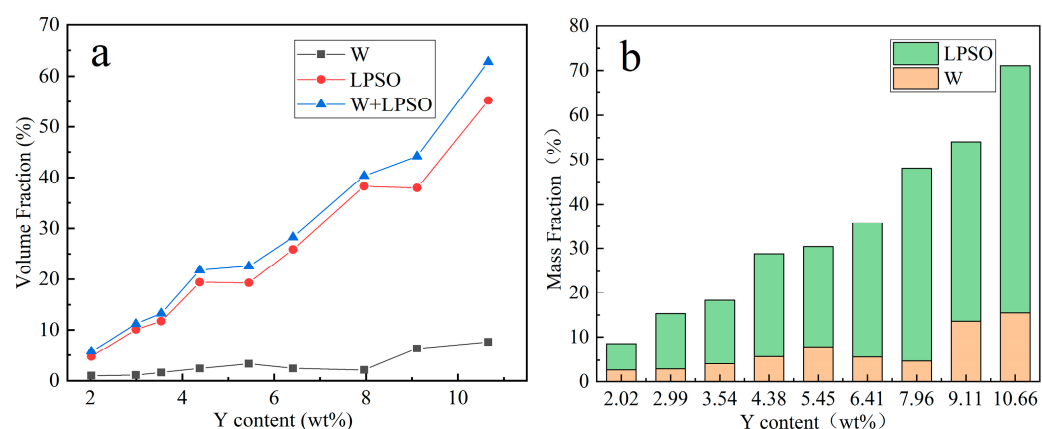


Figure 8. SEM morphology of alloys with different Y content: (a) 2Y, (b) 3Y, (c) 3.5Y, (d) 4.4Y, (e) 5.5Y, (f) 6.4Y, (g) 8Y, (h) 9.1Y, and (i) 10.7Y.

The W/L (volume ratio of W phase to LPSO phase) of the different Y-containing alloys shows fluctuations, due to the difference in the trend of the W and LPSO phases with the increase in Y. The W/L ratio changes are positively correlated with the changes in actual Y/Zn atomic ratio within the low Y content ranges of 2–4.4 wt%.

Table 3. Phase structure analysis of alloys with different Y contents.

Alloy	Position	Element (at%)			Phases	Vol%	Wt%	W/L (Vol)	W/L (Wt)	Y/ Zn	Y/Zn Deviation
		Mg	Y	Zn							
2Y	A1	91.4	5.2	4.4	LPSO	4.7	5.9	0.21	0.43	1.37	+0.07
	A2	84.9	5.5	9.6	W	1.0	2.6				
	A3	99.4	0.3	0.3	α -Mg						
3Y	B1	87.3	6.8	5.9	LPSO	10.1	12.5	0.11	0.22	1.24	−0.06
	B2	55.5	16.6	27.9	W	1.1	2.8				
	B3	99.3	0.4	0.3	α -Mg						
3.5Y	C1	95.9	2.4	1.7	LPSO	11.7	14.3	0.14	0.28	1.33	+0.03
	C2	76.3	10.0	13.7	W	1.6	4.0				
	C3	99.1	0.6	0.3	α -Mg						
4.4Y	D1	90.4	5.4	4.2	LPSO	19.4	23.0	0.12	0.25	1.29	−0.01
	D2	68	11.8	20.2	W	2.4	5.8				
	D3	98.7	0.6	0.7	α -Mg						
5.5Y	E1	90.4	5.4	4.2	LPSO	19.3	22.6	0.17	0.35	1.18	−0.12
	E2	68	11.8	20.2	W	3.3	7.8				
	E3	98.7	0.6	0.7	α -Mg						
6.4Y	F1	97	1.5	1.5	LPSO	25.9	30.1	0.09	0.19	1.25	−0.05
	F2	85.3	6.1	8.6	W	2.4	5.7				
	F3	98.3	0.9	0.8	α -Mg						
8Y	G1	89.4	6.0	4.6	LPSO	38.2	43.2	0.05	0.11	1.42	+0.12
	G2	62.3	15.2	22.5	W	2.1	4.8				
	G3	98.3	1.0	0.7	α -Mg						
9.1Y	H1	89	6.1	4.9	LPSO	37.9	40.5	0.17	0.34	1.36	+0.06
	H2	64.8	13.9	21.3	W	6.3	13.6				
	H3	98.3	0.9	0.8	α -Mg						
	H4	47.5	52.3	0.2	Y Rich particles						
10.7Y	I1	89.4	5.9	4.7	LPSO	55.2	55.6	0.14	0.28	1.39	+0.09
	I2	72.6	11.2	16.2	W	7.6	15.5				
	I3	98.4	1.0	0.6	α -Mg						
	I4	48.7	51.1	0.2	Y Rich particles						

**Figure 9.** The fraction of second phase of the alloys with different Y contents: (a) volume fraction; (b) mass fraction.

The minimum values of the atomic percentages of Y and Zn in several α -Mg phases were obtained by energy spectroscopy, which were converted to mass percentages to obtain the solid solution amounts of Y and Zn in the α -Mg phases of each alloy, as shown in Table 4. The total amount of Y and Zn elements solidly dissolved in the matrix of the 2Y alloy was 1.9 wt%, by adding a Y solid solution amount of 1.1 wt% and a Zn solid solution

amount of 0.8 wt% together. The total solid solution amount of Y and Zn increased with the increase in the Y and Zn additions, until the total solid solution amount reached a maximum value of 5.3 wt% in the case of 8Y.

Table 4. Solid solution of elements in alloys with different Y contents.

Alloy	Samples	Solid Solution Amount			
		/at%		/wt%	
		Y	Zn	Y	Zn
2Y	2.02Y-1.47Zn	0.3	0.3	1.1	0.8
3Y	2.99Y-2.41Zn	0.4	0.3	1.4	0.8
3.5Y	3.54Y-2.65Zn	0.6	0.3	2.1	0.8
4.4Y	4.38Y-3.39Zn	0.6	0.7	2.1	1.8
5.5Y	5.54Y-4.67Zn	0.8	0.6	2.8	1.6
6.4Y	6.41Y-5.14Zn	0.8	0.6	2.8	1.6
8Y	7.96Y-5.60Zn	1.0	0.7	3.5	1.8
9.1Y	9.11Y-6.72Zn	0.9	0.8	3.2	2.1
10.7Y	10.66Y-7.69Zn	0.9	0.6	3.2	1.6

The 4.4Y alloy with the highest toughness was investigated by transmission electron microscopy, as in the results shown in Figure 10. In Figure 10a, two kinds of lamellar structures can be clearly found: one is shorter in length and densely piled up to form a massive phase, and another is longer in length and sparsely piled up to form a fibrous phase. An energy spectral line scan of the black massive phase reveals that the Y and Zn were enriched, as shown in Figure 10b. Selective electron diffraction analysis was performed on the black massive phase, and diffraction patterns were obtained with the incident electron beam parallel to the $\langle 11\bar{2}0 \rangle$ crystal-oriented family, which clearly conforms to the structural characteristics of the 18R-LPSO phase [18], indicating that the block massive phase is the 18R-LPSO phase. The enrichment of Y and Zn can also be clearly observed through energy spectrum line scanning of the fibrous structure, as shown in Figure 10c, d, which can be recognized as an 18R-LPSO phase from its layered structure and atomic enrichment degree. At the interface of the 18R-LPSO phase and the α -Mg matrix co-lattice, the lattice stripes on both sides are continuous and coherent without obvious fractures, dislocations, or steps. The lattice spacing transitions smoothly at the interface, as shown in Figure 10e, f. The LPSO phase has a good co-lattice relationship with the matrix.

A non-lamellar, elongated second phase was present in the 4.4Y alloy, as shown in Figure 10g. Energy spectral surface scanning of this phase revealed that the phase was enriched in Y and Zn atoms, as shown in Figure 10h. The diffraction pattern of this phase by the incident electron beam, parallel to the $\langle 1\bar{1}1 \rangle$ crystal-oriented family, was obtained with selective electron diffraction analysis. The diffraction pattern characteristic was analyzed to be a face-centered cubic structure by CrysTBox 1.10 software, and it was determined that the phase was a W phase. The interface between the W phase and α -Mg matrix had obvious interface traces and an unsmooth lattice transition, and thus, the W phase does not have a co-lattice relationship with the α -Mg substrate.

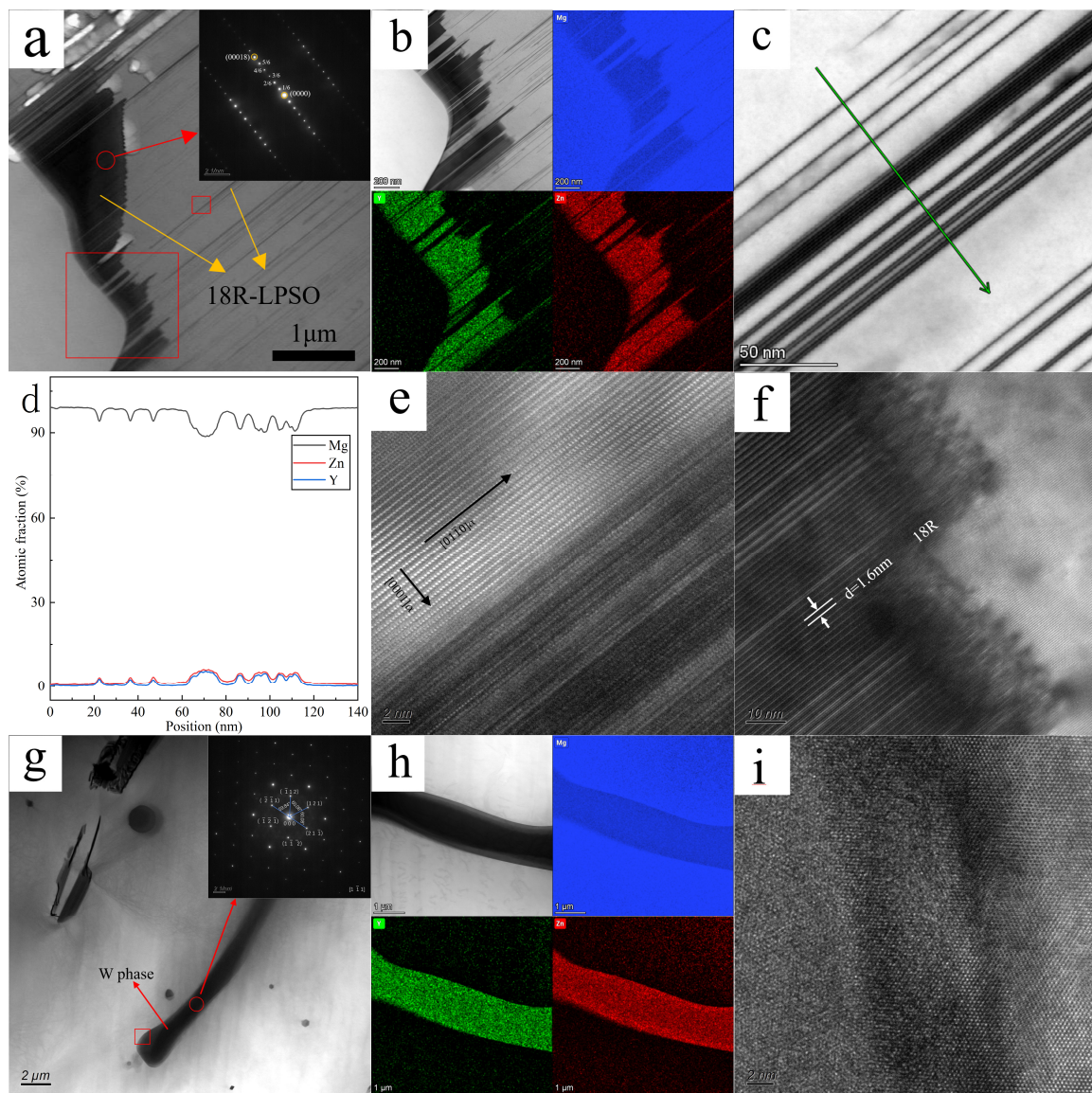


Figure 10. TEM morphology of 4.4YAlloy: (a,g) Bright Field Image; (b,h) EDS Surface Scanning; (d) EDS Line Scanning; and (c,e,f,i) HREM Morphology.

The SEM morphology of the tensile specimen fracture surface of some of the alloys with different Y contents is shown in Figure 11. The 2Y alloy has cleavage planes that are both large and small in area size and a small number of unevenly distributed tear ribs, which can be judged as a characteristic of quasi-deconstructed fracture. 2Y alloy exhibits a certain degree of plasticity. When the Y content of alloying elements increases to 3Y, the area of the cleavage planes significantly enlarges, presenting a typical “river” pattern, which is a characteristic of cleavage fracture [19–21], and the plasticity decreases significantly. As the Y content increases to 4.4Y, the average area of the cleavage planes significantly decreases, while the distribution becomes markedly uniform, and a small number of dimples and tear ridges can be observed in some small areas, which indicate better plasticity. This is confirmed in Figure 1. As the Y content continues to increase, the dimples and tear ridges disappear while the cleavage plain area increases gradually. The plasticity of alloys decreases continuously.

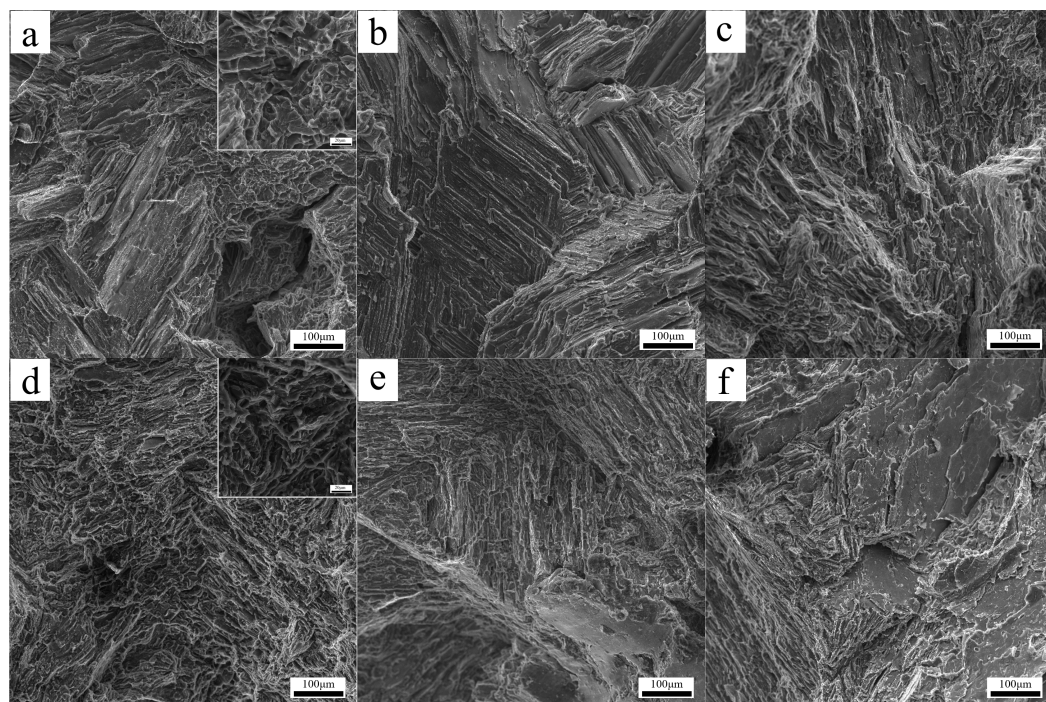


Figure 11. Fracture scanning of alloys with different Y content: (a) 2Y, (b) 3Y, (c) 3.5Y, (d) 4.4Y, (e) 6.4Y, and (f) 10.7Y.

3.4. Toughness and Its Influencing Factors

According to the law of the mechanical properties varying with Y mass content, as shown in Figure 1, the advantageous composition range for UTS is between 3.5 wt% and 8 wt%. According to the toughness evaluated by deformation work before tensile fracture, as shown in Figure 3, the advantageous composition range for deformation work is between 3.5 wt% and 6.4 wt%, especially around 4.4 wt%. The EL (elongation before fracture) and UTS are the main factors that constitute the pre-break deformation work, as shown in Figure 2. The 3.5Y, 4.4Y, and 6.4Y alloys maintain high levels of both UTS and EL, and thus have a relatively high pre-break deformation work, i.e., possess high toughness. At the same time, it should be noted that the 2Y alloy also exhibits a good value of deformation work. But the deformation work during the plastic-deforming phase of the tensile process is also important, and from this point of view, the 2Y alloy is at a disadvantage due to its low YS, despite its advantage of the alloying element cost. The YSs of the alloys are positively correlated with the solid solution amounts of the alloying elements in Table 4, but the YSs no longer increase when the Y mass content is increased to over 8 wt%. Whereas the 3.5Y–4.4Y range reaches a high YS level without causing a decrease in EL. In summary, the optimized range of Y content based on strength and toughness for the alloys with a Y/Zn ratio of 1.3 is 3.5 wt% as the lower limit and 4.4 wt% or an extrapolation value of about 5 wt% as the upper limit, i.e., 3.5–5 wt%, which is an optimized range of Y content with acceptable operability for engineering applications.

The factors affecting the strength and plasticity of the alloys can be analyzed from the dendritic characteristics of the as-cast microstructures, along with the type and percentage of compound phases, etc. As shown in Figure 6, the statistics of the size distribution characteristics and the average size of the dendritic units of each alloy do not present a certain variation pattern with varying Y content. The statistical data comes from a dendrite's size, as shown in Figure 5, and some regions with smaller statistical dimensions are only cross-sections of the dendrite arms of a certain dendrite cell, which cannot represent the volume of the dendrite cell from which they belong. Furthermore, the difference in the

degree of development between the primary dendrites and the secondary dendrites is quite significant for all alloys; in other words, the size, length, and dendrite arm spacing of the primary and secondary dendrite arms are quite different, which leads to the fact that the statistical data cannot reflect the true average size of the α -Mg dendritic unit. It is well known that the spacing of secondary dendrites is also the most important factor affecting the strength of cast alloys, but in Figure 4, the development degree of secondary dendrites in the alloys does not change regularly with increases in the Y content. Therefore, it is not credible to explain the changes in mechanical properties through the refinement of the α -Mg dendrite structure caused by the change in Y content.

The main information regarding the second-phase compounds of this type of alloy is presented in Table 3. The primary phase composition of each alloy consists of α -Mg, W, and LPSO phase. Through energy dispersive spectroscopy and transmission electron microscopy observations of the LPSO phase of the alloy, its composition, morphology, and diffraction pattern indicate that this LPSO phase is 18R-LPSO. Observations of the interface between the LPSO phase and the matrix in Figure 10e, $(0001)\alpha // (0001)\text{LPSO}$ and $[01\bar{1}0]\alpha // [12\bar{1}0]\text{LPSO}$, reveals a good crystal orientation relationship between the LPSO phase and the matrix. A good crystal orientation relationship is beneficial for enhancing the interfacial bonding strength and improving the mechanical properties of the alloy. Previous studies have shown that coexistence of the LPSO phase and W phase is beneficial to the strength and toughness of the alloy. The schematic diagram of the enhanced mechanical properties is shown in Figure 12. During deformation, the LPSO phase can significantly hinder dislocation movement. Additionally, the LPSO phase has a higher Young's modulus, which can withstand more load transferred from Mg matrix grains during deformation, thereby enhancing the strength of the alloy [22–24]. The layered structure of the LPSO phase enables the relative slippage between atomic layers during the plastic deformation process of the alloy, releasing dislocations and thereby enhancing the plasticity of the alloy. In addition, during plastic deformation, the LPSO phase can also reduce stress concentration in the matrix by undergoing kinking [25,26], thereby improving the plasticity of the alloys.

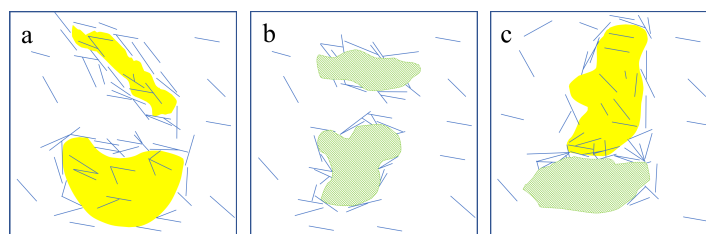


Figure 12. Schematic diagram of the enhanced mechanical properties of the W phase and LPSO phase: (a) alloy with LPSO phase; (b) alloy with W phase; (c) alloy with both LPSO phase and W phase. ■ LPSO phase; ■ W phase; — dislocation.

The EDS (energy dispersive spectroscopy) and TEM (transmission electron microscopy) investigation result shows that the W phase is incoherent with the matrix. Dislocations cannot pass through the W phase, and thus the W phase hinders dislocations, enhancing the strength of the alloy to some extent [17], while, as a brittle phase with an incoherent relationship to the α -Mg matrix, the strength can be improved to a certain extent, but an excessive amount of it will reduce the plasticity. W phases and LPSO phases coexist, and a small number of W phases can help LPSO phases further hinder dislocation movement and enhance the alloy's strength. Overall, a large number of LPSO phases and a small number of W phases in the alloy's second phase can synergistically significantly improve the alloy's mechanical properties.

The regulation of the mass ratio of W phases and LPSO phases in as-cast alloys by keeping the Y/Zn designed mass ratio for the alloy will be affected by a variety of factors, such as the solidification rate, which affects the nucleation rate of α -Mg and the solid solubility, the differences in the concentration of alloying elements, which lead to different dendritic morphology, and the different characteristics of the distribution of inter-dendritic compounds. The alloying element concentration and Y/Zn ratio of local melt form inter-dendritic compounds before nucleation, and solidification may be, in fact, already deviated from the designed Y/Zn ratio; so, it is difficult to predict the mass ratio of the W phases and LPSO phases in the as-cast alloys by the designed composition, and it is more difficult to distill the rule of the contribution to the mechanical properties from the mass ratio or volume ratio of the W phase and LPSO phase. The original intention of the experiment was to control the Y/Zn ratio at a constant value of 1.3, so as to obtain a stable mass ratio of the W phase and LPSO phase (W/L), and then to analyze the effect of the volume percentage increase in the total compounds on the mechanical properties of the alloys. From the results in Table 3, the measured Y/Zn ratio fluctuates, and the fluctuations of Y/Zn and W/L (mass ratio) show a certain positive correlation when the Y content is in the range of 2–4.4%; however, at higher Y content, due to the influence of the higher overall volume fraction of the compounds, the correlation between the two fluctuations is disordered.

Comparing Figures 1 and 9, it was found that with increasing Y content and keeping the Y/Z ratio around 1.3, the mass fraction of both the total compounds phase and the LPSO phase gradually increased, with only a slight stagnation between 4.4% and 5.54%. The W phase maintains an increasing trend at lower Y content until the mass fraction of the W phase reaches a peak of 3.3% at a Y content of 5.54 wt%. Thereafter, a decreasing trend is observed as the Y content increases to 8%, and then the mass fraction of the W phase exceeds 12% when the Y content reaches 9.1 wt%. The proportion of the W phase is a significant factor affecting the mechanical properties, especially when comparing 4.4Y, 5.5Y, and 6.4Y alloys; it can be found that the mechanical properties of 5.5Y are at a disadvantage due to the higher proportion of the W phase. Although the W phase is again reduced to a lower level, and the degree of solid solution and the proportion of LPSO phase are increasing, the UTS does not improve, but rather the plasticity continues to decline, due to the total volume percentage of the second phase dominated by the LPSO phase being too high, which weakens the strong toughness of the alloy. Too much strengthening phase will occupy a large amount of matrix space, destroying the continuity of the matrix, and increasing the interface between the matrix and the second phase, making it easier for crack sources to sprout during plastic deformation and seriously reducing the toughness of the alloy. This phenomenon has been confirmed in the fracture observation; when the Y content exceeds 4.4Y, the tearing edges and dimples on the fracture surface gradually disappear, and the area of the cleavage surface gradually increases, and as a result, the plasticity of the alloy significantly decreases. To achieve good toughness, the mass fraction of the second phase of this type of alloy should be controlled within 3.3 wt%, corresponding to 5.54Y. In practical application, the Y content should be maintained within the range of 3.5% to 5% while the Y/Zn ratio is kept at 1.3 or so.

4. Conclusions

(1) The optimized Y content of Mg-Y-Zn alloy with a Y/Z ratio of about 1.3 to maintain high strength and toughness is in the range of 3.5–5%. When the Y content reaches 4.4%, the comprehensive mechanical property of the alloy reaches the highest level, with the UTS, YS, and EL of 188.9 MPa, 124.4 MPa, and 5.9%, respectively, and the deformation work reaches the maximum value of 0.50 MJ/m².

(2) The secondary phases in alloys with different Y content mainly consist of the 18R-LPSO phase and W phase; while the alloying content exceeds 9.1 wt% Y, a small amount of Y-rich particles appears.

(3) The increase in Y content caused the difference in α -Mg dendrite microstructure and the development degree of primary and secondary dendrites, but no regular change was seen; so, the credibility of explaining the changes in mechanical properties by the statistics of α -Mg dendrite structure is low. Within the 2–4.4 wt% of Y content, the actual fluctuating values of Y/Zn and W/LPSO showed a certain positive correlation. When the Y content is small, the W-phase increases until it reaches a peak of 3.3% at 5.5 wt% Y. The W phase increases to 6.3% when the Y addition exceeds 8Y, and a small amount of Y-rich particles appears at 9.1 wt% Y, which is unfavorable to the toughness.

(4) The absolute mass ratio of the W phase is a relatively significant controllable factor to affect the mechanical properties of the Mg-Y-Zn alloys with a Y/Z ratio of about 1.3. Controlling the W phase of the alloy at about 5.8 wt% and the total mass percentage of the W phase and LPSO phase at 28.8 wt% is favorable for obtaining higher toughness and maintaining the coordination of strength and plasticity.

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