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Development of a new magnesium alloy ZW21

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ABSTRACT

A new magnesium alloy named ZW21 has been developed through orthogonal experiment method and the effects of heat treatment on the alloy's tensile properties have also been investigated. The results indicate that the alloy only has one Mg–Zn–Y(Nd) phase of $Mg_3Zn_3(Y, Nd)_2$ (named W phase) and has higher mechanical properties, lower cost and lighter weight compared with the other congeneric alloys. Its microstructure is composed of small equiaxed dendrites and interdendritic discontinuous net-like eutectic structures. The eutectic structures appear in divorced W phase laths in the thin regions between the dendrites and in regular W + α-Mg lamellar structures in the triangle regions. The eutectic structures, especially the W phase, with such distribution are harmful to the tensile properties and thus proper heat treatment can improve its properties through changing the W phase distribution. Solution treatment at 525 °C for 4 h (T_4 treatment) increases the elongation from 17.75% to 26.5%. Subsequent ageing treatment at 250 °C for 24 h (T_6 treatment) improves the ultimate tensile strength from 210 MPa to 243 MPa. The fracture modes of the as-cast, T_4- and T_6-treated alloys all obey the quasi-cleavage regime. The fracture of the as-cast alloy belongs to a mixed mode of intergranular and transgranular forms, but those of the T_4- and T_6-treated alloys follow the transgranular mode due to the relatively high bonding strength between the grains.

1. Introduction

As the lightest metallic structural materials, magnesium alloys are attracting more and more attention due to their great application potential in the fields of automobile and aerospace [1]. Unfortunately, the mechanical properties of the commonly used magnesium alloys are relatively low and cannot match the requirements in many application conditions. Thus, the present status is still far away from the target that some traditional metallic alloys such as aluminium alloys and ferrous alloys can be substituted by magnesium alloys as many as possible. However, it has been reported that wrought Mg–Zn–Y alloys exhibit significantly improved mechanical properties at room temperature as well as at elevated temperatures [2]. A $Mg_{97}Y_2Zn_1$ (in mol%) alloy produced by rapid solidified powder metallurgy exhibits a yield stress of more than 610 MPa and elongation of 5% at room temperature and a yield strength more than 380 MPa at 200 °C [3]. As-cast monolithic Mg–Zn–Y alloys have yield stress from 180 to 480 MPa at room temperature, depending on their compositions [4]. So Mg–Zn–Y system is an ideal candidate for developing high performance magnesium alloys.

The existing investigations have intensively studied the Mg–Zn–Y alloys from composition, as-cast microstructure, rolled or extruded microstructure, annealed microstructure and their effects on mechanical properties [2–13]. But there are still two great shortages in the present status. First, the study on the composition is not enough and the optimal composition corresponding to a specific mechanical property has not been determined. It is well known that Nd, Zr, Sn and Ca are the most commonly-used alloying elements in magnesium alloy. But the existing investigations have mainly focused on the effects of one of alloying elements (such as Y, Zn, Zn/Y ratio, Nd or Zr) on microstructure and mechanical properties and the other two elements of Sn and Ca have been rarely added in the Mg–Zn–Y alloys [4,5,7,13–19]. Of course, the interactions between the alloying elements have not been considered. In addition, the Zn contents of most of the investigated alloys are not lower than 4% and always around 6% (all percentages in this paper refer to mass percentage if without particularly noted) [2–13]. This undeniably increases the densities of the alloys and leads the most important advantage of magnesium alloys, light weight, to loss to some degree. Second, the effects of ternary equilibrium Mg–Zn–Y phases on mechanical properties have not been comprehensively studied. Generally, there are three kinds of ternary equilibrium phases in the Mg–Zn–Y system alloys, i.e. I-phase (Mg_3Zn_6Y, icosahedral quasicrystal structure, quasi-periodically ordered), W-phase ($Mg_3Zn_3Y_2$, cubic structure) and Z- or X-phase ($Mg_{12}ZnY$) [3]. The I- or Z-phase is closely bonded with the Mg matrix and can effectively retard the basal slip, and then strengthens the alloy greatly [2,3–9,11–13]. But for the W-phase, the existing investigations

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indicate that it easily cracks during tensile testing and the interfaces of W/matrix are not coherent because of the limited symmetry of these phases, and thus the W phase containing alloys have relatively low mechanical properties [4,13,14–18]. However, some investigations indicate that the W phase is beneficial for improving mechanical properties. For examples, the W phase can increase the ductility [4]; When the volume fraction of W phase is between 11.2% and 17.5%, the alloys have superior strength due to the strong bonding interface between W phase and Mg matrix [19]; the alloys containing W + Z phases always exhibit higher comprehensive mechanical properties than those containing unique I or Z phase [15,16]. That is to say that there is a dispute for the effects of W phase on the mechanical properties.

Therefore, in this study, alloying elements that are added into Mg–Zn–Y alloys were first selected based on the existing studies. Then an optimal composition of an Mg–Zn–Y–Zr–Nd–Sn–Ca alloy with high comprehensive as-cast mechanical properties (taking the product of ultimate tensile strength (UTS) and elongation as the parameter for evaluating the comprehensive mechanical properties) is obtained through orthogonal experiments. The results indicate that this alloy only contains one Mg–Zn–(Y, Nd) phase, W phase, which implies that the W phase is not always a harmful phase in Mg–Zn–Y alloys. Finally, heat treatment experiments were carried out to investigate the effects of heat treatment on the microstructure and tensile properties of this alloy.

2. Selection of alloying elements and experimental procedure

2.1. Selection of alloying elements

Precipitation strengthening is the most important principle for improving mechanical properties of alloys. The elements with the precipitation strengthening role all have a common characteristic that their solubilities in Mg matrix always reduce as temperature decreases. In magnesium alloys, the solubility of Zn decreases from 6.2% at Mg–Zn binary eutectic temperature to less than 2% at 100 °C [20]. During ageing, numerous small and dispersive rod like $MgZn'$ phase will precipitate in the Mg matrix of solutionized Mg–Zn alloys and a significant strengthening can be produced [13]. As described above, the Zn content in magnesium alloys is always higher than 4% and mostly around 6% [2–13]. To comprehensively verify the effects of Zn content on microstructure and mechanical properties and then obtain its optimal content, the content range is expanded and chosen within the extent of 2–7% in this work.

Zr element is usually used as a grain refiner in Mg–Zn alloys. The Zr solubility in liquid magnesium is very small and only 0.58% at the peritectic temperature, so Zr particles firstly crystallize during solidification [21]. Due to their same crystal structure and similar lattice with Mg matrix, they can act as the substrates of heterogeneous nucleation to refine Mg grains through a peritectic reaction [20,21]. It can be expected that the Zr particles may coarsen and settle when the Zr content is too high, and then the number of the effective substrates is decreased. In view of the solubility (0.58%) in liquid magnesium [21] and the contents (0.16–0.86%, but most of them are focused within 0.4–0.6%) in the investigated alloys [3–7,13–19], the Zr content in this work is selected within the range of 0.3–0.8%.

The element of Y is the necessaries for forming the ternary phases of I, W and X. In addition, Y can refine Mg–Zn–Zr alloys because its partition coefficient is less than 1 and thus the atoms can hider the growth of grains and form constitutional undercooling to accelerate nucleation [22,23]. So Y is a kind of commonly-used alloying element in Mg–Zn–Zr alloys. In the studied alloys, the Y content has a wide range of 0.5–7%, but is always in the extent of 3–5% in most of the alloys [2–19,22,23]. Therefore, the Y content in this work is selected within 1–5%.

Nd has similar roles to Y in Mg–Zn–Zr alloys [22,23]. In addition, when two or more kinds of rare earth elements are added, the interaction between them can reduce their solubilities in Mg matrix and change the precipitation kinetics of supersaturated Mg solution, and then an additional strengthening can be obtained [22–24]. So Nd is also selected as an alloying element in this work. In the studied Mg-RE or Mg–Zn–Y–Zr alloys, the content of Nd is generally less than 5% [22–24], so its content is controlled within the range of 0.5–4.5% in this work.

The element of Sn does not only improve the castability of magnesium alloys, but also more importantly can form Mg_2Sn precipitates during solution-ageing treatment to enhance mechanical properties [25]. So this element is also selected as an alloying element to add into the Mg–Zn–Y–Nd–Zr alloys. It can be expected that the main alloying elements in this work include Zn, Y and Nd, Sn is only a micro-alloying element. In view of the Sn containing Mg–Al and Mg–Zn alloys, the Sn content is normally less than

Table 1
Selected alloying elements and their content ranges.

Content range (wt.%)	Alloying element						
	Zn	Zr	Y	Nd	Sn	Ca	Mg
	2–7	0.3–0.8	1–5	0.5–4.5	0.5–2.5	0.05–0.25	Balance

Table 2
Factor level table of the orthogonal tests.

Level	Factor (wt.%)					
	A(Zn)	B(Zr)	C(Y)	D(Nd)	E(Sn)	F(Ca)
1	2	0.3	1	0.5	0.5	0.05
2	3.5	0.5	2	1.5	1	0.1
3	5	0.6	3	2.5	1.5	0.15
4	6.5	0.7	4	3.5	2	0.2
5	7	0.8	5	4.5	2.5	0.25

Table 3
Results of the orthogonal tests.

Testing serial number	UTS (MPa)	Elongation (%)	PUE (MPa·%)
A1B1C1D1E1F1	210	17.75	3727.5
A1B2C2D2E2F2	168	5	840
A1B3C3D3E3F3	154	4.5	693
A1B4C4D4E4F4	171	2.75	470.25
A1B5C5D5E5F5	131	0.75	98.25
A2B1C2D3E4F5	139	4.75	660.25
A2B2C3D4E5F1	125	3	375
A2B3C4D5E1F2	158	1.5	237
A2B4C5D1E2F3	228	0.1	22.8
A2B5C1D2E3F4	186	6.5	1209
A3B1C3D5E2F4	154	1.75	269.5
A3B2C4D1E3F5	200	6	1200
A3B3C5D2E4F1	168	2.25	378
A3B4C1D3E5F2	187	5.5	1028.5
A3B5C2D4E1F3	200	5	1000
A4B1C4D2E5F3	171	2	342
A4B2C5D3E1F4	225	6.5	1462.5
A4B3C1D4E2F5	171	2	342
A4B4C2D5E3F1	151	2	302
A4B5C3D1E4F3	210	8.25	1732.5
A5B1C5D4E3F2	155	0.75	116.25
A5B2C1D5E4F3	154	2.5	385
A5B3C2D1E5F4	156	2.5	390
A5B4C3D2E1F5	160	2	320
A5B5C4D3E2F1	167	0.25	41.75