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The Recent Research on Properties of Anti-High Temperature Creep of AZ91 Magnesium Alloy

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1. Introduction

In all magnesium alloys, AZ91 is easy to process, i.e., easy to cast into high strength products in low cost, obtained extensive research and development, as well as industrial application (SHI., 2003; POLMEAR I J., 1994: LI et a1., 2000; KIM Ket a1., 1997; MORDIKE et al., 2001). Whereas the poor anti-high temperature (over 120°C) creep performance and the low corrosion resistance are limiting its further application.

In traditional casting Mg-Al base alloy, β-Mg $_{17}Al_{12}$ is major strengthening phase at room temperature, but the β-Mg $_{17}Al_{12}$ phase's melting point is as low as 437°C. With temperature increasing to 437°C, the atom diffusion accelerated, β-Mg $_{17}Al_{12}$ phases are easily softened and coarsened. This causes the grain boundary to be weakened obviously. So that β-Mg $_{17}Al_{12}$ phase can not pin the grain boundary thus the grain boundary sliding occurs. Currently in the most widely used AZ and AM series magnesium alloys, the microstructures are mainly composed of α-Mg solid solution (the matrix) and a little amount of β-Mg $_{17}Al_{12}$. Whereas in non-equilibrium solidification process, nearby each α-Mg grain boundary aluminium supersaturated solid solution area exists, afterwards the β-Mg $_{17}Al_{12}$ phases formed in situ. During high temperature utility, β-Mg $_{17}Al_{12}$ phases in discontinuous shape separate out of supersaturated solid solution, and become into lamellar precipitates owing to low thermal stability. This is one reason that conventional AZ and AM series alloys have poor creep performance.

The creep failure mode of Mg-Al alloys at elevated temperature is predominantly intergranular fracture. Grain boundary cracks appear at first, the process occurrs at the junctions between the hard β phases and the matrix. With the grain boundary sliding, the cracks extend gradually into cavities under the stress, the cavities expand along the grain boundaries which are vertical to the stress direction and then the cavities in the same stress state link each other. Finally the specimen breaks. On the fracture surface of AZ91 alloy analysis shows that in the grain boundary areas the connections between discontinuous precipitates β-$Mg_{17}Al_{12}$ and the matrix α-Mg are weak, so the cracks are easily generated and formed into cavities at the elevated temperature plus the stress action, then the cavities expand further and link each other and form intergranular cracks through the dislocated moving and grain boundary sliding.

This research reported that the creep of magnesium alloys mainly carried on through two ways of dislocation moving and grain boundary sliding. When the bulk alloy was stretched at room temperature, the magnesium alloy with close-packed hexagonal crystallographic structure had a sliding surface which was (0001) basal plane, and only had three slip directions (Fig.1). So its fracture mode was dominated by brittle fracture, and the grain boundary and the precipitation were main obstacles to dislocation motion. With temperature increasing, non-basal plane dislocations participated in motion, crossing-slip of dislocation, aging precipitates and primary dispersion particles became the main obstacles to dislocation motion (LIU., 2002). By transmission electron microscopy analysis, this viewpoint was confirmed objectively. During magnesium alloy breaking at room temperature, in the matrix only (0001) basal plane dislocations were active; when creep rupture at 150°C, in the matrix except for (0001) basal plane dislocation, there existed also (10¯11) non-basal plane dislocation, this confirms the existence of cross slip at 150°C in creep process. According to the experimental results (REGEV M.,2002; XIAO., 2001; XIAO., 2003), it can be known that despite the hcp structure of magnesium alloy slip system number is less than the fundamental requirement for continuous plastic deformation, but at high temperature it can occur that non-basal plane may slip and form cross slip as well. In addition, at elevated temperature, when loading the magnesium alloy, the atoms at grain boundary of magnesium alloy are unstable, easy to spread, and also the dislocations easy to slip so that creep accelerates. These two aspects are main reasons for weakening high temperature creep resistance property of the magnesium alloy (LIU et al., 2002).

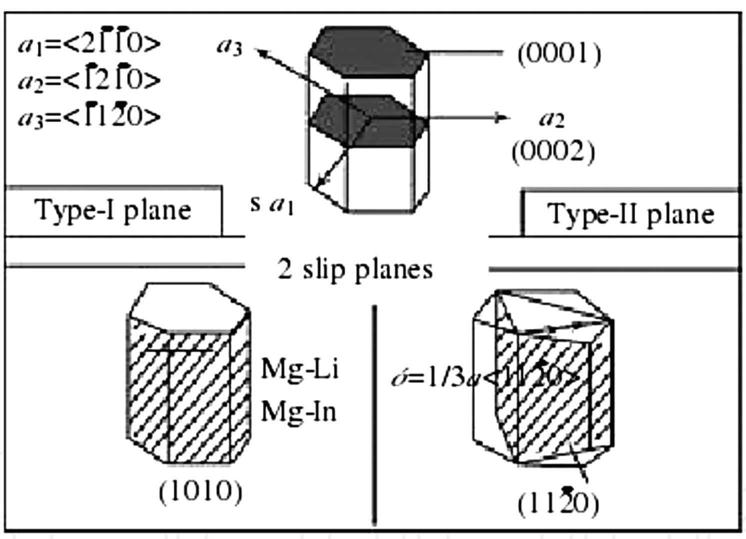


Fig. 1. Sliding system of Mg

The evaluation that resistant creep performance at high temperature of magnesium alloy is good or poor can be done by using the minimum creep rate $\dot{\varepsilon}$ to measure. The smaller the $\dot{\varepsilon}$ is, the better the creep resistance is. Minimum creep rate can be determined with following formula:

$$\dot{\varepsilon} = A\sigma^n \exp(-Q/RT) \quad (1)$$

Where A is constant, σ the stress in the alloy, and n stress coefficient, T the temperature, R gas constant, and Q surface activation energy.

One may know from the above equation that with reducing stress coefficient n, stress σ or increasing superficial activation energy Q, the minimum creep rate may be reduced and then the high temperature anti-creep ability is enhanced.

Therefore, increasing the resistance of intergranuar dislocation movement and grain boundary sliding becomes mostly useful way to improve creep resistance property (HUMBLE P., 1997; YAN et al., 2004). The concrete measures are to strengthen matix and grain boundary, as well as to develop magnesium base composite materials. The former measure is through the micro-alloying to enhance solution strengthening, precipitation strengthening and fine grain strengthening and so on. Simultaneously, small dispersion particles pinning grain boundary and hindering dislocation movement that forms a combined strengthening mechanism for magnesium alloys. Whereas micro-alloying can form the high melting point compounds to reduce or hinder the formation of β-$Mg_{17}Al_{12}$ phase. But the latter measure is through adding strengthening phases to approve anti-high temperature creep performance of the magnesium alloy.

2. AZ91 magnesium alloy micro-alloying research

The effective alloying elements to magnesium alloy should have the following characteristics:

1. The solubility degree of alloying elements in magnesium should drop sharply with temperature reducing, so that they produce precipitation hardening effect during aging or annealing treatment;
2. Alloying elements exist in precipitates in high content, so easy to obtain a large number of dispersed second-phase precipitation;
3. Alloying elements themselves should have high melting point;
4. When adding alloying elements, one should take into account the interaction with other alloying elements, so as to use multi-alloying method to increase the number of precipitates.

The alloy elements used for enhancing thermal stability of magnesium alloy mainly have the rare-earth elements, the alkali soil elements (Ca, Sr, Ba) and the IV,V Race elements (Si, Sn, Sb, Bi). Because the rare-earth element assumes trivalent electron, through strengthening Mg^{2+} interionic attraction, it may reduces atom diffusion speed. The rare earth elements can form high melting point compounds, distributes good thermal stability of intermetallic compounds with Mg, Al and other alloying element (for example, Zn, Mn, Zr) to realize dispersion strengthened, thus the heat resistance and high temperature creep properties of magnesium alloy are enhanced (GUO et al.,2002; LIU et al.,2003）.

The rare earth elements have above advantages but the price is quite high. While the alkali soil elements cost low, and simultaneously they may form high melting point intermetallic phases in the Mg-Al alloy. The intermetallic phases are not easy to decompose and can prevent grain boundary movement effectively at elevated temperature; so that they are obviously improved the high temperature mechanical properties of magnesium alloy especially the anti-creep ability (MIN et al., 2003).

The die casting manufacturability of magnesium alloy added the alkali soil elements is poor, therefore the influence of the IV,V Race element (Si, Sn, Sb, Bi) on magnesium alloy of high temperature stability becomes another research hot spot.

2.1 Rare earth elements effect on the high temperature creep properties of the AZ91 magnesium alloy

Because of unique extra atom nuclear electron distribution, in metallurgy and material fields the rare earth elements obtain widespread applications and researches. People have obtained quite thoroughful understanding already to the function of rare earth element in magnesium alloy (LI et al., 2005; TENG et al., 2007).

Ele-ment	Atomic radius /nm	Atomic radius D-value with magnesium(%)	Electro negativity	Ele-ment	Atomic radius /nm	Atomic radius D-value with magnesium(%)	Electro negativity
Mg	0.160	0	1.31	Dy	0.175	10.8	1.22
La	0.188	17.3	1.10	Ho	0.175	10.4	1.23
Ce	0.183	14	1.12	Er	0.174	9.8	1.24
Pr	0.183	14.3	1.13	Tm	0.176	9.1	1.25
Nd	0.182	13.8	1.14	Yb	0.194	21.2	1.1
Sm	0.179	12.6	1.17	Lu	0.173	8.4	1.27
Eu	0.199	27.6	1.2	Y	0.182	12.6	1.22
Gd	0.178	12.6	1.20	Sc	0.165	2.6	1.36
Tb	0.176	11.4	1.2				

Table 1. Atomic radius and electronegativity of the magnesium and RE element

As showing in Table 1, the atomic radius and the electronnegativity of the majority of rare-earth elements are close to the magnesium's, and the atomic radius relative differential value between rare earth elements and magnesium are in about 15%, moreover the electronegativity differential value is smaller than 0.4. According to Hume-Rothery and Darken-Gurry theory, it can be obtained that the rare-earth elements have big solid solubility degree in the magnesium (showed Table 2) to realize solution strengthening and precipitation strengthening. Simultaneously they are also effective aging strengthening elements. Some rare earth elements also have dispersion strengthening effects. So the rare earth elements may enhance the alloy's room temperature intensity of the magnesium alloy as well.

RE element	Sc	Y	La	Ce	Nd	Yb	Gd	Dy
Atomic number	21	39	57	58	60	70	64	66
Eutectic temperature/°C	-	565	613	560	548	592	548	559
Max-solid solubility/wt%	25.9	12	0.79	1.6	3.6	3.3	23.5	25.8
compounds generated with magnesium	MgSc	$Mg_{24}Y_5$	$Mg_{12}La$	$Mg_{12}Ce$	$Mg_{12}Nd$	Mg_2Yb	Mg_5Gd	$Mg_{24}Dy_5$
Alloy system	peritectic	eutectic	eutectic	eutectic	eutectic	eutectic	eutectic	eutectic

Table 2. RE elements solubility degree in Mg and compounds formed with Mg

At present the rare-earth elements added into magnesium alloy are roughly divided into two categories: one is the elements with small solid solubility such as Ce, Pr element and so on, another is the elements with large solid solubility such as Y, Nd, La element etc. Many rare-earth elements by preformed alloy forming are added to the magnesium alloy (Mordike., 2002).

Generally believe that the rare earth elements with Al element form high melting point's Al-rare earth intermetallic compounds in the AZ91 alloy. The kind of compounds enhance the thermal and mechanical performance of magnesium alloy.
The primary reasons lie in following several aspects:
First, in casting solidification process, the high melting point Al- rare earth intermetallic compounds firstly separated out. These compounds become the nuclear core of α-Mg to enhance nucleation rate, or were pushed to grain boundary area to hinder α-Mg grain growing up, and refine magnesium alloy grain;
Second, because of the forming of Al-rare earth intermetallic compounds the content of Al element in the matrix alloy was dropped, the quantity of β-$Mg_{17}Al_{12}$ phase in the grain boundary place reduces. Along with the rare earth element content (within a certain range) increasing, the size of β-$Mg_{17}Al_{12}$ phase reduces gradually, and the shape of it is also changed from continual lattice gradually to spherical discrete distribution;
Third, because the Al- rare earth compounds are thermally stable phases, moreover the quantity of β-$Mg_{17}Al_{12}$ with poor thermal stability reduces and the shape of it changes, thus these all enhance the anti-high temperature creep property of magnesium alloy.
In addition, the binding capacity of rare earth elements and oxygen is greater than the binding force of magnesium and oxygen; this urges magnesium to response with hydrogen and water vapor during melting. Joining appropriate rare-earth elements into the magnesium alloy can not only remove gas, mixed, but may also increase the fluidity of solution, reduce the tendency of casting producing shrinkage porosity and enhance the density (LI., 2005).
In all the alloy elements, the rare earth elements are one of the most effective, the most direct alloy element to improve heat resistance. Due to rare earth elements have small diffusion coefficient in magnesium alloy, they slow recrystallization process, increase the recrystallization temperature, decrease grain boundary and phase boundary diffusion permeability and reduce the phase boundary aggregation. The most main are that the high melting point rare earth compounds made of the rare earth and Mg, Al or other elements (for example Zn, Mn and so on) anchor grain boundary and hinder dislocation movement for improving the high temperature strength and creep resistance. The rare earth elements form precipitation in the magnesium alloy, the precipitation process is: at 170 ~ 200°C hexagonal β "phase is generated which is superlattice structure; at 200~250°C body-centered cubic structure β′ phase appears, above 300°C face-centered cubic β phase is formed and heterogeneously distributed in grain and on grain boundary . The dispersed, thermally stable particles make magnesium alloy showing good heat resistance (GUO et al., 2002).
Rare earth element Y has the effect on the microstructure and mechanical properties of the AZ91D magnesium alloy by adding different contents in the alloy. Y element obviously refined the microstructure, formed square block $A1_6Mn_6Y$ phase and rod $A1_2Y$ phase .These two phases were high melting point phases and appeared in the liquid metal before solidification , thus became the core of non-spontaneous crystallization. So, they hindered grain growth, refined dendrites, and enabled their distribution to disseminate. Finally, the mechanical properties of the alloy were enhanced. However, the addition quantities of rare earth elements were required .The alloy with 1.5% Y had better comprehensive mechanical properties than others, while when the Y content increased above 2%, tensile strength, ductility and hardness all were decreased(WU et al.,2006).
Lu Y Z , Lu S f and so on(2000;2006) have studied the influence of the rich Ce rare earth on the microstructure and the performance of AZ91 magnesium alloy. They found that after

having added Ce into the alloy, bar $Al_{11}Ce_3$, $Al_{11}La_3$, $Al_{11}Pr_3$, $Al_{11}Nd_3$ and so on precipitated phases appeared, the quantity and the size of β-$Mg_{17}A1_{12}$ were reduced; These phases were high melting point compounds and mainly gathered at the grain boundary area, by grain boundary strengthening way to effectively improve the thermostability and the high temperature performance of AZ91 magnesium alloy. Ce content was also influential to the microstructure and the mechanical properties of AZ91 magnesium alloy. Joining 0.2%~0.8%Ce into the AZ91 alloy could obviously refine grain, made its size drop to approximately 32μm ,while before refinement the size of α-Mg grain was 108μm, and made the tensile strength to enhance 31MPa compared to the substrate(LIU.,2006).

Ce and Ce-rich series rare earth mixture have good solution strengthening effect to the magnesium alloy. Y series have remarkable aging strengthening effect and precipitation phases have low diffusion coefficient, have good contact surface union with the magnesium matrix. Therefore, the researchers joined Y together with Ce to the AZ91 magnesium alloy to observe their roles to the microstructure and the property. After have been added in alloy, with Al element, Y, Ce formed $Al_{11}Ce_3$, Al_2Y heat-stable phase respectively. These two phases separated out during solidification process firstly, and thus prevented grain growing and grain boundary sliding at high temperature. Forever, Ce ,Y and these heat-stable phases could commonly refined the grain. The interaction of solution strengthening of Y element and precipitation strengthening of $Al_{11}Ce_3$ and Al_2Y enhanced the properties of the magnesium alloy either room temperature or high temperature. The experiment proved: When joining 0.6%Ce and 0.3%Y, the room temperature tensile strength of the magnesium alloy achieved 245MPa, enhancing 64% compared to the AZ91D matrix; the yield strength achieved 213MPa, enhancing 71% compared to the AZ91D matrix(WANG et al.,2007).

The rare earth Nd added into AZ91D magnesium alloy generated new rare earth compound $Al_{11}Nd_3$, reduced the quantity and the size of β-$Mg_{17}Al_{12}$ phase, and changed the shape of the β-$Mg_{17}Al_{12}$ phase from discontinuous net to dissemination distribution. $Al_{11}Nd_3$ phase effectively hindered grain boundary sliding and fracture growing, and refined the microstructure of the alloy. Finally it enhanced the mechanical properties of the alloy. Adding different contents Nd in the die-casting AZ91D alloy, although the break way of alloy still belonged to the brittle fracture, but when the Nd content was 1%, the number of dimple in alloy fracture increased and the character of the ductile rupture was remarkable (YANG.,2007).

Through researching the influence of rare earth La on the microstructures and the properties of the AZ91 alloy, it is obtained that after having added La element, the microstructures of AZ91 alloy have some changes such as grain refinement, net shape β-$Mg_{17}Al_{12}$ separation, smaller and thinner, black spot MnAl compounds segregation obvious depletion, needle rare earth phase ($Al_{11}La_3$) appearing at grain boundary. $Al_{11}La_3$ phase made of La and Al element is high melting point and high stability phase, and it improves the distribution of the grain boundary phase and the macro hardness of cast. After solution and aging treatment, lamellar β-$Mg_{17}Al_{12}$ phase precipitates at grain boundary, and with aging time elongation the hardness of alloy increases further (PEI et al., 2005).

2.2 Alkali soil elements influence on the AZ91 magnesium alloy

Because the atom size and the negativity of rare-earth element are close to the magnesium, the rare-earth element may strengthen interatomic binding force of the magnesium alloy, forms the high melting point compound, remarkably refines the microstructure of the magnesium alloy, and enhances the room temperature mechanical properties, the high temperature mechanical properties and the creep performance of the AZ91 magnesium alloy. But, rare-earth element's price is expensive; this has limited its widespread application. Therefore, by adding inexpensive alkali soils elements (Ca, Sr, Ba) in alloy to improve the heat-resisting performance becomes research another hot spot about the magnesium alloy.

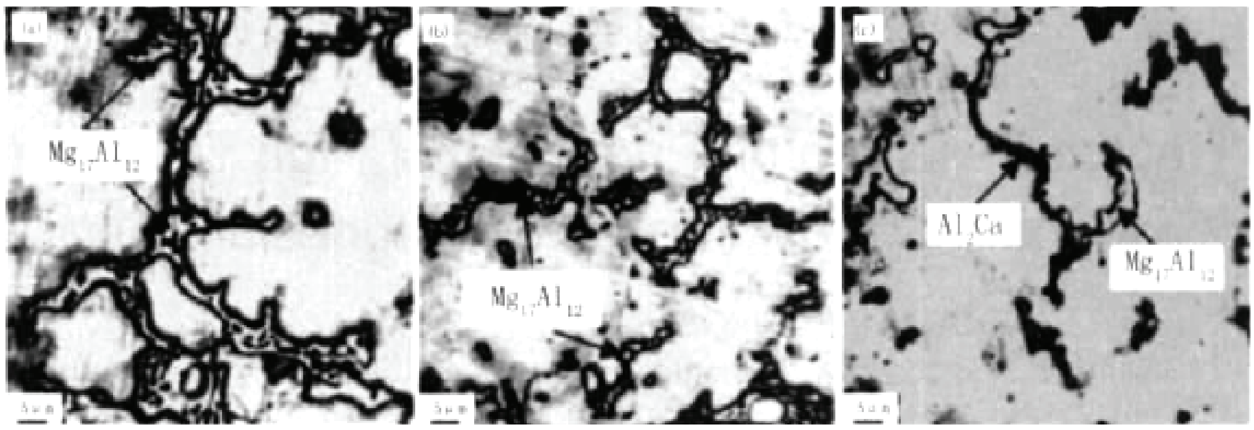
The price of Ca element is low, the melting point low, and the density is quite close to the magnesium's; so at present it has become the most frequently using alkali soil element to enhance the magnesium alloy heat-resisting performance. Studies have shown that adding Ca element to the conventional magnesium alloy can not only enhance oxidation combustion temperature of magnesium alloy, but also refine as-cast structure so as to improve mechanical performance and high temperature creep of magnesium alloy. After Ca had been added, the hardness of the alloy was increased significantly. When the mass ratio of Ca and Al was greater than 0.8, not only the hardness of magnesium alloy was increased rapidly, but also high thermal stability $(Mg, Al)_2Ca$ phase is formed in grain boundary place. It effectively hindered grain boundary sliding during high temperature creep, thus significantly improved the heat resistance of the alloy (LIU.,2002; GUO.,2004; LI.,2005; YANG.,2005).

Another study shows that Ca added AZ91 alloy raises the eutectic reaction temperature of alloy and improves the melting point of β-$Mg_{17}Al_{12}$ phase, so it improves the weakness of stability of β-$Mg_{17}Al_{12}$ phase lower. While β-$Mg_{17}Al_{12}$ phase mostly distributes in the grain boundary, its stability enhancement can better prevent grain boundary sliding (CHEN., 2007) at elevated temperature.

Some points are worth paying attention: Microcontent Ca may refine as-cast and aging structures. Studies find that only few of Ca added in the alloy is dissolved in the matrix, massive Ca dissolutions in β-$Mg_{17}Al_{12}$.This indicates that Ca mainly salutes in the AZ91 alloy, rather than forms second phase. Because after Ca solution in β-$Mg_{17}Al_{12}$ phase it can inhibit the dissolution of β phase and improves the thermal stability of β phase, eventually enhances the room temperature and high temperature tensile property of the alloy (SUN et al, 2001).Along with the Ca content increasing, its refinement effect is also more obvious, but the tendentiousness of hot cracking of the alloy increases (TANG et al., 2004; LI et al, 2005).

The researches show: After Ca has been added in the AZ91 magnesium alloy, what phase is formed relating to the content of Ca (LI et al.,2005;MIN et al.,2002;FAN et al.,2005). When the Ca contents are lower than 1% (quality score, when similarly here and after), it mainly is saluted in β-$Mg_{17}Al_{12}$(MIN et al.,2002). Through the way of strengthening $nC^{Al\text{-}MgII}$ and $nD^{Al\text{-}MgII}$ bond which control the stability of β-$Mg_{17}A1_{12}$ phase, through the way of causing the shared electron to even assign in the principal linkage and the entire structure, Ca element enhances the melting point of β-$Mg_{17}Al_{12}$ phase and the high temperature performance of the magnesium alloy. When the Ca content is 0.8%, the Al_2Ca presents in grain boundary area of the alloy, simultaneously, β-$Mg_{17}Al_{12}$ phase reduces (see Fig.2). But the Al_2Ca worsens the tensile strength and the plasticity of the alloy (LI et al, 2005).

Generally thinks (BERKMORTEL et al., 2000; WANG et al., 2000), the reason that Ca causes the anti-thermal crack performance of the magnesium alloy dropping is because during solidification period, at grain boundary place Al_2Ca owing different cooling rate from the matrix alloy leads the stress to be created, or is because Al_2Ca gathering in the grain boundary by netted form enlarges the thermal crack tendentiousness of alloy. In addition, there is a substantial cause is: Ca promotes the divorce eutectic reaction, enhances the separation temperature, reduces the packing ability of the alloy melt. In order to eliminate or reduce the influence of Ca element on anti-thermal crack performance of the magnesium alloy (TANG et al., 2004), many researchers are searching other microcontent alloying element to coordinates with Ca element.



(a)0%Ca (b)0.4%Ca (c)0.8%Ca

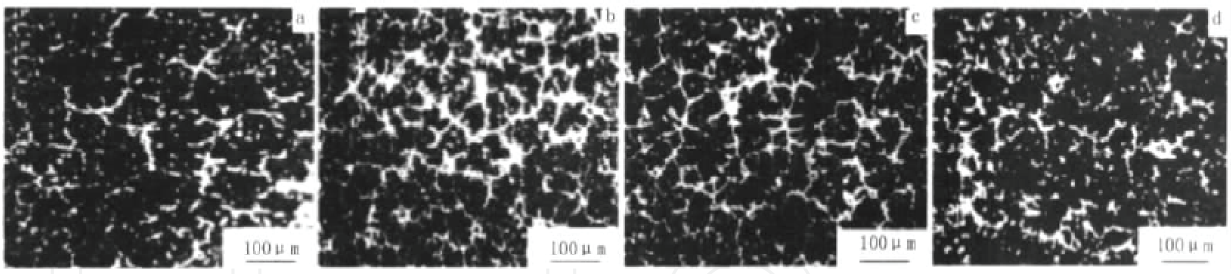
Fig. 2. Microstructure of AZ91D alloy

Some researches indicate Ca/Sr composite addition into AZ91D alloy may make the anti-thermal crack performance of the alloy to restore to the closing AZ91D alloy level, but Sr addition will counter-balance the grain refinement effect of Ca element on the microstructure of the magnesium alloy (TANG et al., 2005). Others, because the AlSr and the Al-Ca-Sr ternary compounds were produced, the number of β-$Mg_{17}Al_{12}$ precipitations reduces as a result, simultaneously, at grain boundary place the shapes of β-$Mg_{17}Al_{12}$ and Al_2Ca have some changes, thus the embrittlement function of the Al_2Ca on the matrix is weakened (LI et al.,2004).

In AZ91- Ca magnesium alloy, joining Si or rare earth elements again, the room temperature and the high temperature mechanical properties of the alloy may obviously be improved; The high temperature creep resistance of the alloy was enhanced enormously because of producing high melting point Mg_2Si second phase or $Al_{11}RE_3$ phase (MIN et al., 2002). Simultaneously joining 1%Ca and 1%RE may make the tensile strength of the AZ91 magnesium alloy to enhance 15.9% (WU et al., 2005).

Sr can refine grains, improve the creep properties of the alloy, also is advantageous to the anticorrosion performance. Little content Sr (0.2%~0.5%) can refine as-cast structure and make the size of α-Mg grain dropping from 107μm not refinement to 60μm ; net and block shape β-$Mg_{17}Al_{12}$ phase becomes tiny dissemination. When Sr content is 0.8%, rod Al_4Sr phase appears(see Fig.3). Refinement mechanisms are that on the one hand Sr reduced the liquidus and solidus temperature of the alloy and caused the supercooling degree of alloy to reduce; on the other hand, Sr concentrated in front of the solid-liquid interface to cause α-Mg grain growing to block, thus further to refine grain(LIU et al.,2006).

Ba enhances obviously the room temperature and the high temperature tensile strength of the AZ91 alloy. It is main reason that Ba has solution strength effect on the alloy and Al_4Ba phase with high melting point and thermal stability has dispersion strengthening effect. When the content of Ba is 0.2wt%, the room temperature tensile strength of the alloy enhances 9.2%; the high temperature tensile strength enhances nearly 19%. However when the content of Ba is above 0.3%, the number of Al_4Ba phase having separated out in the crystal boundary increases and this phase gathers to group. These make Ba refinement role



(a) 0%Sr (b) 0.2%Sr (c) 0.5%Sr (d) 0.8%Sr

Fig. 3. Effect of Sr content on the as-cast microstructure of AZ91D alloy

dropping and lead to lower grain boundary cohesion, to stress increasing. When plastic deformation occurring, the fracture easily occurs at grain boundary and the mechanical properties of the alloy decrease (LI et al., 2005).

2.3 The IV. V race element (Si, Sn, Sb, Bi,) role on AZ91 magnesium alloy

Si element added in AZ91 magnesium alloy may form an effective high-temperature strengthening phase Mg_2Si.

Magnesium alloy components	Casting mode type	Alloy element	Adding element Content (%) 0	0.5	1	2	Reinforcing phase	Reinforcing phase Morphology, distribution	Melting point of reinforcing phase/°C	crystal structure of reinforcing phase
			Yield strength/MPa							
Mg-9Al-0.8Zn	Metal mode	Bi	125	-	152	161	Mg_3Bi_2	Most in grainboundary, Little in grain	823	partyD_5
Mg-9Al-0.8Zn	Water-cooling metal mode	Sn	70	130	115	120	Mg_2Sn	Most in grainboundary, Little in grain	778	reverseCaF_2 structure
Mg-9Al-0.8Zn-0.2Mn	Metal mode	Sb	95	140	-	-	Mg_3Sb_2	Most in grainboundary, Little in grain	1228	hexagonal D_5 structure

Table 3. Effect of Bi, Sn, Sb addition on yield strength of magnesium alloy at 150°C

Because Si is very cheap, therefore it may become one of first choice adding elements to enhance high temperature performance of magnesium alloy .Alloy obtained can be used for the occasions that work temperature is below 150°C (LUO, 2004), The alloy production suits in using die-casting with fast solidification speed to carry on, but is not suitable with the sand casting way to produce. Because the main strengthening phase Mg_2Si in the condition of slower solidification rate will become like thick, it easily leads to stress concentration and thus seriously damages the performance of the alloy.

Sn element has refining grain function to the alloy. Table3 has listed the research results (YUAN et al., 2001). Adding Sn element has suppressed β-$Mg_{17}Al_{12}$ separation, promoted Al

atom solution in Mg and caused its solid solubility to increase. Content 0.5% Sn has expanding α-Mg region' function (TENG et al., 2007). Few Sn can enhance effectively the thermal stability of the alloy. Moreover, excessively many Sn will cause the intensity of the alloy dropping. After having added Sn into the alloy, high melting point Mg_2Sn appears in microstructure and distributes in the grain boundary. This phase may prevent effectively grain boundary slipping at the time of the high temperature stretch, so it can improve the thermal stability of the alloy. The strengthening role of Sn on the magnesium alloy will not go away along with temperature increment (Sun et al., 1999).
According to Pekguleryuz et al.(PEKGULERYUZ M O ,AVEDESIAN M M ,1992) report, it can be known that excessively high Sn content in the magnesium alloy would cause the intensity of alloy to drop, This is because the excessive Sn content easily led Mg_2Sn grain coarsening so as to cause its high temperature strengthening effect to be weaken.

添加元素及其含量(%)						拉伸性能						参考文献
						室温			高温			
Ca	Si	Sr	Bi	Sb	RE	σ_s/MPa	σ_b/MPa	δ(%)	σ_s/MPa	σ_b/MPa	δ(%)	
0.4	-	-	-	-	-	77.9	138.6	0.98	-	-	-	(LI PJ,2004)
0.4	-	0.01	-	-	-	80.3	134.0	0.94	-	-	-	
0.4	-	0.05	-	-	-	79.3	148.8	1.37	-	-	-	
0.4	-	0.10	-	-	-	76.8	173.7	1.86	-	-	-	
0.3	-	-	-	-	-	120.0	163.0	2.2	101.0	144.0	16.1	(MIN X G,2002)
0.3	0.2	-	-	-	-	160.0	200.0	4.4	111.0	154.0	11.4	
0.3	0.6	-	-	-	-	152.0	190.0	3.3	113.0	151.0	12.1	
0.3	-	-	-	-	1	140.0	175.0	4.0	110.0	142.0	16.0	
0.3	-	-	-	-	2	129.0	174.0	4.2	103.0	137.0	17.8	
-	-	-	0.5	-	-	132.0	232.0	4.7	132.0	180.0	24.3	(YANG G Y,2001)
-	-	-	1.0	-	-	166.0	250.0	4.6	134.0	180.0	21.7	
-	-	-	2.0	-	-	184.0	265.0	4.4	138.0	184.0	19.6	
-	-	-	3.0	-	-	162.0	224.0	3.2	119.0	172.0	12.1	
-	-	-	-	0.1	-	134.0	238.0	5.0	121.0	183.0	34.5	
-	-	-	-	0.4	-	177.0	264.0	4.5	138.0	185.0	34.0	
-	-	-	-	0.7	-	172.0	257.0	4.4	135.0	180.0	26.8	
-	-	-	-	1.0	-	165.0	244.0	2.7	133.0	172.0	18.9	
-	-	-	0.5	0.4	-	172.0	262.0	3.6	138.0	183.0	16.3	
-	-	-	1.0	0.4	-	178.0	269.0	3.3	140.0	187.0	14.8	

Note: In high temperature tensile properties, in literature (MIN X G, 2002) temperature is 200°C, (YANG G Y,2001) temperature is150°C; — is element not be added or performance undetected.

Table 4. Mechanical properties of AZ91 magnesium alloys microadded alloyings

The strengthening mechanism of Sb to the magnesium alloy had been studied. The research results indicated that when adding content of Sb was 0.4%, in microstructure, α-Mg was thinning, strip shape β-$Mg_{17}Al_{12}$ no longer assumed lattice and block distribution, but became thinning, short structure and dissemination distribution, and white granulated Mg_3Sb_2 was distributed in the grain and the grain boundary relatively. The tensile strength of the alloy was enhanced 20MPa comparing to the matrix. Analyzing the above reason, it is though that Sb strength effect stems from the interaction of grain refinement, the original β-$Mg_{17}Al_{12}$ morphology changing and the new particle Mg_3Sb_2 appearance (WANG et al., 2005).
Regarding Bi/Sb composite addition into AZ91D alloy ,the researches indicated that Al, Bi, Sb played solution strength role to reduce structure energy through saluting in α-Mg grain or grain boundary. In AZ91 magnesium alloy, Bi or Sb was easier than Al to gather in the grain, so suppressed Al element to gather in the grain boundary and promoted continual β-

$Mg_{17}Al_{12}$ to separate from the matrix. Thus the room temperature performance of the AZ9l magnesium alloy was improved. In the AZ91 magnesium alloy, main alloying element Al and microcontent element Bi, Sb could form big quantity, order Mg_3Sb_2 (821) or Mg_3Bi_2 (1280°C) phase in the grain boundary area. Therefore Mg_3Sb_2 or Mg_3Sb became main separation phase in the grain boundary area to hinder effectively dislocation movement during the high temperature distortion process, thus it enhanced the high temperature performance of magnesium alloy (Zhang et al., 2005; Yuan et al., 2001; Yuan et al., 2001).
Table 4 carries on the performance contrast which was obtained from the present the part micro alloy researches to the AZ91 magnesium alloy. Although existing the different of the raw material matching, the alloying element choosing, the material preparation craft and in table researcher's data, we still may see some change tendencies, namely the multi-elements coordinate effect surpassing the sole element.

3. AZ91 magnesium alloy base compound materials research

Magnesium alloy itself has some shortcomings such as high temperature strength poor (MORDIKE et al., 2001), elasticity coefficient low and anti-corrosive performance poor, therefore the people take their visions on the relatively high performance magnesium matrix composites. The researches began in the 1970s; To the beginning of the 21st century (GU et al., 2004) it has become research hot spot. Presently, the researches about magnesium matrix composites mainly concentrate in the fiber reinforcement and the particle strengthening two kinds of composites.
Early researches focused on the long fiber and whisker reinforced composites, such as adding graphite, SiC, Al_2O_3, B_4C and other fibers or whiskers into the AZ91 matrix.
Trojanová Zuzanka et al(2004) added 20vol. % δ-Al_2O_3 short fiber to the AZ91 magnesium alloy. In 20~300°C temperature period, the compressive test was carried on. The results demonstrated that the yield stress of the AZ91 magnesium alloy strengthened by δ-Al_2O_3 short fiber had remarkable enhancement comparing to not to be strengthened, while the experimental temperature continues to elevate the fiber reinforcement effect was not remarkable.
Zheng M Y et al (2003) inspected the aging behavior of squeeze cast SiCw/AZ91 magnesium matrix composite. The results showed that adding SiC whiskers changed the distribution of β-$Mg_{17}Al_{12}$ precipitation phase and made it maintaining an orientation relationship with SiC whisker priority precipitating at the interface between SiC whisker and AZ91. This kind of priority precipitation phase had consumed alloying element existing in the matrix, so the age-hardening effect of SiC/AZ91 was low compared to the alloy not to adding the SiC.
The complexity and high cost of the fiber and whisker reinforcement's process limited the marketing application. While the magnesium matrix composites reinforced with particles as reinforcements, because of these advantages such as high strength, high stiffness, good dimensional stability, excellent casting performance and property isotropic, become one of the most practical engineering materials. They have received people's attention.
Recently, the researches of magnesium matrix composite using particles as reinforcements mainly have concentrated on the selection of the particles and on the processing. At present, the particles mainly have TiC (CHEN et al., 2005; WANG et al.,2006), SiC(LEE et al.,2006), Al_2O_3 (HASSAN et al.,2006; HASSAN et al.,2005), TiB2(WANG et al.,2006) and so on.
WANG J J et al (2006) by infiltration process in situ reactive had fabricated TiC/AZ91D composites. The test results indicated that compared with the AZ91 alloy not enhanced, the

TiC/AZ91 alloy's high temperature longitudinal strength enhanced 180%; simultaneously, the break behavior of the alloy had also the change from along $Mg_{17}Al_{12}$ phases break to along the TiC/AZ91 surface break.
WANG Y et al (2006) had fabricated TiB_2 particle reinforced magnesium matrix composites by two-step processing method. TiB_2 in the AZ91 matrix was relatively uniform distribution. With the content of TiB_2 (2% to 7.5% in the period) increasing the hardness and the wear resistance properties of composites were improved, but the porosity also was increased.
Length scale of particle has a remarkable influence on microstructure and tensile properties of AZ91 magnesium alloy. Literature (HASSAN et al., 2005) demonstrated that the yield strength and tensile strength of the nano-Al_2O_3 particles reinforced AZ91 magnesium matrix composite enhanced higher than those micron-Al_2O_3 particles with higher volume fraction. Other, SUO ZY et al (2005) prepared reinforced AZ91 magnesium alloy with flow casting method. The research results showed that Ni-Nb Amorphous bond could enhance the tensile strength of AZ91 magnesium alloy, but the increasing rate decreased with increasing of volume fraction of the Ni-Nb amorphous band.
Particles reinforced magnesium matrix composites have made great progress. However, the factors such as particle uniformity, interface infiltration, reaction, and type, size, quantity of enhanced particle and so on are controlled by the nucleation and the growth kinetics, so further studies will be perfected (Aikin.,1997).

4. The research trends of AZ91 magnesium alloy on creep resistance property

In summary, in order to break through the bottleneck that AZ91 magnesium alloy high temperature creep resistance performance is poor, to meet the service requirements of high temperature applications such as automotive components, to promote its commercial application, many years, a series of researches have started in various countries and considerable progress has be made, but there are many problems and deficiencies.

1. In the creep performance of AZ91 magnesium alloy, whether alloy or composite, in the alloy side the researches mainly concentrated in the choice of elements or reinforcements; in the composite side mainly focused on the choice of process. The mechanism of the various elements or reinforcements influencing on the performance of AZ91 magnesium alloy remains to be further study.
2. Rare earth elements have active role in the creep resistance property of AZ91 magnesium alloy, but the rare earth elements, after all, are more expensive, it is also necessary to carry on the thorough discussion in the multiple element micro alloy aspect, aiming at in suppressing the adverse effects of single element aspect and developing the high performance-to-price ratio’s magnesium alloy. Simultaneously, those should also become further goals to improve the mechanism of rare earth elements impacting on the heat-resistant magnesium alloys, to deeply study the influences of the alkali soil elements and the IV, V group elements on the heat-resistant property of AZ91 magnesium alloy.
3. Since fiber reinforced magnesium matrix composites have the shortcomings such as the complexity of fabricating process and the obvious anisotropy of materials. While the preparation of particle reinforced the AZ91 magnesium matrix composites has diversity and economy. Therefore, they will possibly become study focus. But it is need that to further study and improve the interface structure of AZ91 matrix composites, the

forming mechanism of the interface phase, the crystal structure and surface characteristics of the reinforced phase. Through this we can control and optimize the interface to improve the properties of AZ91 magnesium matrix composites.

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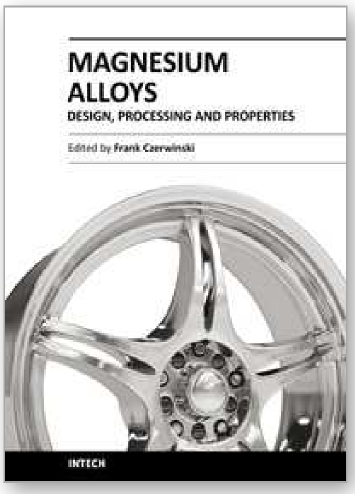

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Scientists and engineers for decades searched to utilize magnesium, known of its low density, for light-weighting in many industrial sectors. This book provides a broad review of recent global developments in theory and practice of modern magnesium alloys. It covers fundamental aspects of alloy strengthening, recrystallization, details of microstructure and a unique role of grain refinement. The theory is linked with elements of alloy design and specific properties, including fatigue and creep resistance. Also technologies of alloy formation and processing, such as sheet rolling, semi-solid forming, welding and joining are considered. An opportunity of creation the metal matrix composite based on magnesium matrix is described along with carbon nanotubes as an effective reinforcement. A mixture of science and technology makes this book very useful for professionals from academia and industry.