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Review

Applications of magnesium alloys for aerospace: A review

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Abstract

With the increasingly excellent performance of magnesium alloy materials, magnesium alloys are increasingly widely used under the urgent need for weight reduction in aerospace applications. However, due to the severe aviation environment, the strength, corrosion resistance and electrical conductivity of magnesium alloy materials need to be further improved. Many scholars are committed to studying higher comprehensive mechanical properties. Besides, they have studied surface treatment processes with space application characteristics, such as high emissivity oxidation and high anti-corrosion electroplating. To further improve the safety and reliability of magnesium alloys and expand their applications, this paper discusses several kinds of magnesium alloys and summarizes their research progress. The whole manuscript should be revised by an expert who has more experience on English writing. At the same time, the surface treatments of magnesium alloy materials for aerospace are analyzed. Besides, the application of magnesium alloy in aerospace field is summarized. With the in-depth research of many scholars, the improvement of material properties and the development of surface protection and functional technology, it is believed that magnesium alloys will be used in more and more aerospace applications and make more contributions to the aerospace field.

Keywords: Magnesium alloy; Aerospace; Application; Review; Surface treatment.

1. Introduction

As the development of space technology, it is urgent to reduce the weight of structural materials to improve the carrying capacity of payloads and comprehensive performance of spacecraft. Magnesium (Mg) alloys have great advantages such as low density, high specific strength, good biocompatibility and good electromagnetic shielding, which is an ideal metal structure material for weight reduction in aerospace applications [1–3]. However, as the spacecraft should go through special service environments such as launch vibration, vacuum, atomic oxygen, ultraviolet irradiation, electron irradiation environment [4–6] and manned space mission environment [7,8], the structural materials used in the aerospace must consider strength, modulus, adaptability to space environment, and electrical conductivity or anti-corrosion properties [9–13].

With the development of magnesium alloy, the application of magnesium alloys in space aerospace field has become more and more diverse. They are used as structural materials and energy materials, including rockets, planetary missions, resource utilization and spacecraft [14–17].

Magnesium combustion in CO_2 is considered as the primary energy production cycle [16]. In order to fully develop the resource for Mars missions, the Mg powder is employed to react with CO_2. It is found that the Mg powder and liquid CO_2 bipropellant rocket engine can work properly, delivering a qualified ignition and good combustion performance, which is shown in Fig. 1 [18,19]. The 200 kg hopper with the 25–30 kg CO_2/Mg rocket propulsion system and 9–13 kg CO_2 acquisition unit can perform 10–15 hops on Mars's surface with a total range of 10–15 km for 180 Martian days, which

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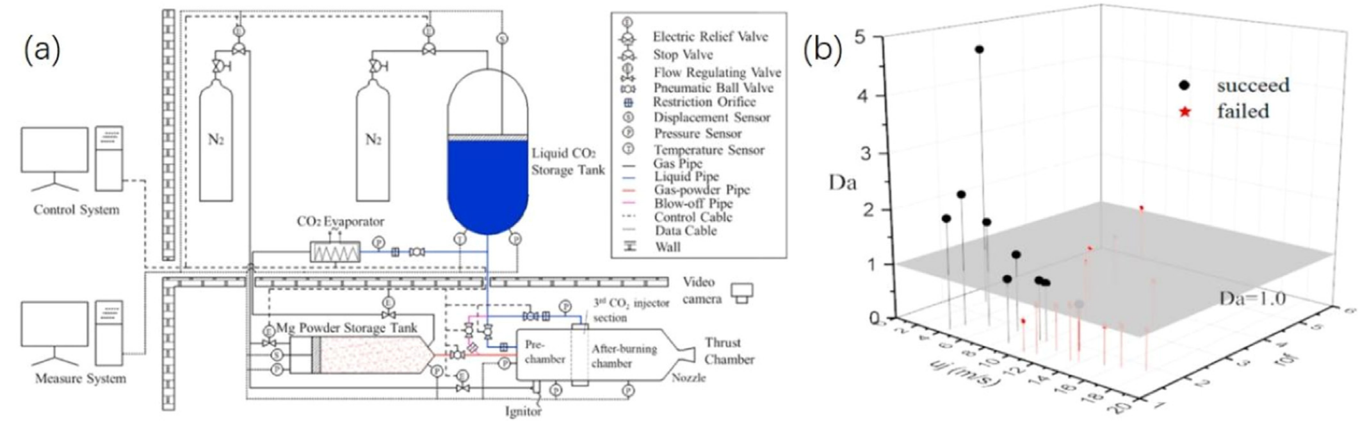

Fig. 1. Experimental system of powdered Mg and liquid CO_2 (a) and results of stable flame under different operating conditions (b) [18].

can significantly increase the range of hopper and decrease the duration of mission [20].

Magnesium has been found in the form of olivine (Mg, Fe_2SiO_4), containing 32% of magnesium oxide (MgO) [21]. Magnesium can be used to form stand-alone structural members and has unique physical characteristics, such as electromagnetic shielding, which makes it suitable for extraterrestrial construction [22,23]. To reduce the cost of sustained space program, the magnesium obtained from asteroidal and planetary soils is identified as possible fuel for the hybrid rocket propellants, thereby facilitating the exploration and industrialization of the inner solar system [24]. It has been proposed to use combustion of lunar regolith with Mg for the production of construction materials on the Moon missions [25].

In this paper, it is focused on the application of magnesium alloys in spacecraft. The application and needs of special properties of magnesium alloys for space service are reviewed. By discussing the differences in surface function between space and earth, some suggestions are listed to promote the application and development of new magnesium alloys in the aerospace field.

2. Development of Mg alloys for space applications

As the lightest metal structural engineering material, magnesium alloys show important application prospects in transportation, energy, aerospace and other fields because of its high specific strength, high specific stiffness, strong damping and vibration reduction, good liquid formability, shielding electromagnetic radiation, and easy recycling, etc. [26–29]. However, the poor high temperature strength and poor corrosion resistance severely limit the wide application of magnesium alloys [9,30,31]. Adding alloying elements is an effective method to solve this problem. By adding different alloying elements (such as Al [32,33], Mn [34,35], Zn [36–38], Si [39,40], Ca [29,41,42], Li [43,44], RE [9,45–48], etc.), the microstructure and structure of the alloys can be adjusted to achieve the expected properties.

2.1. RE-free Mg alloys

According to whether the main elements added are rare earth elements (RE), magnesium alloys are divided into RE-free Mg alloys and containing RE Mg alloys. RE-free Mg alloys mainly include Mg-Al-based and Mg-Zn-based alloys. Mg-Al-based alloys are the most widely used, including AZ series (Mg-Al-Zn), AM series (Mg-Al-Mn) and AS series (Mg-Al-Si), etc. [33]. Mg-Zn alloy has poor high temperature performance, and the aging strengthening ability is weak [49]. Appropriate addition of zirconium (Zr) can refine the grain and improve the mechanical properties of the alloy. ZK series (Mg-Zn-Zr) is one of the most widely used Mg-Zn-based alloys [50].

AZ series is the most widely used die-casting magnesium alloy. However, the mechanical properties of AZ series are relatively poor. So far, much research has been carried out to solve the problem, including adding alloying elements [29,41], work hardening [36,49], etc. Idris Gokalp et al. [29] investigated the effect of Ca addition on elevated temperature mechanical properties of AZ series magnesium alloys. With the increase of added Ca and Al content, more $(Mg,Al)_2Ca$ and Al_2Ca phases precipitated in grain boundaries and interiors. AZX211 alloy possesses the optimum tensile properties. The tensile and yield strengths at 25 °C are 152 ± 5.4 MPa and 95 ± 4.1 MPa, respectively. Chaudry et al. [51] studied the superplasticity of AZ31 magnesium alloy containing 0.5 wt.% Ca. The addition of Ca results in the precipitation of fine second phase particles at grain boundaries, and the microstructure stability is improved, leading to the alloy's superplasticity of the alloy at 300 °C.

AM series has excellent toughness and plasticity, and is used for workpieces with high impact load and bending resistance requirements. It is often used in wheels, doors, seat frames and equipment dashboards. However, due to the poor thermal stability of the β-$Mg_{17}Al_{12}$ phase, the heat resistance of AM magnesium alloy is poor, which limits its application to a certain extent. Rare earth elements combined with Al in magnesium alloy produce Al-RE compounds with a high melting point, which is beneficial for improving high temperature performance [52]. Han et al. [34] studied the effects of different Ce content on the microstructure and tensile properties of AM80 alloy at room and high temperatures. With the addition of Ce, the alloy consisted of α-Mg, β-$Mg_{17}Al_{12}$ and Al_4Ce, and the microstructure was refined. When the amount of Ce is 1.5 wt.%, the maximum tensile strengths at room temperature and high temperature are 175.9 MPa and 146 MPa, respectively.

AS series containing a low aluminum content possesses good strength and excellent toughness. Due to the addition of Si, the stable precipitated Mg_2Si phase with fine and dispersive distribution is formed at the grain boundary, and the creep resistance of the alloy is improved. The morphology, size and distribution of the Mg_2Si phase significantly influence the alloys' properties. Fine and dispersive particles are beneficial for improving the mechanical properties of the alloy, whereas coarse Mg_2Si particles can deteriorate the mechanical properties of the alloy [39]. The refinement and uniform distribution of Mg_2Si particles is the key to improving the properties of alloys. Chen et al. [53] refined the grains and $Mg_{17}Al_{12}$ s phase of AS41 magnesium alloy by alternating frequency ultrasonic melting technology eliminating the accumulation of Mg2Si and improving the strength of the alloy.

ZK series has good comprehensive mechanical properties. According to ASTM standard, Mg-Zn-Zr alloy mainly includes ZK21A, ZK31, ZK40A, ZK60A, ZK51A and ZK61, etc. [54]. Among them, ZK60 alloy is a typical superplastic magnesium alloy with good comprehensive properties at room temperature, and the extrusion elongation is more than 17% [55], which has attracted more and more attention. Liang et al. [56] fabricated ZK60 Mg alloy by laser powder bed fusion (LPBF), and analyzed the effect of preheating temperature on microstructure and mechanical properties of LPBF-treated ZK60 alloy. The specimens treated at a preheating temperature of 180 °C exhibit the best comprehensive mechanical properties (yield strength of 201 ± 5 MPa, ultimate tensile strength of 291 ± 7 MPa, and elongation of 14.7%± 0.8%).

2.2. Containing RE Mg alloy

Rare earth elements (RE) in magnesium alloys can not only be dissolved but also form high melting point intermetallic compounds with different types, distributions and morphologies, refined grains, and improve the casting properties and mechanical properties of alloys. At present, the widely used Mg-RE alloys are Mg-Gd, Mg-Y, Mg-Nd, Mg-Sm, etc. [33,57,58]. Compared with the traditional Mg-Al or Mg-Zn series alloys, the developed high performance Mg-RE alloys have higher mechanical properties and relative density.

The limit solubility of Gd in magnesium is extensive, reaching 24 wt.% at 542 °C, and the solution solubility decreases with the decrease of temperature, reaching only 4 wt.% at 200 °C. Mg-Gd alloy is a typical aging strengthening alloy, and many nanoscale precipitates formed during aging make the alloy have excellent mechanical properties at room temperature and high temperature [31,59,60]. In addition, the addition of Gd element also improves the corrosion resistance of the alloy, and the β' phase content precipitated by aging plays a decisive role in the corrosion resistance of the alloy [61]. Other Mg-Gd-RE alloys developed on this basis, such as Mg-Gd-Nd [62], Mg-Gd-Y-Nd [63] and Mg-Gd-Sm [64], have good performance at room temperature and high temperature. The JDM2 alloy developed by Shanghai Jiao Tong University is a high-strength Mg-Gd-Y alloy with more than 10 wt.% Gd [27]. At room temperature, the tensile strength and yield strength are 370 MPa and 240 MPa, respectively, and the elongation is about 4%. Chongqing University has studied the Mg-xGd-0.6Zr alloy with 2 wt.%–6 wt.% Gd [65], and developed the high plasticity Mg-Gd alloy with moderate strength, and the plasticity is more than 30%. Gao et al. [66] studied the mechanical properties of Mg-Gd-RE alloy with Zn or Ag element, and found that the mechanical properties of Mg-Gd-RE alloy under peak aging condition were higher than those of Mg-Gd-RE alloy with β' phase as strengthening phase precipitated only on the prismatic surface.

Due to the high solubility of Y in the α-Mg matrix and the strong aging hardening ability of magnesium alloys containing Y, Mg-Y alloys have attracted wide attention [48,67]. Mg-Y-RE ternary alloy has been widely studied and applied due to its good high temperature strength and creep resistance [68]. Currently, two kinds of alloys, WE43 and WE54, with the highest degree of commercialization, have been developed, which can maintain excellent mechanical properties in the service environment up to 300 °C and are widely used in aerospace power system components [69,70]. The addition of 0.2% Zn to WE43 alloy can significantly shorten the alloy's peak aging time, and the alloy's tensile properties, especially the elongation, are significantly improved [71]. The oxidation tendency of rare earth element Y is greater than that of Mg and other rare earth elements at high temperatures, which leads to the oxidation and burning loss of Mg-Y alloys in the casting process, and the introduction of Y2O3 inclusions into the melt affects the purity of the melt. In order to solve this problem, Gd element can be used to partially replace Y element while keeping the total amount of rare earth elements unchanged. The optimized Mg-2Y-3Gd-2Nd-0.5Zn alloy has not only good casting process performance but also its room temperature and high temperature mechanical properties are equivalent to WE43 alloy, which is more suitable for producing thin-walled complex aerospace casting products [72].

Nd is a light rare earth element, and its maximum solid solubility in magnesium can reach 3.6%. The Mg-Nd alloy with solution treatment can precipitate a series of metastable strengthening phases during aging, which has a strong aging strengthening effect [73]. The grains of cast Mg-Nd binary alloys are often coarse and cannot meet the service performance requirements as structural materials. Therefore, it is usually necessary to add Zr to refine the grains to improve the mechanical properties. Wang et al. [74] studied the effect of adding 0.5% Zr on the microstructure and properties of Mg-2.7Nd-0.6Zn alloy. It was found that Zn_2Zr_3 nano-strengthening phase was formed in the alloy after solution treatment, which significantly improved the hardness of the alloy. In addition, the high-strength heat-resistant Mg-Nd-Zn-

Zr alloy (ZM6) has excellent mechanical properties (tensile strength > 250 MPa, elongation > 7%) and corrosion resistance [75]. It is stable in the high temperature environment of 250 °C and has been widely used in defense industry.

Sm has high solid solubility in magnesium [76]. At the eutectic temperature of 542 °C, the maximum solid solubility of Sm in Mg is 5.8 wt.%, so Sm has good solid solution strengthening and aging strengthening effects in Mg alloys. For Mg-Sm binary alloys, scholars have conducted a lot of research on the aging precipitation process and precipitates of Mg-Sm binary alloys. Xie et al. uncovered a diffusional-displacive dominated formation mechanism for the $\beta1$ phase of Mg-Sm binary alloy [77]. Li et al. [6] found that the aging precipitation sequence of Mg-4Sm-0.4Zr alloy is super-saturated solid solutions (S.S.S.S) $\rightarrow \beta'' \rightarrow \beta' \rightarrow \beta1$ (fcc) $\rightarrow \beta$ (bct). After continuous in-depth research, people have deepened the understanding of the aging process of Mg-Sm alloy. Compared with other high strength magnesium alloys, the strength level of Mg-Sm binary alloy is still low. In order to further improve its mechanical properties, other rare earth or non-rare earth elements, such as Gd [46], Y [78], Zr [54], Zn [64] and Yb [47], were added to the Mg-Sm binary alloy for multi-alloying to optimize the microstructure of the alloy. The mechanical properties of the Mg-Sm alloy were improved by fine grain strengthening, solid solution strengthening and second phase strengthening. Mao et al. [46] studied the effect of Y element on the microstructure and mechanical properties of Mg-4Sm-0.6Zn-0.5Zr alloy. The mechanical properties of Mg-4Sm-7Y-0.6Zn-0.5Zr alloy increase with the increase of Y content. When the Y content reaches 6.89%, the yield strength, tensile strength and elongation of as-cast Mg-4Sm-7Y-0.6Zn-0.5Zr alloy are 118 MPa, 193 MPa and 10.5%, respectively.

2.3. *Superlight Mg-Li alloys*

Mg-Li alloys have attracted much attention due to their advantages of high specific strength, good damping properties, excellent electromagnetic shielding properties, and good forming properties [79,80]. Moreover, the density of Mg-Li alloy is 1.35–1.65 g/cm^3, which is 1/3–1/4 lighter than the traditional Mg alloy [81–83]. Thus, Mg-Li series alloys are a class of ultra-light alloys that can effectively promote the lightweight process in aerospace, 3C, et al. At present, the most commercial Mg-Li alloys are LA141, LA91, LAZ933, etc. The microstructure and mechanical properties of Mg-Li alloys will differ with the Li content change. When the Li content is below 5.7 wt.%, the Mg-Li alloy is α-Mg phase (hexagonal crystal structure, HCP); when the Li content is 5.7 wt.%–11.5 wt.%, it is α-Mg phase and β-Li phase (body-centered cubic structure, BCC); when the Li content is more than 11.5 wt.%, the Mg-Li alloy is the β-Li phase. However, the low absolute strength and poor corrosion resistance of Mg-Li alloy greatly limit its further application. Therefore, many researchers consider methods such as alloying and deformation to strengthen Mg-Li alloys.

LA alloys are one of the most commonly used alloys in Mg-Li alloys and have been used in weapons and aerospace. The density of Al is similar to Mg, and the Al element has an excellent solid solution strengthening effect in Mg-Li alloys. However, ternary Mg-Li-Al alloys have the problems of low mechanical properties and poor thermal stability. Guo et al. [84] studied the effect of solution treatment on Mg-9Li-6Al alloy. The result shows that MgLi2Al dissolved in the β-Li phase and the AlLi phase precipitated in the α-Mg phase during the solid solution. Meanwhile, the hardness of the alloy is improved after solution treatment. Al element refines the grain of as-cast Mg-14Li alloy with the influence of solute elements [85]. Takahiro Mineta et al. [86] prepared Mg-Li-Al alloy by multi-directional forging and heat treatment process. The specific yield strength of LA143 alloy reached 263 kN·m·kg-1. Tang et al. [87] investigated grain boundary decohesion in Mg-Li-Al alloy. The results showed that the grain boundary precipitation (GBPs) formed by Al-rich ordered phases would weaken the bonding between the atoms in the grains. Particles free zone (PFZ) would be formed near the GB, which would easily lead to local stress exceeding the cohesion of the grain boundary, resulting in intergranular/cleavage fracture of the alloy.

LZ series are also common Mg-Li alloys with good mechanical properties and clinical application potential. Wu et al. [88] studied the corrosion resistance of LZ61-KBMS (Kumta Bioresorbable Magnesium Stents) alloy was evaluated in a simulated dynamic flow environment juxtaposed. They realized the feasibility of ultra-high ductility LZ61-KBMS alloy biodegradable airway stents. Zhou et al. [89] studied the microstructure and mechanical properties of LZ91 alloy after friction stir welding (FSW). The results show that the stir zone of the alloy is composed of fine equiaxed α-Mg and β-Li phases, and they realized the optimized strength and ductility in the stir zone. Zhang et al. [90] prepared high strength Mg-13Li-9Zn by solid solution, annealing and rolling. The pure grain boundary supersaturated solid solution obtained during annealing contributes to the introduction of α-Mg nanoparticles and ordered B2 nanoparticles into the β-Li matrix during subsequent rolling. The yield strength of the alloy is 380 MPa and the specific yield strength is 251 kN·m·kg-^{1}. Yang et al. [91] studied rolling and annealing processes on LZ91 alloy. With increasing the rolling reduction and adequate annealing process, the corrosion resistance of the alloy continues to increase.

LT series has good thermal stability and high mechanical properties, which are a kind of alloy with great development potential. Sn element can refine the grains of as-cast alloy and promote Mg-Li alloy to obtain equiaxed grains. Besides, adding Sn can form dispersed Mg_2Sn and Li_2MgSn phases with good strengthening effects and thermal stability in the Mg-Li alloy. Zhou et al. [92] studied the effect of extrusion on Mg-Li-Al-Sn alloy. The results show that after extrusion, abundant dispersed Sn-rich phases exist in the alloy, and massive $\langle c + a \rangle$ dislocations are activated, which contributes to the improvement of the strength and plasticity of the alloy. The room temperature tensile strength and elongation of Mg-7Li-2Al-1.5Sn alloy reached 324 MPa and 11.9%, respectively. The high temperature (423 K) tensile strength and elongation of Mg-7Li-2Al-1.5Sn alloy reached 237 MPa and 26.7%, respectively. Maurya et al. [93] prepared LAT971 alloy by solution treatment. The AlLi phases are entirely dissolved in the matrix after the alloy is dissolved above 350 °C. At the same time, the existence of thermal stable Mg_2Sn phases improves the hardness and tribological properties of the alloy after solid solution. Acikgoz S compared the effect of Sn, Nd, and Ca elements on Mg-8Li-2Al alloy [94]. The results show that adding Sn element has the best effect on improving the alloy's mechanical and corrosion properties.

LX series alloys, as a kind of alloy with good biocompatibility, have also received extensive attention from researchers [95]. The Ca element can improve the microstructure and mechanical properties of Mg-Li alloys. Gao et al. [96] investigated the microstructure and mechanical properties of Mg-9Li alloy and Mg-9Li-0.3Ca alloy after extrusion by comparative analysis. The results show that adding Ca weakens the texture and increases the proportion of DRX grains to improve the plasticity of the alloy. In addition, Ca, as a major component of human bone, can be combined with Mg-Li alloys to play an important role in biomedicine. Cui et al. [97] prepared an infection-resistant coating on biomedical Mg-Li-Ca alloys. Mg-1Li-1Ca alloy has good antibacterial properties and corrosion resistance with Ca-P-Sn coating. Han et al. [98] studied the corrosion characteristics of as-extruded dual-phase Mg-Li-Ca alloy in Hank's solution. As-extruded Mg-Li-Ca alloys undergo overall corrosion, and the corrosion products are jammed into the micro-cracks of the natural oxide film. In addition, they proposed a new concept of the Pilling-Bedworth ratio to elucidate the corrosion mechanism of dual-phase Mg-Li-Ca alloys.

Moreover, the addition of Mn [99], Nd [100], Er [101], Y [102], and other elements can also improve the mechanical properties and damping properties of Mg-Li alloys. For example, Yang et al. [99] reported that as-extruded Mg-4Li-3Al-0.3Mn alloy has high strength and damping properties. Wu et al. [101] investigated the origin of age hardening and age softening of Mg-Li-Zn alloy. They improved the age softening of Mg-Li alloy by adding Er element. Although Mg-Li alloy research has made many achievements, critical issues of Mg-Li alloys still need to be solved. For instance, the corrosion mechanism of Mg-Li alloy has not been thoroughly studied, and the alloying mechanism of Mg-Li alloy is unclear, especially the influence of different alloying elements within the dual-phase matrix.

3. Surface treatment of magnesium alloys for space applications

Although magnesium offers the potential for considerable weight savings, it does not come without some drawbacks, namely corrosion and flammability. With the use of Wenchang launch site, the corrosion of magnesium alloy is one of the key problems affecting its aerospace applications. The corrosion resistance of magnesium alloy is extremely poor due to the high electrochemical activity of magnesium [103,104]. Many efforts have been made to improve the corrosion properties of magnesium alloys, such as treatments, electroplating, chemical conversion films, oxidation films, coatings and other related surface-treating processes [105–109]. However, there is something different about the surface treatment of magnesium alloys for aerospace applications compared with that used in earth. It should satisfy the function demands and space environment requirements, which need to add thermal control, electrical conductivity, welding and other functions in addition to anti-corrosion.

Fig. 2. Morphology of micro-arc oxidation coatings with thermal control of magnesium alloys [110].

3.1. Thermal control coatings of magnesium alloys

Thermal control coatings are the most commonly used aerospace functional coating, which is used to control the temperature by the ratio of solar absorptance (αS) and emittance (ε) on the surface, namely $\alpha s/\varepsilon$. Electrochemical conversion coatings by chemical oxidation, micro-arc oxidation and so on are often employed to obtain thermal control coatings [110,111]. By adding iron salt and vanadium salt in the micro-arc oxidation process, a thermal control film with infrared emissivity $\varepsilon \geq 0.85$ was obtained, and it had good corrosion resistance and was successfully applied in aerospace (Fig. 2) [110,112,113]. Wang et al. [114] prepared several colorized coatings with solar absorptance from 0.439 to 0.918, expanding the application of magnesium alloys. The electrolytes have a great influence on the property of the coating: Phosphate is about equal to silicate, and silicate is greater than aluminate. The thermal control performance of phosphate coating is the best. The higher the blackness of the coating, the better the absorption of the coating [115]. However, the corrosion properties of the thermal control coating still have to be improved.

3.2. Conductive coating of magnesium alloys

Nickel-plating technology is another common surface treatment process for aerospace, which can obtain good conductive corrosion resistance and meet the welding needs of magnesium alloy [1,2]. The process, corrosion properties, and deposition mechanism of Ni-P coating are widely studied [116–121]. The Ni-P coatings are not only formed during the coating growth stage, but also generated in the initial deposition stage of electroless Ni-P plating [117]. The typical

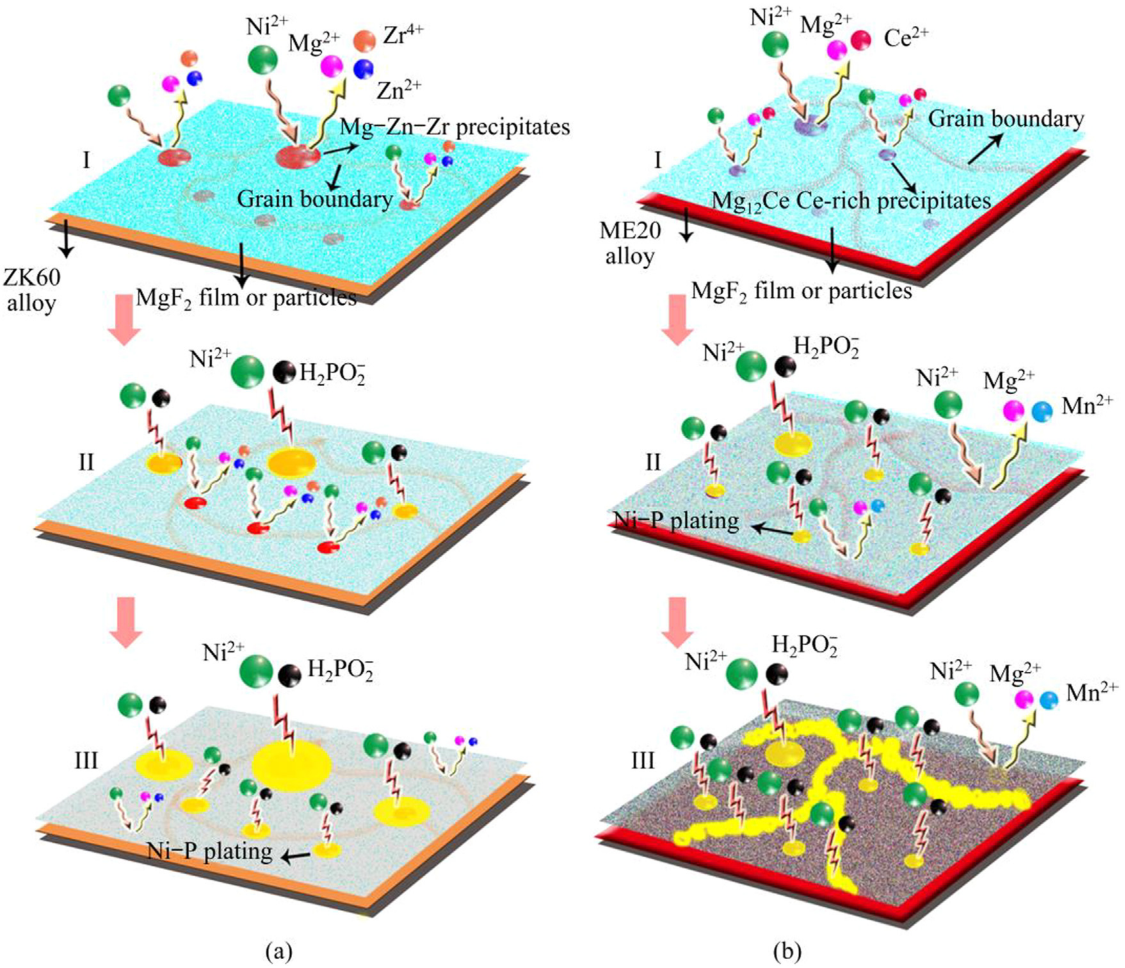

Fig. 3. Initial deposition process of electroless Ni-P coating on ZK60 (a) and ME20 (b) alloys [2].

growth mechanism of Ni-P plating of ZK60 and ME20 is given in Fig. 3. The initial deposition of the coating on ZK60 alloy occurs preferentially on highly active Zn-Zr precipitates and the compactness of the MgF_2 film mainly control the initial deposition of the coating on ME20 alloy. The coating properties can be improved by a ternary ligand system [118], transition layer [119,120], pretreatment [121], and so on. The bi-layer coating is formed, composed of a micro-arc oxidation coating (MAO) and an electroless plated Ni-P coating, and the corrosion property is improved by 2.8 times [122].

3.3. Other functional surface treatment of magnesium alloys

Other coatings with special properties, such as wear, anti-corrosion et al., may also be used in aerospace [106,123–125]. Sun et al. [123] fabricates a Fe-based amorphous coating, the wear property of which is 170 times higher than that of the bare LA141 magnesium alloy substrates, which may be applicable to aerospace structures or mechanisms. Wang et al. prepares a super-hydrophobic and corrosion-resistant coating with thin thickness [125], which may be used inside the manned cabin. The high bactericidal property and low vacuum performance are also expected when used in the manned cabin. By adding antibacterial metallic elements or biopolymer/calcium phosphate coating based on micro-arc oxidation coatings can improve these properties [124].

4. Spacecraft applications of magnesium alloys

In the 1950s and 1960s, the United States carried out a lot of research on magnesium-lithium alloys, and used them as secondary structural materials such as brackets, bushing, beams and other structures in the aerospace field. The Soviet Union also developed MA21 and other brands for lunar landers (Fig. 4) [56,126,127].

Magnesium alloy components have also been used in satellites and spacecraft in China. Beijing Spacecrafts Manufacturing Factory Co., Ltd. solved the anti-corrosion treatment, machining and welding technology problems of large magnesium alloy surfaces, and has realized the application of large magnesium alloy structures on multiple spacecraft. The G04 magnesium alloy developed by the Institute of Metals of the Chinese Academy of Sciences has been successfully used in the electric cabinet of the Shenzhou VI manned spacecraft, reducing its weight by about 13 kg. The National Engineering Research Center for Light Alloy Precision Form-

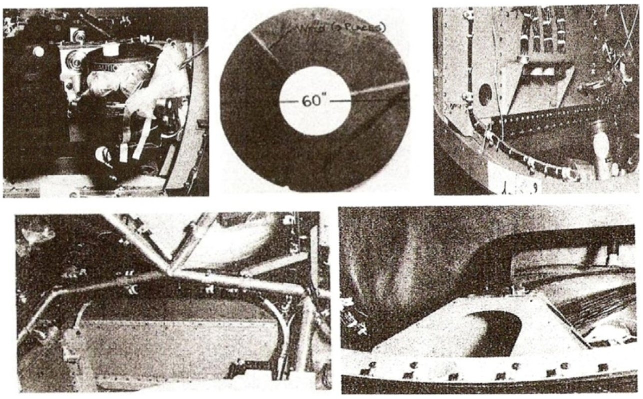

Fig. 4. The Mg alloy developed by Lockheed for the satellites. (The gyroscope installation frame plate, the vibration diaphragm at the load transfer joint, the corner tray for installing electronic devices, the drawer partition, and the microwave device installation frame, respectively).

Fig. 5. Satellite bracket.

ing of Shanghai Jiao Tong University has prepared a variety of aerospace components, which meet the operating requirements of a satellite and Mars probe and achieve a weight reduction effect of 20%–30% (Fig. 5) [128–130].

4.1. Applications for structure material of spacecraft platform

The structural material is the main body of the satellite and accounts for the main weight of the satellite platform. When used magnesium for structural materials instead of aluminum alloy, the traditional aerospace metal structural material, it can reduce the weight of the structure obviously. A panel for panel extension satellite is shown in Fig. 6, the test model made by aluminum is about 700 g. Moreover, it can be calculated that the weight of this design made of magnesium is less than 500 g [131].

Electronic chassis is one of the most widely used magnesium alloys. A typical electronic package for spacecraft application consists of Printed Circuit Boards (PCBs), electronic components and supporting structures. With trade-off between weight, strength, stiffness, radiation and Electro Magnetic Interference (EMI) protection, magnesium is always used as the supporting structure, as shown in Figs. 7 and 8 [132].

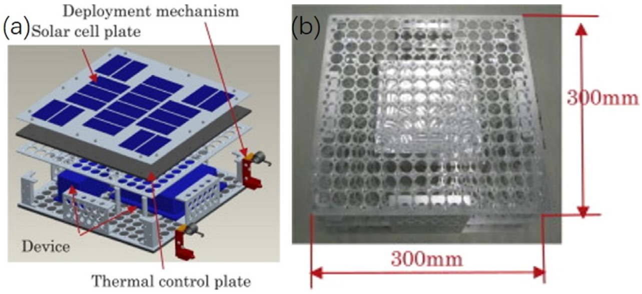

Fig. 6. Composition (a) and structure (b) of panel for panel extension satellite [131].

Although it is not as strong as aluminum on a weight basis, magnesium is approximately 30% lighter. Application of magnesium in electronic chassis can result in weight savings of approximately 25% over aluminum, containing the plating on the magnesium surface (8).

With the improvement of magnesium alloy's toughness, corrosion resistance, forming performance, etc., magnesium is gradually considered for use in products such as brackets, storage tanks, heat pipes, honeycomb panel skins, and embedded parts [14,133,134]. However, the lightweight of structure causes a lowering of stiffness, thus the way for weight saving for some structures is not so flexible, and the same value of stiffness must be kept while weight saving. Moreover, some other properties need to be considered. When used as the seat structure, the flammability properties are needed to be considered. Two types of magnesium alloys are investigated in separate tests and the results showed that the magnesium alloy of WE43 has a well-performing, a poor-performing for AZ31, respectively [135,136].

Magnesium alloys may also be used in structural plates. Through the development of magnesium alloy skin and honeycomb, the weight of the structural plate can be effectively reduced. Magnesium foam has been studied and the foam with 50 wt.% carbamide sintered at 630 °C has a density of 0.61 g/cm^3, porosity of 64.7% and compressive strength of 5 MPa [137]. Chongqing University independently developed a new type of high-strength rare earth magnesium alloy, and trial produced components for a certain type of spacecraft with low pressure casting [138]. The engineering application research of large and complex magnesium alloy components has also been developed and successfully realized. Shanghai Aerospace Precision Machinery Research Institute s has carried out research on the engineering application of magnesium alloy for large-size and complex components in recent year. They developed the high-performance heat-resistant casting VW63Z, which has realized the batch engineering application of VW63Z magnesium alloy in the aircrafts with high mechanical properties under the engineering conditions of large melting volume and slow cooling of the sand. It meets the indexes of room-temperature tensile strength of the casting body $\geq$ 300 MPa and high-temperature tensile strength of $\geq$ 280 MPa [139].

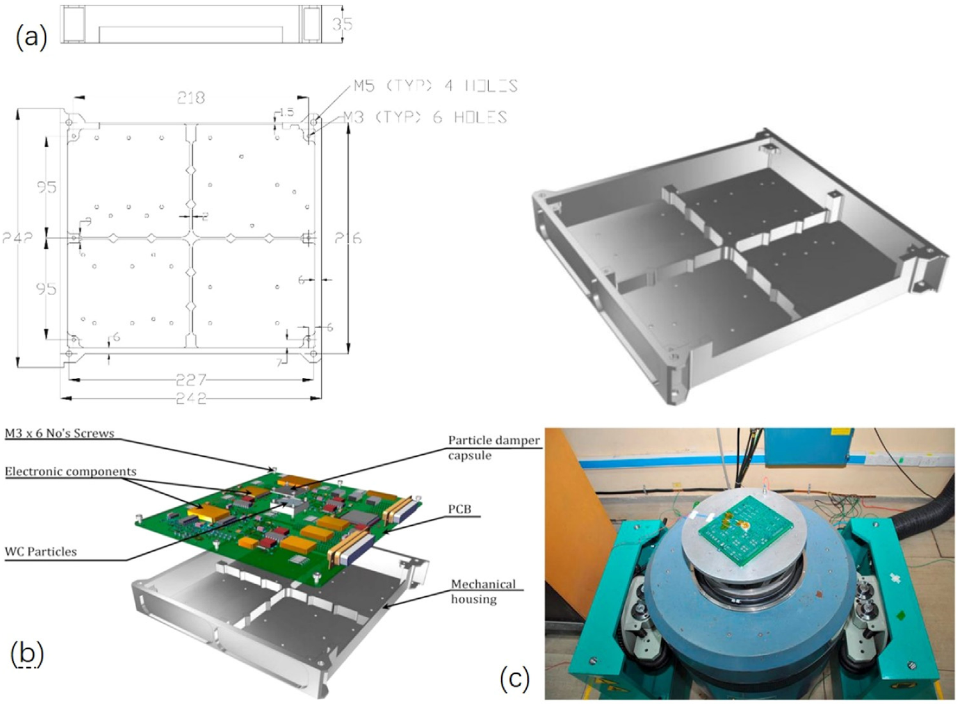

Fig. 7. The application of magnesium as structure (a) and its electronic package (b), and random vibration test (c) [132].

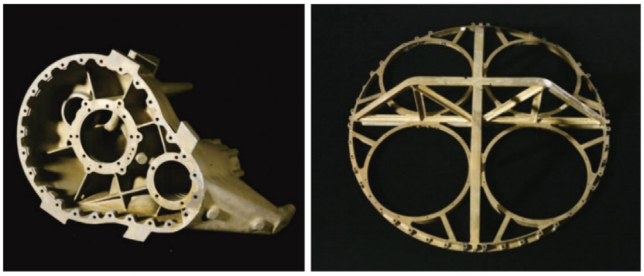
Gearbox
Rackets

Fig. 8. Large-size magnesium alloy products developed by Shanghai Spaceflight Precision Machinery Institute.

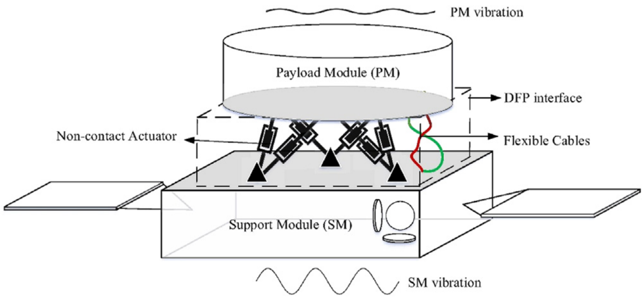

Fig. 9. Disturbance-Free payload architecture of spacecraft [140].

Fig. 10. The scientific payloads of CE-5 [142].

4.2. Applications in spacecraft payload

Payload is the most important part of the satellite, which has an important influence on the performance of the satellite. The typical payload layout and load type are shown in Fig. 9 and Fig. 10, respectively [140–142]. The application of magnesium alloy for some effective loads can reduce weight and optimize performance.

The antenna is a typical payload, which is often used in various space communication systems. The antenna consists of a conical corrugated horn, waveguide, and feed generating high-frequency electromagnetic radiation, shown in Fig. 11 [143–145]. To perform successfully during launch and on-orbit, space antennas must be strong, stiff, and lightweight with small thermal distortions [146]. With specific strength, specific rigidity, elastic modulus and good high and low temperature toughness, magnesium has been tried to use as the waveguide of the antenna [147,148]. Li et al. [147] pointed

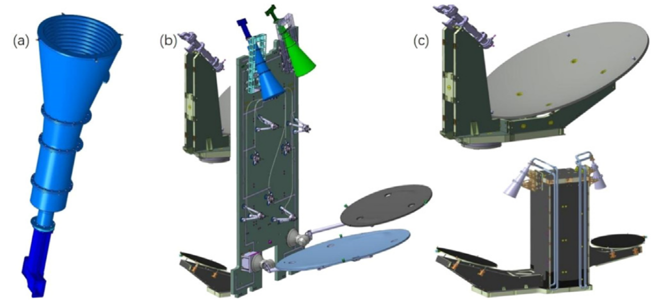

Fig. 11. Metallic corrugated horn antenna (a), corrugated horn feeds (b) and conventional designs of the offset mirror antennas (Courtesy of ISS – Reshetnev Company) (c) [143,144].

Table 1
Key parameter comparisons between magnesium and lithium metals for rechargeable metal ion batteries [151,155].

Information	Lithium	Magnesium
Market price (k$/ton)	64.8	2.7
Volumetric capacity (mAh·cm^{-3})	2061	3833
Gravimetric capacity (mAh·g^{-1})	3884	2206
Anode potential versus SHE (V)	–3.04	–2.36
Stability in air?	No	Yes
Dendrite growth?	Yes	No
Atomic weight	6.9	24.3
Cationic radius (nm)	0.068	0.065

out that the weight of the antenna parts could be reduced by about 20%, considering the structure strength and the antenna products based on magnesium alloy would be more widely used in the aerospace field. S. F. Zhou and Z. X. Xu demonstrated that after seven months of ground environment and more than one year of space environment test, the gold-plated magnesium alloy layer of the communication satellite omnidirectional antenna has been in good use, and the signal returned to the ground is clear and normal [149,150].

Magnesium alloys are also designed and fabricated for applications to space-borne telescopes and optics in instruments. A 175-mm magnesium-alloy mirror with a spherical mirror surface and a backside hexagonal cutout structure reduce the mass of the mirror, as shown in Fig. 12 [151].

4.3. Applications in energy subsystem of spacecraft

Magnesium alloys have good energy storage and electrical properties, so they are widely studied as energy materials, which can be used in the energy subsystem of spacecraft [152–154].

Mg is a lightweight metal (1.74 g·cm^{-3} density) yielding a theoretical volumetric capacity of magnesium (3833 mA·h·cm^{-3}) that is twice that of lithium (2061 mA·h·cm^{-3}), and the properties compared with Li-ion batteries are listed in Table 1 [151,155]. According to the table data, rechargeable magnesium battery is a high-safety energy storage technology that may have potential applications in aerospace. Magnesium can also be used as energy carriers for renewable and thermal energy storage. A concept of thermal battery based on advanced metal hydrides is studied for the heating and cooling of cabins in electric vehicles [156].

Fig. 12. The fabricated 175-mm spherical magnesium-alloy mirror. The left and the right panels show the mirror surface and backside of the mirror, respectively.

Fuel cell is one of the most important energy sets, which may be applied to aerospace and the hydrogen storage ability is the key problem of lightweight in space application for the fuel cells. Hydrogen storage in magnesium compounds is believed to be one of the most promising hydrogen-storage technologies for high efficiency, low risk and low cost [157,158]. The hydrogen capacities can reach 14.9 wt.% by mass and 145–147 kg·cm^{-3} by volume, which has a significant weight advantage over current cylinder hydrogen storage. Thus, it is a promising hydrogen storage material for space fuel cell applications.

Declaration of competing interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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