

Research Status and Application Prospect of Aluminum Matrix Composites

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Abstract:

Aluminum matrix composite is one of the most attractive metal matrix composites. It is a kind of material with strong vitality emerging in response to the needs of modern scientific development. Compared with traditional materials, aluminum matrix composites have the advantages of low density, good electric conductivity and heat conductivity, good wear resistance and oxidation resistance, high specific strength and stiffness, high temperature resistance, good heat treatment performance and flexible preparation process, which make them widely used in the fields of aviation, aerospace, and automobile. In this paper, the factors affecting the properties of aluminum matrix composites, the strengthening mechanism, classification and preparation methods of aluminum matrix composites are summarized. The research status, development direction and application prospect of aluminum matrix composites are briefly introduced.

Keywords: aluminum matrix composites; research status; application prospect

1. Introduction

Metal matrix composites (MMCs) are composite materials with metal or alloy as matrix and fiber, whisker or particle as reinforcement phase^[1,2]. With the increasingly serious threat of energy and environmental problems to human survival, people's demand for lightweight high-strength metal matrix composites with multiple structures and functions is growing^[3]. Aluminum matrix composites (AMCs) have been paid more and more attention because of their advantages, such as low density, good conductivity and thermal conductivity, good wear resistance and oxidation resistance, high specific strength and stiffness, high temperature resistance, good heat treatment performance and flexible preparation process. As early as 1924, Schmit studied the preparation of Al₂O₃/Al composite by sintering. In the 1960s, aluminum matrix composites became an important branch of composites. In the 1980s, Toyota first applied ceramic fiber reinforced aluminum matrix composite to the piston of diesel engine and achieved some success. In recent years, aluminum matrix composite materials have attracted much attention, which benefits from its unique, light, hard and strong characteristics for engineers in many fields. Compared with alternative materials that may be considered in the same type of application, aluminum matrix composite

materials have many advantages, such as high strength and rigidity, corrosion resistance and wear resistance and can be produced and prepared by common equipment^[4]. Alvant, a British company famous for exploring liquid pressure forming (LPF) as a process for manufacturing aluminum matrix composite materials, announced in 2018 that at the invitation of the project leader of Safran landing systems, a first-class system and equipment supplier in the aerospace and defense industry, it will participate in a two-year £ 28 million project entitled "future large landing gear"^[5]. At present, a large number of researchers and research institutes at home and abroad have carried out research on aluminum matrix composites^[6-9]. In this paper, the factors that affect the properties of aluminum matrix composites, the strengthening mechanism of aluminum matrix composites, the classification and preparation methods of aluminum matrix composites, the application at home and abroad, as well as the application prospect and development trend at home and abroad are reviewed and the future development direction and application prospect of aluminum matrix composites are predicted.

2. Factors affecting the properties of Aluminum Matrix Composites

The properties of composite materials have a great

relationship with the types of matrix alloys and reinforcements (including microstructure, distribution and volume fraction of reinforcements, etc.) [10,11].

2.1 Selection of matrix

At present, Al-Cu, Al-Mg and Al-Si are the main aluminum matrix. Different aluminum matrix has different properties, so the wettability, performance complementarity and practical application requirements of the matrix material are mainly considered in the selection [12].

In the process of preparing aluminum matrix composite, both pure aluminum and aluminum alloy can be used as the matrix, but generally, aluminum alloy is selected because there are alloy elements in aluminum alloy, which can not only strengthen the matrix alloy, but also form metal compound precipitates with the matrix metal. In addition, aluminum alloy also has advantages of corrosion resistance, good conductivity and thermal conductivity, good recycling and no low temperature brittleness [13].

The selection of matrix is generally as follows: if the strength of the matrix is required to be high, aluminum

copper alloy can be used; if the matrix is required to be light, aluminum lithium alloy can be used; if the matrix is required to have a high heat-resistant temperature, aluminum iron alloy can be used.

2.2 Selection of enhancement phase

The microstructure of the base alloy is changed by the addition of reinforcement phase, so as to improve and make up the deficiency of base metal. The influence of the properties of the reinforcing phase on the composite is due to the following factors: the interface bonding state between the matrix and the reinforcing phase, the interface reaction and wettability and the need for the properties of the aluminum matrix composite. Particle reinforced aluminum matrix composites are widely studied for their low density, high strength weight ratio, superior physical properties, high rigidity, good wear resistance and other mechanical properties at relatively low cost [14]. At present, the commonly used reinforcing particles are SiC, Al₂O₃, TiC, Si₃N₄, B₄C and graphite. Table 1 describes some reinforced ceramic particles and their related properties [15].

Table 1. Enhanced Ceramic Particles and Some Properties

| Grain | performance | | | |
|--------------------------------|------------------------------|--|----------------|-----------------------------|
| | Density (g/cm ³) | Coefficient of thermal expansion (10 ⁻⁶ /°C) | Strength (MPa) | Modulus of elasticity (GPa) |
| B ₄ C | 2.25 | 6.08 | 2579(24°C) | 448(24°C) |
| SiC | 3.21 | 5.40 | – | 324(1090°C) |
| TiC | 4.93 | 7.60 | 55(1090°C) | 269(24°C) |
| ZrC | 6.73 | 6.66 | 90(1090°C) | 359(24°C) |
| Al ₂ O ₃ | 3.98 | 7.92 | 221(1090) | 379(1090) |
| SiO ₂ | 2.66 | < 1.08 | – | 73 |
| MgO | 3.58 | 11.61 | 41(1090°C) | 317(1090°C) |
| BeO | 3.01 | 7.38 | 24(1090°C) | 190(1090°C) |
| ZrO ₂ | 5.89 | 12.01 | 83(1090°C) | 132(1090°C) |
| AlN | 3.26 | 4.84 | 2069(24°C) | 310(1090°C) |
| Si ₃ N ₄ | 3.18 | 1.44 | – | 207 |

The properties of aluminum matrix composites are also related to the content, morphology and distribution of reinforcing phases. For example, Quan Gaofeng et al. [16] took SiC particles as reinforcement phase, 2024 aluminum alloy, 7075 aluminum alloy and pure aluminum as matrix respectively and studied the influence of reinforcement phase content on the mechanical properties of aluminum matrix composite. The results showed that with the increase of reinforcement phase content, the elastic modulus of SiCp/2024Al increased, other strength indexes increased and the reinforcement efficiency of SiCp on Al and 2024 aluminum alloy was higher, while that of 7 aluminum alloy was higher. In addition, the fracture elongation of three composites decreased with the increase of content of reinforcement phase. Wang Tao et al. [17] studied the

influence of shape and distribution of the reinforcement phase on mechanical properties of the aluminum matrix composite with 6061 aluminum alloy as the matrix, SiC particles and Si₃N₄ as the reinforcement phase. The results showed that the elastic modulus of uniformly strengthened aluminum matrix was the same while the content of SiCp reinforcement phase was the same. The yield strength of the double structure is higher than that of the uniform particles, but the modulus of network Si₃N₄ is similar.

Generally speaking, while using long fiber as reinforcement, the matrix mainly plays a fixed role and the matrix with larger strength deviation can be selected; while using short fiber as reinforcement, the matrix mainly plays a bearing role and the matrix with higher strength should be selected.

2.3 Compatibility and interface between matrix and reinforcing phase

The compatibility of the interface between matrix and reinforced phase is a very important factor affecting properties, especially when the aluminum alloy is used as the matrix, the enrichment of oxide elements often occurs on the interface and sometimes chemical reactions occur to form new phases, such as Al_4C_3 , Al_3Ti , etc. In addition, due to the different thermal expansion coefficient between matrix and the reinforcing phase, the mismatch stress will induce high-density dislocation, grain size change, residual stress, etc. in the matrix. Therefore, it is often necessary to adjust composition of matrix alloy according to the different reinforcing phases, so as to avoid the reaction between interface and formation of harmful substances. It is a common method to enhance the compatibility of the matrix and reinforced phase by surface treatment, adding other components to the matrix or choosing a suitable molding method.

In addition, the interface bonding between the matrix and reinforcing phase also has an important influence on the properties of aluminum matrix composites [18]. The temperature time interface reaction is the main reason that most aluminum matrix composites can not play their best performance. The interface structure and performance is the key to form stable interface combination and obtain higher strength, so the interface optimization is needed. In general, the methods of matrix alloying, surface coating of reinforcing phase and changing adhesive are used to optimize the interface.

3. Strengthening mechanism of aluminum matrix composite

At present, the strengthening mechanisms of aluminum matrix composites are mainly Orowan strengthening, fine grain strengthening, solid solution strengthening and dislocation strengthening. These strengthening mechanisms can be expressed as [1]:

$$\sigma_{\text{composite}} = \sigma_{\text{Orowan}} + \sigma_{\text{grain}} + \sigma_{\text{solution}} + \sigma_{\text{dislocation}} \quad (1-1)$$

3.1 Orowan enhancement

The strength improvement of the composite is partly due to dispersion strengthening (Orowan mechanism). In the process of Orowan strengthening, the nanoparticles in the matrix grains restrain the dislocation movement. The finer the particles and the smaller distance between them, the more effective strengthening mechanism is. The particle spacing can be expressed by the following formula:

$$\lambda = D \left[\frac{\pi}{6V_f} - \frac{2}{3} \right]^{\frac{1}{2}} \quad (1-2)$$

D is the average diameter of the particle; V_f is the volume fraction. According to [19]:

$$\sigma_{\text{Orowan}} = \frac{2Gb}{2\pi(1-\nu)^{\frac{1}{2}}} \frac{1}{\lambda} \ln \left(\frac{D}{b} \right) \quad (1-3)$$

Where G is the shear modulus of the matrix, B is the

Berger's vector and Poisson's ratio. Formula (1-4) can be obtained from formula (1-2) and (1-3):

$$\sigma_{\text{Orowan}} = \frac{2Gb}{2\pi(1-\nu)^{\frac{1}{2}}} \frac{1}{D \left[\frac{\pi}{6V_f} - \frac{2}{3} \right]^{\frac{1}{2}}} \ln \left(\frac{D}{b} \right) \quad (1-4)$$

According to the Orowan mechanism, the yield strength increases with the increase of the content or the decrease of the size of the reinforcing phase. Among many strengthening mechanisms, Orowan strengthening contributes the most to the composite. Generally, it is suitable for particle reinforced aluminum matrix composite with size less than 10 μm .

3.2 Fine grain strengthening

Fine grain means that there are many grain boundaries in the material, which can effectively prevent dislocation movement. According to Hall Petch formula, the effect of grain size on strength is [20]:

$$\sigma_{\text{grain}} = \sigma_0 + kd^{\frac{1}{2}} \quad (1-5)$$

Where, σ_{grain} is the yield strength of the grain; σ_0 is the friction resistance of dislocation movement in the grain; k is the material constant; d is the average radius of the grain. The equation shows that the smaller d is, the larger σ_{grain} is. No matter in the strengthening mechanism of any kind of material, the strength and hardness increase while the grain refinement, but the plasticity and toughness do not decrease obviously, so the fine grain strengthening is the most popular strengthening method. This strengthening method plays an important role in strengthening of micron particle reinforced aluminum matrix composites.

3.3 Solution strengthening

The additional atoms can not only block the dislocation movement, but also produce lattice distortion, which results in stress field and interaction with dislocation. The increase of yield strength caused by solution strengthening depends on the concentration of solute atoms, the difference of shear modulus between solute and matrix and the difference of size between solute and solvent atoms (causing lattice distortion as an obstacle to dislocation movement). No matter what kind of solid solution, there is a symmetrical stress field. According to literature [21], the interaction between stress field and dislocation can be expressed as follows:

$$\sigma_{\text{solute}} = G\varepsilon \sqrt{\frac{X_f}{4}} \quad (1-6)$$

Where, G is the shear modulus; ε represents the change rate of the diameter difference between the foreign atom and the matrix atom; X_f is the concentration of the foreign atom. It can be seen from formula (1-6) that the larger the ε or X_f is, the stronger the solution strengthening ability is. However, due to the limited number of solution atoms and the priority of solution atoms is grain boundary and dislocation, the effect of solution strengthening on aluminum matrix composites is not obvious.

3.4 Dislocation strengthening

Due to the different thermal expansion coefficients between the matrix and the reinforcing phase, during the preparation process, those with large thermal expansion coefficients (generally the matrix) will produce plastic deformation and form high-density dislocations, thus strengthening the effect [22-24]. The increment of dislocation density can be expressed by the following formula [25,26]:

$$\Delta\rho = \frac{NS\Delta\gamma\Delta G}{b} \quad (1-7)$$

Among them, $\Delta\gamma\Delta G$ is the thermal mismatch strain; N is the number of particles; S is the total surface area of a single particle; b is the Bernoulli vector. The increase in strength due to the proliferation of dislocations can be expressed as:

$$\Delta\sigma = aG_p b \sqrt{\Delta\rho} \quad (1-8)$$

Where G_p is the elastic modulus of the reinforced particles and a is the coefficient.

It can be seen that for large particles, the greater the difference between the thermal expansion coefficient of the reinforced particles and the matrix, the better the strengthening effect; however, because the reinforced phase of small particles may not meet the size requirements of dislocation nucleation, it is impossible to judge whether there is dislocation. Zhang et al. [27] found that the theoretical value of yield strength calculated under the condition of neglecting dislocation strengthening is almost the same as the experimental result when the particles of strengthening phase are very small, but it is still widely used. It is usually used in aluminum matrix composites reinforced by whiskers and particles (about 10-100nm) with aspect ratio less than 4.

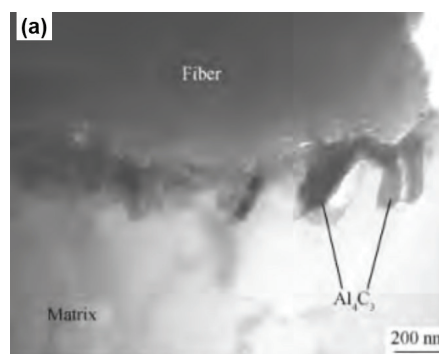
4. Classification and preparation of Aluminum Matrix Composites

4.1 Classification of Aluminum Matrix Composites

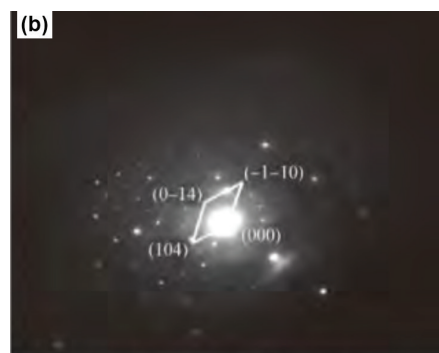
There are many classification methods of aluminum matrix composites, the most commonly used classification method is divided into continuous fiber reinforced aluminum matrix composites and discontinuous particle reinforced (short fiber or whisker, particle) aluminum matrix composites, according to the different reinforcement phases.

4.1.1 Continuous fiber reinforced aluminum matrix composite

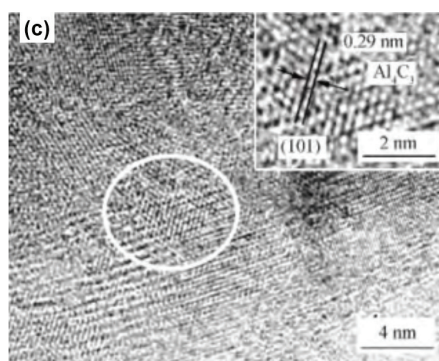
At present, the main continuous fiber reinforcements are boron fiber, carbon fiber, silicon carbide and alumina. Boron fiber is the first reinforced fiber, but the diameter of boron fiber is large, the composite material made of boron fiber has poor performance and the manufacturing cost is quite high. The room temperature properties of aluminum alloy and boron fiber composite with different components are shown in Table 1 [1]. Carbon fiber has light weight, high strength, good lubrication and wear resistance and its price is about one tenth of that of boron fiber [28,29]. In the graphite fiber reinforced aluminum matrix composite, the transmission electron microscope is shown in figure 1 [30].



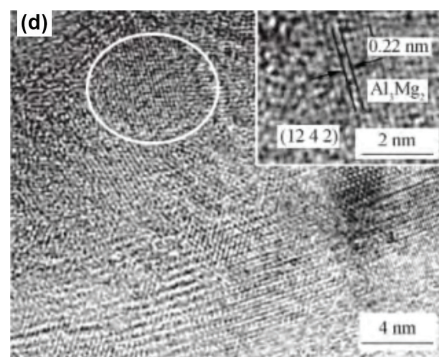
(a) Morphology of interface product



(b) Electron diffraction pattern



(c) Photograph with high magnification for Al_4C_3



(d) Photograph with high magnification for Al_3Mg_2

Figure 1. TEM analysis of M40 / ZL301 composites

Because of its high tensile strength and modulus of elasticity, good high temperature strength and heat resistance, excellent wettability with metal and small fiber diameter, SiC fiber can be used as reinforcement fiber of heat-resistant materials and various matrix materials [31].

Al₂O₃ generally has two forms of α-Al₂O₃ and γ-Al₂O₃. Compared with carbon fiber, the strength of alumina fiber is slightly lower, but its high-temperature mechanical properties and corrosion resistance, electrical insulation and high-temperature stability are excellent [32]. The

application and development of fiber-reinforced aluminum matrix composites are restricted due to the complex preparation process, high cost and unstable performance level of materials.

Table 2. Longitudinal Tensile Properties of Aluminum/Boron Fiber Composites at Room Temperature

| Matrix | Volume fraction of boron fibers/% | Tensile strength /MPa | Modulus of elasticity /MPa | Longitudinal fracture strain/% |
|----------|-----------------------------------|-----------------------|----------------------------|--------------------------------|
| 2024 | 47 | 1421 | 222 | 0.795 |
| | 64 | 1528 | 276 | 0.72 |
| 2024(T6) | 46 | 1459 | 229 | 0.81 |
| | 64 | 1924 | 276 | 0.755 |
| 6061 | 48 | 1490 | 217 | – |
| | 50 | 1343 | – | – |
| 6061(T6) | 51 | 1417 | 232 | 0.735 |

4.1.2 Discontinuous particle reinforced aluminum matrix composite

Discontinuous particle reinforced aluminum matrix composite has the advantages of simple preparation process, low cost and isotropy. Particle reinforced aluminum matrix composites are widely used because of their high modulus of elasticity, good wear resistance, good thermal conductivity and low coefficient of thermal expansion. At present, the commonly used particle reinforcements are silicon carbide, titanium carbide, titanium diboride and alumina. In recent years, graphene has also been used as reinforcement particles in aluminum matrix composites.

SiC is the most widely used reinforcement because of its high strength and high modulus. SiC particle reinforced aluminum matrix composite has the advantages of high strength, high modulus, high damping, high temperature resistance, wear resistance, fatigue resistance, good dimensional stability, small thermal expansion coefficient [33,34], which is often used to manufacture components of missiles and spacecraft, engine parts, aircraft tail balancer, etc. The microstructure of short carbon fiber and SiC particle reinforced aluminum matrix composite is shown in figure 2 [35].

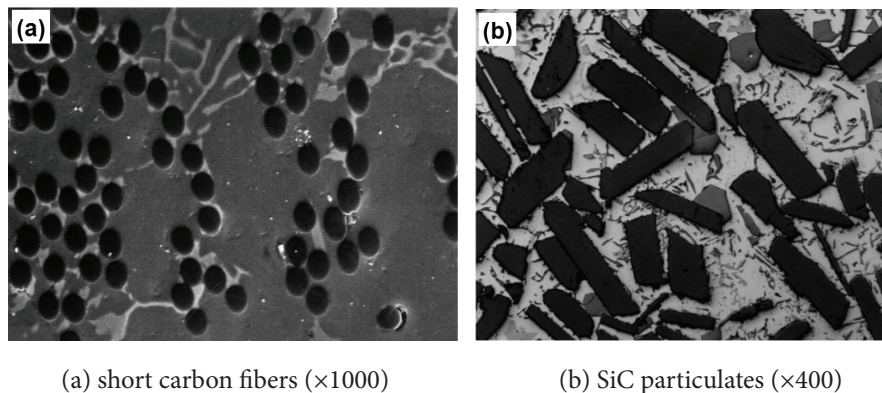


Figure 2. Microstructures of pressure-cast Al MMCs reinforced with [35]

TiC particles have the characteristics of high hardness, high modulus and high bending strength. It is an ideal reinforcement material for aluminum alloy, but its disadvantage is that the compatibility of TiC and Al matrix is poor. Therefore, various wettability methods are usually used to obtain good particle distribution. Lekatou et al. [36] added submicron WC particles, K₂TiF₆ and Al powder into the Al melt uniformly according to a certain proportion, so that the molten salt played an auxiliary role in the uniform distribution of TiC. The research shows that the sliding wear performance, corrosion resistance and fracture resistance of the aluminum matrix composite reinforced by WC, TiC

and aluminide particles are significantly improved.

TiB₂ has the characteristics of high melting point, good wear resistance and oxidation resistance [37]. TiB₂ as reinforcement has been widely used in AMCs, ceramic materials, cemented carbide and other mechanical and electronic fields. Bij et al. [38] prepared TiB₂ reinforced 7075 aluminum matrix composite by laser cladding. The results show that the hardness of alloy increases first and then decreases with the increase of TiB₂ content. The SEM of different times is shown in figure 3; Zhang et al. [39] prepared TiB₂/6063Al composite by high energy ball milling and in-situ synthesis. Compared with the traditional method, the

temperature of TiB_2 /6063Al composite is lower and the reaction time is shorter. Its strength in as cast state is about

23% higher than that of 6063Al.

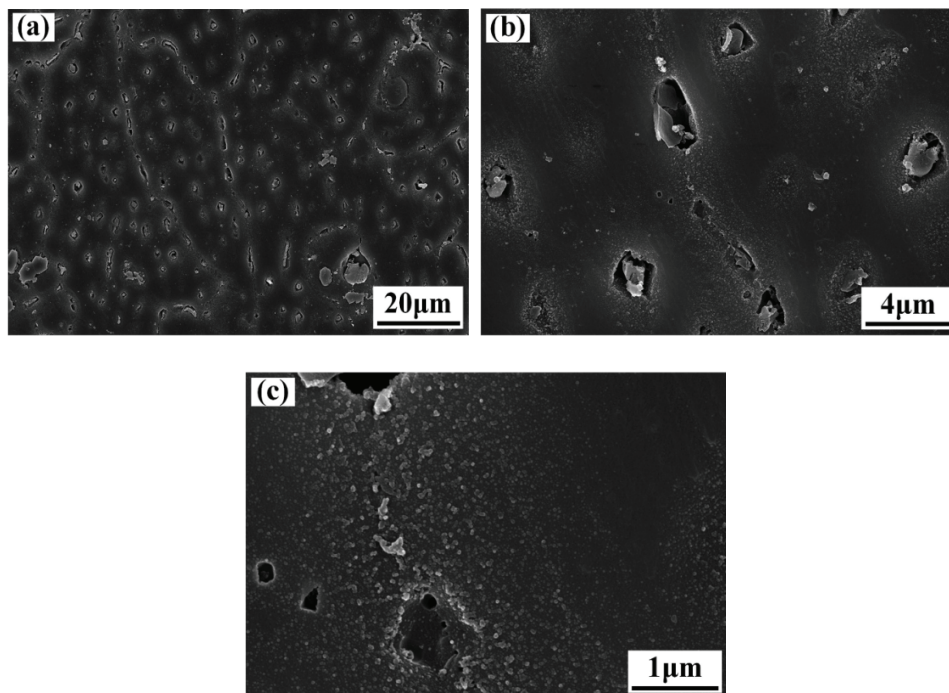


Figure 3. Different magnifications of SEM images of the etched 2wt% TiB_2 /7075 AMCs sample: (a) $\times 1000$, (b) $\times 5000$, and (c) $\times 20000$ [39]

The aluminum matrix reinforced by Al_2O_3 has the advantages of high strength weight ratio, high tensile strength and high fracture toughness. If submicron or nano particles are used for strengthening, the effect is better, the hardness increases by 92% and the tensile strength increases by 57% [40] compared with pure aluminum. Compared with the matrix aluminum alloy, the Al_2O_3 particle reinforced aluminum matrix composite does not have a very high improvement at room temperature, but it will be significantly higher than the matrix aluminum alloy at a higher temperature, so it is commonly used in the manufacture of automobile drive shafts.

Graphene is the first two-dimensional (2D) material. The hexagonal honeycomb like flat film composed of carbon atoms has only one thickness of carbon atoms. The applicability research in various applications has a growing prospect in the field of materials science and shows a very high strengthening quality. Graphene is a kind of efficient conductor with good fire resistance and flexibility, which is 200 times stronger than steel and ultra light materials. It is the thinnest and hardest nano material known to human beings. Chen et al. [41] found that in the preparation of graphene reinforced aluminum matrix composite, the dispersion is poor and interface reaction is easy to occur, so this is an urgent problem to be solved in the future research of graphene reinforced aluminum matrix composite, [43] found that the addition of graphene to aluminum alloy will increase the strength and hardness of the material, increase the thermal conductivity, and maintain the ductility of aluminum alloy, so graphene reinforced aluminum matrix

composite has a good prospect.

4.2 Preparation method of aluminum matrix composite

Aluminum matrix composites can be divided into two types: ex situ and in situ. The so-called exogenous type refers to that the reinforcement phase is directly added to the matrix and then mixed with the matrix by some appropriate process methods, but it has the problems of high cost, complex process and poor compatibility between the matrix and the reinforcement phase; the endogenous type is also called autogenous type, which is to mix the component materials of the reinforcement phase and the matrix and then form thermodynamically stable through in-situ chemical reaction under certain conditions. The reinforcement phase is dispersed in the matrix. The advantages of this method are small size of the reinforcement phase, good compatibility with the matrix and high interface bonding strength. Therefore, the endogenetic preparation method is commonly used in the preparation of aluminum matrix composite [1].

4.2.1 Preparation of aluminum matrix composite by exogenesis

The common processes of exogenic mold preparation include powder metallurgy, squeeze casting, liquid stirring, spray deposition and so on. These processes are described as follows:

① Powder metallurgy. Gatti A first used this method to prepare reinforced iron-based composite in 1959. It was not until the 1970s that Gatti A began to receive widespread attention. It is the most common process in preparation of aluminum matrix composite. This method has the

advantages of small particle size, uniform distribution and good interface combination, but the process is complex and the cost is high. Slipenyuk et al. [44] prepared SiCp/Al composite by powder hot extrusion process, the results showed that the tensile strength and yield strength of the composite increased with the increase of SiC content and the elongation decreased. Youjiang et al. [45] selected the same powder hot extrusion process to prepare SiCp/Al composite, the results showed that SiC particles were evenly distributed in the matrix aluminum alloy, only a very small area appeared agglomeration.

② Squeeze casting. It is a kind of casting technology that extrudes the alloy into the mold smoothly at a lower speed and a larger flow rate and pressurizes the alloy instantaneously, so that the alloy can accurately duplicate the mold and solidify under high pressure, which is also called liquid forging. This method combines the advantages of press forging and die forging, reduces the defects in the casting process, has high production efficiency, but requires high superheat, promotes the interface reaction and affects the properties of composite materials. Ding et al. [46] prepared SiC particle reinforced aluminum matrix composite by squeeze casting method. The results show that proper extrusion can reduce the content of harmful gases in the composite and obtain high-quality composite with almost no shrinkage porosity and porosity.

③ Liquid agitation. After the metal is melted, the reinforcing phase is added and the blade made of appropriate material is selected for stirring. This method can speed up diffusion of reinforcement phase, promote reaction and the process is simple and efficient, but the high temperature and long time make the chemical reaction easy to occur and then reduce the properties of composite materials. Ma Ying et al. [47] prepared CuO/Al composite by liquid agitation method and the properties of the composite were improved by the formation of Al_2O_3 . The results showed that with the increase of CuO content, the strength and hardness first increased and then decreased. When the content was 10%, the properties reached the optimal value.

④ Spray deposition. It was first put forward and reported by Professor singer in 1970. It is a technology between powder metallurgy and traditional casting process. The principle is to melt the metal, atomize the metal with inert gas and then rapidly solidify the atomized metal to deposit on the substrate. It can be used to prepare copper base, nickel base and magnesium base composite, but the most commonly used one is the preparation of aluminum base composite. This method has the advantages of simple preparation process, low cost, excellent properties, high porosity, long contact time between reinforcement and matrix and easy to produce harmful substances through interface reaction. Yang et al. [48] prepared TiC/Al composite by spray deposition method. The results show that compared with the matrix alloy, the silicon particles in the composite with 5% TiC are obviously refined (2 mm), which shows that adding TiC can reduce the coarsening rate of silicon particles and improve the properties of the composite.

4.2.2 Preparation of aluminum matrix composite by endogenetic method

The common endogenetic processes are self propagating high temperature synthesis, radiation dispersion, contact reaction, gas-liquid reaction and mixed salt reaction.

① Self propagating synthesis (SHS). It was first proposed by Merzhanov, a famous scientist of the former Soviet Union, in 1967, which was mainly used for the synthesis of high-temperature refractory materials. It was not used for the preparation of metal matrix composites until the end of 1980s. This method has the advantages of simple equipment, short cycle, high efficiency, low energy and material consumption, good product quality, but it is difficult to control because of its high porosity, low density and too fast reaction process. LI et al. [49] prepared TiC particle reinforced aluminum matrix composite by SHS method. It was found that Al content had the most significant effect on the size of SHS tic in Al-Ti-C system.

② RADIODIFFUSION method (XDTM). It was first proposed by Martin of the United States in 1983 and improved on the basis of self propagating synthesis. This method has the advantages of high density and low cost, but the working procedure is multi period and long, the raw material must be powder and can not be directly poured. ZHU et al. [50] synthesized aluminum matrix composite by XD method and found that the elongation increased and the tensile strength decreased.

③ Contact reaction (CR). It is developed on the basis of the first two processes. The principle is that the component elements of the reinforcement phase, or compounds containing the component elements of the reinforcement phase, which are fully mixed and pressed into the matrix alloy liquid for direct contact and chemical reaction to generate the reinforcement phase and then mechanically stirred to make it disperse. This method has the advantages of low cost, full contact and reaction between matrix and reinforcing phase, and is the most popular technology at present.

④ Gas liquid reaction synthesis (VLS). It is a patented technology invented by Koczak. The advantages of this method are low cost, short reaction time and small grain size, but the types of strengthening phases are limited and the required temperature is very high^[1].

⑤ Mixed salt reaction (LSM). It is a patented technology of London & Scandinavian Metallic (LSM) Company in UK. This method has the advantages of simple process, short cycle, wide source of salt and low cost, but TiB_2 will be coated by salt film, which will reduce the reinforcement effect, low volume fraction of particles and corrosive to experimental tools^[1].

5. Application of aluminum matrix composite

5.1 Application of foreign aluminum matrix composite materials

In the late 1990s, electronic grade SiCp/Al composites with high volume fraction were widely used in advanced aerospace vehicles, which attracted worldwide attention

^[51]. Alvant, a British company that led the development of aluminum matrix composite materials, was initially established as CMT in 2003. The goal is to explore the potential of liquid pressure forming (LPF) as a process for manufacturing aluminum matrix composite materials, so advanced liquid pressure forming (ALPF) ^[52] has been produced.

The SiCp/Al composite prepared by DWA company in the United States by Pressureless Infiltration meets the performance requirements for microelectronic packaging substrate. The SiCp/Al Composite replaces the original printed circuit board core and reduces the weight by 70%. In addition, the company also uses SiCp/6092Al alloy composite material for the fuselage and tail of jet fighter. The high-speed flying aircraft is more stable and the wing life will also be improved ^[53]. Boing replaced graphite / polymer composites with aluminum matrix composites for engine guide vanes, thus improving the impact damage of foreign objects (such as birds) ^[54].

British Aerospace metal matrix composite company (AMC) prepared SiC and Si mixed particle reinforced aluminum matrix composite by mechanical alloying method, which was applied to the civil helicopter produced by Eurocopter company in France due to its high modulus and fatigue resistance ^[55, 56]. Cercast used SiC/A357Al instead of titanium alloy to make aircraft steering frame, which not only reduced the cost, but also reduced the overall weight of the aircraft ^[57].

It can be seen that the United States, Britain and other developed countries have started to produce aluminum matrix composite materials in different scales as commodity supply and have been widely used in aerospace, automobile industry, sports equipment and other aspects ^[58].

5.2 Application of aluminum matrix composite in China

Chinese research on aluminum matrix composite materials is close to the international advanced level. It can not only be applied in the field of aerospace, but also some products have been mass produced. For example, in 2018, Chalco Shandong Branch successfully developed particle reinforced SiCp aluminum matrix composite, whose density is only one-third of that of steel, but its specific strength is higher than that of pure aluminum and medium carbon steel. It is the first large-scale production of aluminum matrix composite in China, breaking the long-term dependence on imports in China. Then, the fatigue performance of SiCp/Al aviation parts developed by Beijing General Research Institute of non ferrous metals. It has reached the international advanced level and has been applied to the aircraft; SiCp/Al composite material is used by Changchun Institute of optics, precision machinery and physics of Chinese Academy of Sciences to prepare the main bearing frame of the aircraft, which depends on the excellent thermal control function and bearing function of the material and it is also prepared to be applied to key components ^[59]. With increasing temperature in service (missile body parts, high-speed flying aircraft fuselage), the requirements for materials are also increasing and aluminum matrix composite materials can withstand

temperatures above 300 °C, which makes the research and use of this material more reasonable.

The launch of chang'e-3 probe on December 12th, 2013 further proves the rapid development of science and technology in China. The mobile subsystem of Yutu lunar rover and the optical system of chang'e-3, which were separated on the 15th, are a variety of high-performance aluminum matrix composite materials and components developed by the state key experiment of metal matrix composite materials of Shanghai Jiaotong University, which not only makes great contribution to the development and progress of national science and technology, but also establishes the international status of Chinese aluminum matrix composite materials.

In addition, with the development trend of today's era, UAV platform has become an emerging unmanned war weapon, which can not only conduct close detection, but also carry out the impact. At this time, high-performance aluminum matrix composite materials more meet the requirements of researchers for key components of UAV, with a good market prospect ^[60].

6. Application prospect and development trend of aluminum matrix composite

After decades of hard research and development, continuous fiber-reinforced aluminum matrix composite materials have made great progress in basic theory, preparation process and performance test ^[61]. Many materials have been used in aerospace, automobile industry, weapons and other military industries, which are increasingly used in civil applications ^[62]. However, compared with traditional materials, the preparation process of fiber-reinforced aluminum matrix composite is complex, the fiber price is high ^[63] and there are many uncertainties in its performance, such as porosity ^[64].

Particle reinforced aluminum matrix composites have been favored by most researchers. Not only the preparation methods and mechanical properties, including the strength, modulus of elasticity, ductility and fracture ^[65], but also strengthening mechanism, fracture mechanism and solid-state phase transformation, phase equilibrium relationship, phase transformation direction and driving force of particle reinforced aluminum matrix composites are studied from physical and thermal dynamics directions. At present, from material performance, plastic deformation of components, precision machining of parts to application test, particle reinforced aluminum matrix composite has made a major breakthrough ^[66]. However, there are still some problems such as high cost, low preparation efficiency, uncertainty of reliability and stability.

Aluminum matrix composite materials are essential for the development of high-tech technology and the realization of four modernizations in China. We should pay close attention to the development trend of foreign countries and strive to develop aluminum matrix composite materials in China. The future development should mainly focus on the following aspects:

(1) In order to improve the properties of the composite,

the interface of the composite was studied deeply;

(2) Optimize the preparation process of aluminum matrix composite. Reduce the damage and consumption in the process of processing and preparation, reduce the manufacturing cost and promote the production and application of engineering;

(3) Develop new preparation technology. Looking for a new method with low cost, high efficiency and controllable reliability;

(4) Innovate in composition to make it more customized and multifunctional;

(5) Further study on composite materials with large size and complex shape, uniformity of distribution and by-products of reaction are also urgent problems to be solved. It can be combined with laser melting, mechanical stirring, high-pressure torsion and other processes to promote the dispersion distribution and grain refinement of the reinforcement phase and improve the mechanical properties.

After nearly 30 years of efforts and exploration, the fiber-reinforced aluminum matrix composite has made great progress in basic theory, preparation process, performance level, etc. It is the first to be applied in aerospace, aviation and weapons and the application in civil industry is also increasing. However, its application is not as wide and deep as people expect and it is impossible to completely replace the traditional metal materials in a short period of time. There are still many problems to be solved, such as the complex preparation process of this material, high fiber price and unstable performance level of the material, which restrict its application and development^[67]. In order to further improve the properties of the material, reduce its manufacturing cost and accelerate its industrialization process, the following basic issues need to be further studied: (1) around the economical, effective and easy to operate surface coating technology of fiber reinforced body; (2) the influence of the alloying of aluminum and aluminum alloy on the interface stability and structure; (3) fiber reinforced body and aluminum alloy influence of the interface bonding strength of the gold matrix on the properties of the material; (4) the practical research and application of preparation process of the fiber-reinforced aluminum matrix composite.

7. Concluding remarks

Aluminum matrix composite is an ideal structural material for aerospace vehicles, which has been widely used in the field of aerospace. In the high-tech war with aircraft and missile as the main means of combat, aluminum and aluminum alloy occupy a very important position, which has been listed as one of the key light structural materials for the key development by the country. At the same time, it is considered as a new generation of materials that can improve the performance of aluminum and increase the use range of aluminum materials, which will become the candidate materials for ultra high speed aerospace vehicles and the next generation of aeroengines. However, there are still some problems in the preparation of aluminum matrix

composites, such as uneven distribution of reinforcement phase, poor surface wettability, interface reaction between particles and matrix and so on. Therefore, future research should focus on these problems and on the basis of solving these problems, further optimize all aspects of the performance of aluminum matrix composite to make it more customized and multifunctional^[68].

Author Contributions: Wanwu DING is responsible for the overall idea, design and revision of the paper. Yan CHENG write and modify. Data collected and written by Taili CHEN, Xiaoyan ZHAO and Xiaoxiong LIU.

Conflicts of interest: There are no conflicts to declare.

Acknowledgments: Thanks for the support of the National Natural Science Foundation of China (51661021). Thanks for the support of Key Research and Development Projects of Gansu Province (18YF1GA061) and China Postdoctoral Science Foundation (2019M653896XB).

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