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REVIEW

Review on Improvement Methods for Wear Resistance of Aluminum Alloys

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Abstract: The aluminum alloy is one of the widely used high-performance metal structure materials in aerospace field. However, due to the low hardness and inferior wear resistance, the aluminum alloy parts can be easily worn or scratched during the application. This research reviewed the methods for the improvement of wear resistance of aluminum alloys in terms of surface coating and nano-particle reinforcement, which provides important practical significance and scientific value for the exploration of new preparation methods of wear-resistant aluminum alloys and for the enhancement of the mechanical properties of aluminum alloys.

Key words: wear resistance; surface coating; nano-particle reinforcement; aluminum alloys

The lightweight materials have attracted much attention in the aerospace field due to their clear advantage in weight reduction. Cao et al[1] prepared the lightweight isometric-phase AISI 301 stainless steel with excellent comprehensive properties, including the strength, hardness, and ductility. Compared with those of the dual-phase stainless steel, its hardness, yield strength, and ductility increase by 310%, 242%, and 31%, respectively, presenting the great application potential in the aircraft and automobile industry. However, the high-strength stainless steel is too heavy to satisfy the lightweight design of components in aerospace field[2,3].

The aluminum alloy is popular in various fields, particularly in the aerospace field, because of its excellent mechanical properties and easy-processing characteristic. The commonly used aluminum alloys for aerospace applications are summarized in Table 1[4-6]. It can be seen that the 7A04 ultrahigh strength aluminum alloy can replace the steel in the hub, mast, and other parts of aircraft. Although the density of aluminum alloy is 30% lower than that of the steel, the tensile strength of aluminum alloy is higher than 500 MPa[7,8]. However, even after alloying and heat treatment, the low elastic modulus of aluminum alloy has not been ameliorated (Fig. 1) and its wear resistance is still poor. Besides, the hardness of HB20-150 aluminum alloy is not comparable to that of the steel. These problems all significantly restrict the application of aluminum alloys[4]. Thus, the selection of preparation technique is crucial for the performance optimization of materials.

The preparation method of wear-resistant composites by adding reinforced particles into the aluminum alloys attracts much attention[9-11], which retains the excellent plasticity and toughness of materials and significantly improves the specific strength, specific modulus, deformation resistance, and wear resistance of the substrates. During the friction process between the particle-reinforced composites and the friction pair, the hard reinforced particles undertake partial external load and play an anti-wear role for the composites. Thus, the resistance against the plastic deformation is strengthened, and the wear resistance of the composites is also increased[12]. Hence, the particle-reinforced aluminum-based composites have gradually replaced the traditional wear-resistant materials. In addition, the low cost and simple operation of the

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preparation process are also two important influence factors, which lead to the wide use of this preparation method for structural parts, such as aircraft fuselage and bulkheads[13-16].

According to the statistics analysis, merely in the mineral mining operations, the wear and failure of equipment parts waste huge energy, large spending, and many resources, which is very unfavorable to the environment protection[17]. The wear-resistant coatings can protect the substrates in the particular working environment, and repair various parts, thereby reducing the industrial production costs[18-20]. Therefore, the improvement in the wear resistance of aluminum alloys is indispensable. The composite coating has good toughness, high hardness, and excellent wear resistance, presenting important industrial applications and broad application prospects. Hence, the preparation of composite coatings has become another development direction for the enhancement of the wear resistance of aluminum alloys. In this research, the preparation techniques of materials and composite coatings were reviewed, providing references for the design of new aluminum alloys with excellent properties.

1 Improvement by Nano-Particle Reinforcement

According to various reinforcing phases, the composites can be divided into the particle-reinforced aluminum-based composites, whisker-reinforced aluminum-based composites, and fiber-reinforced aluminum-based composites. Because of the brittleness of fibers and whiskers, they easily fracture during the preparation process, resulting in the inferior machinability of composites and limited applications. The particle-reinforced composites have become one of the most promising and large-scale produced new materials because of their simple preparation process, stable properties, and secondary processing possibitity, such as rolling extrusion[21-23].

The nano-technology is the main development direction of the particle-reinforced aluminum-based composites[24]. Currently, the aluminum-based composites are preferentially designed as the nano-structured composites. The nano-size effect and the design configuration jointly lead to the novel aluminum-based composites with excellent performances[25]. The novel lightweight composite materials can satisfy the requirements of aerospace craft and the rocket, such as high strength, high hardness, and high wear resistance, thus improving the flight speed[26-30]. The aluminum alloys with SiC, Al_2O_3, TiC, TiB_2, BC, carbon nanotubes (CNTs), graphene (Gr), boron nitride nanotubes (BNNTs), and other nano-particle reinforcements present high elastic modulus and excellent mechanical properties, so they have been widely researched. Based on different introducing methods of nano-particles, the preparation methods can be mainly divided into the liquid-phase metallurgy, solid-phase metallurgy, and friction stir welding[26,31] processes, as listed in Table 2.

1.1 Liquid-phase metallurgy process

The liquid-phase metallurgy process involves the addition of nano-particle reinforcement into the liquid or molten aluminum, and it mainly contains two methods: stirring casting (eddy current casting) and infiltration. During the stirring casting, the reinforced particles are added into the eddy current which is generated by the mechanical, ultrasonic, and electromagnetic stirring, and then the composites are formed through casting. The particles can be fully in contact with the matrix after the stirring casting. Low manufacturing cost, simple process equipment, and batch production[37] are the advantages of the liquid-phase metallurgy process. The micron-sized particles of 25vol% can be evenly dispersed into the liquid aluminum after the liquid-phase metallurgy process, resulting in the fact that the liquid-phase metallurgy becomes a widely used preparation method for SiC_p/Al, Al_2O_3/Al, and other composites[38,39]. However, when the size of the reinforcement particle is at nano-scale, due to its high specific surface and cluster effect, the reinforcement phase can easily form the floating or sinking segregation, leading to the uneven dispersion of reinforcement particles. Therefore, the stirring casting method cannot be used to prepare the nano-particle reinforced aluminum-based composites with low content of reinforcement. Su et al[40] proposed the concept of Al carrier and conducted the experiment that the 0.6wt% Al_2O_3 nano-

Table 1 Pre-treatments, temper treatments, and applications of the commonly used aluminum alloys in aircraft structure components[4-6]

Aluminum alloy	Pre-treatment	Temper treatment	Application
2XXX series Al-based alloy (Al-Cu alloys)	Sheet	2024-T3, 2524-T3/351	Fuselage/pressure cabin skin
	Plate	2324-T39, 2624-T351, 2624-T39	Lower wing cover
		2024-T62	Tactical aircraft fuselage panel
		2124-T851	Tactical aircraft bulkhead
	Extrusion	2024-T3511, 2026-T3511, 2024-T4312	Lower wing stringer, fuselage/pressure cabin stringer
7XXX series Al-based alloy (Al-Zn-Mg-Cu alloys)	Extrusion	7075-T73511, 7075-T79511, 7150-T6511, 7175-T79511, 7055-T77511, 7055-T79511	Fuselage stringer and frame, upper wing stringer, floor beam, seat rail
	Plate	7050-T7451, 7X75-T7XXX	Internal fuselage structure
		7150-T7751, 7055-T7751, 7055-T7951, 7255-T7951	Upper wing cover
		7050-T7451	Spar, rib, other internal structures
	Forging	7175-T7351, 7050-T7452	Wing/fuselage attachment

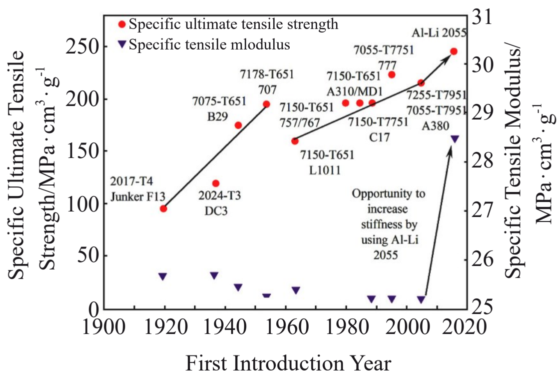

Fig.1 Mechanical properties of commonly used aluminum alloys in aircraft[4]

particles with aluminum is ground into powder and then added into the molten 2024 aluminum by stirring casting. Compared with those of the original composite, the yield strength, hardness, and tensile strength of the prepared aluminum-based composites increase by 59%, 58%, and 16%, respectively. Tian et al[41] added the nano-sized TiC particles prepared by the self-propagation high-temperature synthesis (SHS) into the intermediate alloy which was subsequently immersed into the molten Al-Cu alloy to obtain the 0.3wt% nano-sized TiC particle-reinforced aluminum-based composites. It is reported that the cryogenic creep performance of the prepared composites improves by 3~17 times, compared with that of the original Al-Cu alloy.

An infiltration process is as follows: the nano-particles are firstly dispersed by ball milling and sintered into the porous matrix; then the matrix with nano-particles is immersed into the molten aluminum. The infiltration process also has two types: the pressure-free infiltration method and pressured infiltration method. In the pressured infiltration process, the liquid aluminum fills a specific container under the vacuum condition and then solidifies under pressure. This process can effectively avoid the casting defects, such as pores, and form the composites with dense microstructure and good comprehensive properties. However, the vacuum equipment and pressure equipment greatly increase the manufacturing cost. Yang et al[42] prepared the nano-graphene sheet-reinforced Al-20Si composites by the pressured infiltration process. After adding 1.5wt% graphene, the tensile strength and flexural strength of the composite are increased by 130% and 230%, respectively; besides, the HB hardness of the composite is increased from 490 MPa to 1470 MPa. It is revealed that the preparation of preforms is the critical factor of the infiltration process, which significantly influences the properties of composites.

The nano-particle dispersion in aluminum matrix and the interfacial bonding between the nano-particles and aluminum matrix directly affect the wear resistance of the composites[9]. However, the wettability of nano-particles is inferior on the liquid aluminum, resulting in the weak interfacial bonding. Usually, the wettability of nano-particles can be improved through the surface modification, namely coating technique. Oh et al[43] found that the wetting angle between the copper-coated graphite and aluminum is 58°; in contrast, the wetting angle between the uncoated graphite and aluminum is 140°. It is reported that the electroless copper plating on the surface of CNTs can significantly improve the dispersion effect of CNTs in liquid aluminum[44]. However, only when the content of nano-particles is lesser than 1wt%, the nano-particles show good dispersion effect in the matrix by the liquid metallurgy process. Therefore, the infiltration method is not suitable to prepare the composite with nano-particles of high content[45].

1.2 Solid-phase powder metallurgy process

The solid-phase powder metallurgy is the most-used method to prepare the nano-particle-reinforced aluminum-based composites. The high energy ball milling can effectively disperse the nano-particle-reinforced phase in the Al powder. Through the solid-state hot-pressing sintering and extrusion, various nano-particle-reinforced aluminum-based composites can be obtained. Fan et al[46] proposed the bionic nano-lamination theory and prepared the Al-based composites with 3vol% CNTs by the sheet powder metallurgy. The distribution of the nano-particle-reinforced phase is improved, and the tensile strength and elongation are increased by 65.7% and 8.8%, respectively, after the modification process presented in Fig.2. The tensile strength, Young's modulus, and elongation of 1.5wt% CNT/6061Al composites prepared by the same method reach 428 MPa, 81.1 GPa, and 12.6%, respectively[47]. This method is also applied to prepare the reduced graphene oxide (RGO)/Al-based nano-bionic structure composites, as

Table 2 Reinforcement particles, preparation methods, and mechanical properties of particle-reinforced Al-based components

Reinforcement particle	Preparation method	Mechanical property					Ref.
		Elastic modulus, E/GPa	Yield strength, σ_{ys}/MPa	Ultimate tensile strength, σ_{UTS}/MPa	Elongation, ε_f/%	Abrasive resistance	
SiC	Solid-phase metallurgy	-	269	448	5.5	Wear ratio =0.1684%	[32,33]
Al_2O_3	Liquid-phase metallurgy	76.4	47	91.6	36	-	[34]
B_4C	Solid-phase metallurgy	54	420 (compression)	485 (compression)	12.1 (compression)	Coefficient of friction=0.3	[35]
Gr	Friction stir welding	80	148.7	244.3	20.1	-	[36]

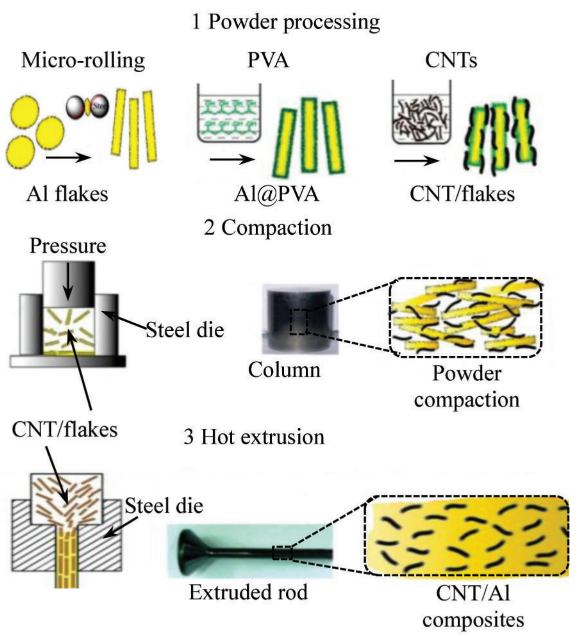

Fig.2 Schematic diagram of preparation process of CNTs/Al matrix composites by flake powder metallurgy[47-50]

shown in Fig.3. The transmission electron microscope (TEM) is commonly used to observe the composite microstructures. When 1.5vol% RGO is added into the Al matrix, the strength, Young's modulus, and the total elongation of Al-based composites reach 302 MPa, 87 GPa, and 5.3%, respectively[48]. The volume fraction of reinforcement can also be improved by the powder metallurgy process. Jiang et al[49] used the polyvinyl alcohol (PVA)-modified Al powder to adsorb CNTs and dispersed 20vol% CNTs into the Al powder. However, the complex process, high preparation cost, and incapacity of preparation of parts with high size requirements and complex shapes still restrict the development of powder metallurgy.

1.3 Friction stir welding process

The friction stir welding process is a solid-state welding process realized by the heat of the friction process and plastic flow of the stirring process. Because the heat is only generated by the friction, the welding temperature is low and the thermal impact on the matrix is small. Therefore, the strength of the substrate is high, the residual stress is low, and the deformation after welding is relatively small. The friction stir welding process has high efficiency and low energy consumption, which is beneficial to the mechanization and automatic operation, thereby presenting great potential in industrial production. The nano-particles can be evenly dispersed on the surface of aluminum matrix by rotating the welding tools, so the process is widely used for the preparation of composites[51-53]. Liu et al[54] used the friction stir welding method to prepare the multi-walled carbon nanotubes (MWCNTs) -reinforced aluminum matrix composites. When the content of MWCNTs reaches 6vol%, the tensile strength of aluminum-based composites is doubled. Liu et al[55] prepared CNTs/Al composites by combining the powder metallurgy process and friction stir process. When the CNTs addition is 1wt% and 3wt%, the strength of the CNTs/Al composites is increased by 23.9% and 45.0%, respectively. Liu et al[56] prepared the 3.0vol% CNTs/2009Al composite by the friction stir welding and rolling, obtaining the aligned CNTs, as shown in Fig.4. The friction stir welding process can further improve the mechanical properties of CNTs-reinforced aluminum matrix composite: the tensile strength can increase to 600 MPa and the elongation can reach 10%. However, due to the characteristics of the welding process (weldments must be rigidly fixed and supported), the friction stir welding method cannot be widely applied to the preparation of complex parts.

2 Improvement by Composite Coatings

In addition to the improvement of wear resistance of materials, the repair and maintenance of worn devices are also necessary. The wear-resistant coatings play an essential role in the enhancement of the efficiency and service life of the parts. The common coating techniques can be divided into two main categories. One is to optimize the surface properties of aluminum matrix by changing the surface composition through the micro-arc oxidation, cold spraying, thermal spraying, and physical vapor deposition. The other is to improve the performance of aluminum matrix by forming a

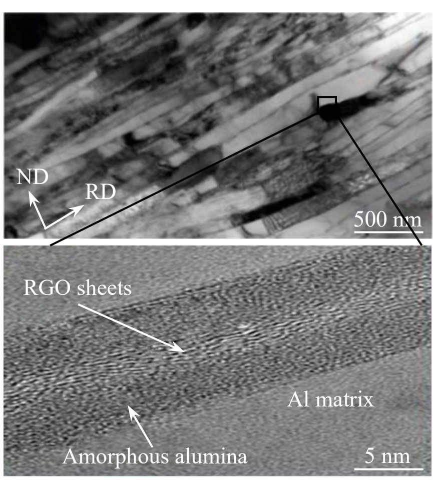

Fig.3 TEM microstructures of RGO/Al-based nano-bionic lamination[48] (ND: normal direction; RD: rolling direction)

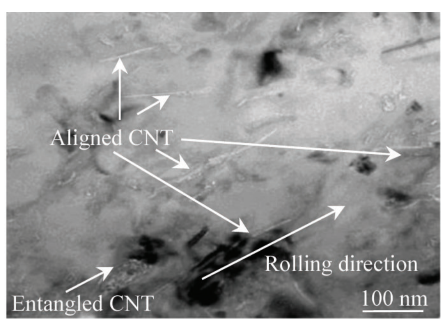

Fig.4 TEM microstructure of 3.0vol% CNTs/Al composite prepared by friction stir welding and rolling[56]

new alloying surface through the laser cladding coating[57-59]. Because the higher requirements on the structure, performance, and service life of the coating materials have been proposed, the composite coating prepared by the nano-composite materials is introduced, which has more advantages in coating performance. Therefore, the preparation of nano-composite coating has become one of the research hot-spots[60-62]. Table 3 shows the materials, thickness, and mechanical properties of common coatings. Table 4 summarizes the bonding type and bonding strength of the coatings prepared by different preparation processes, and the advantages and disadvantages of each preparation process are also presented.

2.1 Micro-arc oxidation

The micro-arc oxidation process is based on the plasma production. The complex reactions occur to form the hard ceramic layers on the surface of aluminum alloys by short arc discharge[77]. The extremely high temperature is rapidly achieved at the aluminum surface and the reactions occur. The reactants are in contact with the electrolyte drops and then rapidly cooled down (cooling rate of 10^8 K/s) to form the coating with highly stable phases (α-Al_2O_3, β-Al_2O_3) or the amorphous alumina. Due to these generated phases, the as-oxidized film has high hardness, excellent wear resistance, and good corrosion resistance[78]. The micro-arc oxidation process has the advantages of simple operation, high treatment efficiency, and controllable coating thickness. Moreover, it can be used for the surface treatment of complex components without special environment requirements, and produces little environment pollution. Therefore, the micro-arc oxidation is mainly considered as an environmental-friendly surface treatment technique[63,67]. However, the film produced by the micro-arc discharge is porous and fragile. Thereby, it is easy to peel off during the impact or deformation[77,79]. Furthermore, the high operation voltage requires additional refrigeration equipment. Thus, the investigations of the process parameters and supporting equipment should be further studied.

By adding nano-particles to the coating, the disadvantage of the porous film can be effectively ameliorated. Li et al[80] prepared a wear-resistant coating containing nano-hexagonal boron nitride (HBN) particles on the surface of aluminum alloy through the micro-arc oxidation. It is found that the addition of a small number of nano-particles can effectively

Table 3 Materials, thickness, and mechanical properties of common coatings

Material	Thickness/μm	Hardness/MPa	Coefficient of friction	Ref.
Oxidation ceramic	26.8	11 760	0.30	[63]
NiCrBSi/TiN/h-BN	-	9477.58	0.35	[64]
CrSiCN	19.6	13 860	0.67	[65]
Al-25wt% Si	16.5	2303	-	[66]

Table 4 Bonding type, bonding strength, and advantages/disadvantages of different coating methods

Coating method	Bonding mode	Bonding strength	Advantage	Disadvantage	Ref.
Micro-arc oxidation	Metallurgical bonding	High	Excellent comprehensive performance; strong controllability; wide adaptability; non-pollution; suitable for industrial production	Porous and fragile; large power consumption and high requirements for supporting equipment	[63,67]
Cold spraying	Mechanical bonding	Low	Comparable coating properties to those of raw materials; dense coating; friendly to oxidation sensitive coating materials	Poor stability; requirement of helium protection	[68,69]
Thermal spraying	Mechanical and metallurgical mixed bonding	Moderate	High spraying efficiency; fast deposition rate; fast coating forming; wide applicability; controllable coating thickness	Easy oxidation; poor coating bonding strength; easily affected by high temperature	[70,71]
High-power pulsed magnetron sputtering	Mechanical bonding	Low	High metal ionization rate; high density film; smooth surface	Slow deposition rate; high equipment requirement	[72-74]
Laser cladding	Metallurgical bonding	High	Low dilution; high binding strength; fast cooling speed; generation of new phases	Difficult dispersion of nano-particles; easy damage of nano-particles caused by high temperature	[64,75,76]
Friction stir welding	Mechanical bonding	Low	Low processing temperature; low residual stress; high efficiency; low energy consumption	Poor wear-resistance of mixing head; restricted application fields	[51-53]

fill the micro-pores and micro-cracks of the coating, thereby improving the coating compactness and reducing the coefficient of friction. The wear rate of nano-particle-reinforced coating is only 33.3% of that of the original oxidation coating. However, when the content of nano-particles exceeds a specific value, the uniformly dispersed nano-coating cannot be obtained. Moreover, larger cracks are formed near the agglomerated nano-particles, which is not conducive to the densification of the coating.

2.2 Cold spraying

The cold spraying process involves the high speed spraying (500~1000 m/s) of materials on the substrate surface, resulting in the coating with high plastic deformation and good metallurgical bonding. This approach is suitable for the heat-sensitive and oxidation-sensitive aluminum alloys. Due to the low temperature during spraying process (around 500 °C), the driving force of phase transformation is small and then the solid particle structure can be maintained. Moreover, the performance of the coating material is closer to that of the initial powder. The cold spraying process is suitable for the preparation of amorphous or nano-crystalline coatings. In addition, it has little thermal effect on the matrix and the coatings are dense[68,69].

Bakshi et al[81] prepared the CNTs/Al-Si powder by the spray drying method, and then mixed the powder with pure Al powder. Then, the mixed powder was used to prepare the aluminum composite coating on the surface of 6061Al alloy by cold spraying method (Fig. 5). It is revealed that the aluminum composite coatings with CNTs of 0.5wt% and 1.0wt% can be prepared by the cold spraying method. However, the quality of the coating is strongly related to the properties of the particles and the substrate. In the process of high-speed spraying, the length of CNTs is reduced due to the shear fracture. The distribution of CNTs in the coating cannot achieve the nano-scale uniformity, resulting in uneven mechanical properties of the coating. Meanwhile, a large amount of helium gas is required for protection, which increases the preparation cost.

2.3 Thermal spraying

The thermal spraying can be categorized into the plasma spraying, high-speed oxygen fuel spraying, and suspended plasma spraying. The main process of the thermal spraying is as follows: firstly, the coating material is sheared and deformed in the high-temperature and high-speed flame flow; secondly, the substrate surface is processed into the semi-molten state; finally, the coating forms[70]. With the high temperature and high speed of flame flow, various types of coatings can be efficiently prepared on complex parts, such as ceramic coatings, Ni-Cr alloy coatings, and metal/metal carbide composite coatings[66,82-84]. Moreover, the thickness of the coatings is at the millimeter-level, which is commonly used for the maintenance of turbine blades and other components[71,82]. Bakshi et al[85] prepared the CNTs/Al-Si composite coatings with 5wt% and 10wt% CNTs by the plasma spraying method. It is found that compared with those of the alloy coating, the elastic modulus of the composite coating with 5wt% and 10wt% CNTs increases by 19% and 39%, respectively; the tensile strength of the composite coating with 5wt% and 10wt% CNTs increases by 17.5% and 27%, respectively. Besides, the wear characteristic of the coating containing 5wt% CNTs reduces by 68%. However, for the composite coating with 10wt% CNTs, CNTs cannot be evenly dispersed, and the proportion of the clusters is as high as 18.8%, resulting in the decline of the wear resistance of coatings. Because the film can be easily oxidized at high temperatures, the oxidation easily occurs in the thermal spraying process. The oxide film affects the bonding between the aluminum matrix and the coating, resulting in the relatively low bonding strength between the wear-resistant coating and the matrix[86,87]. Xing et al[88] studied the process parameters of atmospheric pressure plasma spraying technique for the deposition of cast iron on the surface of aluminum alloys. It is concluded that increasing the spraying temperature and speed can significantly improve the adhesion between droplets and aluminum matrix. However, the high heat input can lead to the loss of nano-particles, grain growth, and even the damage to the particle structure. During the thermal spraying process, the nano-materials, such as CNTs, can be oxidized and graphitized due to the relatively high temperature. In addition, the aluminum can easily form the harmful phases (Al_4C_3), CNTs, and carbonaceous materials at high temperatures.

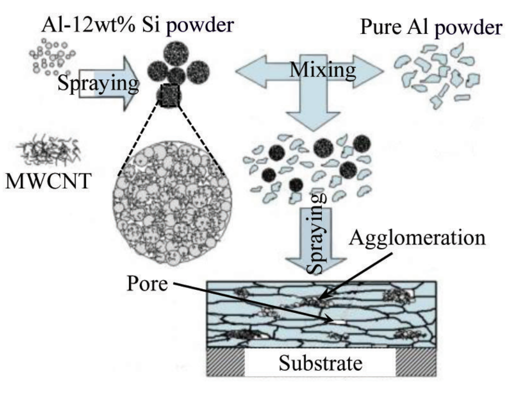

Fig.5 Schematic diagram of CNTs/Al composite coating prepared by cold spraying[81]

2.4 High power pulsed magnetron sputtering

Compared with the chemical deposition, the physical vapor deposition is more popular because of its low temperature, internal compressive stress, and environmental-friendly characteristics[89,90]. However, with the development of physical vapor deposition, the disadvantages of low film density, low adhesive strength, and low metal ionization rate all restrict its further development. Therefore, the high-power pulsed magnetron sputtering technique is proposed. This method has high metal ionization rate, thereby achieving the high density and smooth surface of as-prepared films. The interfacial strength between the coating and the substrate is effectively improved. Thus, the high-power pulsed magnetron sputtering method is widely used for the semiconductor materials[72,73]. The low deposition rate is the most significant disadvantage of this technique[91,92]. Samuelsson et al[93] tested the deposition rate of this technique and found that the particle ionization is inferior and the results are not satisfying when the sputtering rate is low. Moreover, this technique has high requirements for the equipment and therefore cannot be used in industrial applications for the time being.

2.5 Laser cladding

The laser cladding process involves the melting of the alloy powders (NiCr, TiC, or WC) or ceramic powder (Al_2O_3) by laser and then the formation of surface coating with low dilution and high bonding strength on the surface of the aluminum alloy, which is a suitable coating technique for most materials. Because of the advantages of high reaction temperature and fast cooling speed, the new phases can be easily generated in the coating, providing another method to enhance the wear resistance of aluminum[64,75,76]. Xu et al[94] prepared the nano-TiB_2-reinforced aluminum-based composite coating by the laser cladding. The nano-TiB_2 is in-situ synthesized from the mixed powder of Fe-coated B and Ti on the surface of the aluminum alloy. Under the load of less than 8.9 N, the wear resistance of the composite coating is better than that of aluminum alloy. However, under a high load, the wear resistance decreases obviously due to the peeling of the coating. Blum et al[95] used a method, which was similar to the preparation method of electrostatic spray for nano-diamond, to prepare the nano-diamond-reinforced aluminum-based composite coating on the surface of A319 alloy. It is found that the nano-diamond is transformed into the graphite and amorphous graphite after laser cladding. Due to the embedding of nano-diamond, it is difficult to evenly disperse the nano-diamond into the aluminum alloy matrix. Currently, the problems still exist in the preparation of nano-particle-reinforced aluminum-based composite coatings by laser cladding, such as complex dispersion of nano-particles and erosion damage of nano-particle-reinforced phase at high temperatures.

2.6 Friction stir welding

The friction stir welding method is also a common method to obtain the composite coatings[96,97]. Normally, the surface temperatures are too high during the processing, which is not conducive to the uniform dispersion of nano-particles of high content in the matrix, and may cause the harmful interface products. Therefore, Zhang et al[98] conducted the real-time temperature measurements on the surface of aluminum-manganese-based alloys processed by the high-speed friction stir welding. It is reported that with varying the processing speed from 1000 r/min to 8000 r/min, the temperature of the alloy surface is always lower than 400 °C. Thus, the friction stir welding method belongs to the low-temperature surface processing. Kishan et al[61] cut the square grooves on the surface of 6061-T6 aluminum alloy, added TiB_2 nano-particles, and then fixed the grooves by friction stir welding with a composite layer of 3.6 mm in thickness. The content of TiB_2 in the composite layer reaches 8vol% at most, and the composite hardness is increased from 1019 MPa to 1294 MPa. Mishra et al[99] prepared the 27vol% nano-SiC-reinforced aluminum-based coating with the thickness of 50~200 μm on the surface of 5083 aluminum alloy by the friction stir welding method. The hardness of the coating is twice higher than that of the substrate. Therefore, this method can solve the dispersion problem of nano-particles in composites with high nano-particle contents.

However, the mixing head is consumable, thereby increasing the manufacture cost. Liu et al[100] designed a new friction coating process to solve this problem: the traditional stirring head is replaced by the one with coating material. Under the friction temperature of 300~420 °C, the pure aluminum coating is prepared on the aluminum alloy through a specific rotation angle (Fig.6). The process mainly consists of two parts: preheating (stage I~III) and coating (stage IV). When the rotation device reaches a specific position, the pure aluminum is pressed to the aluminum surface at a preset speed. The plastic deformation occurs with friction, and the softened pure aluminum moves laterally on the aluminum alloy surface. When the friction temperature is high enough, the coating material can be deposited on the alloy surface. This method can reduce the replacement cost of stirring heads and the equipment, providing a new approach to solve the dispersion problem of nano-particles with high contents.

3 Summary and Prospects

This review presents the advances and development trends of the preparation methods of nano-particle-reinforced aluminum-based composites and coatings. The nano-particle-reinforced aluminum-based composites or coatings can

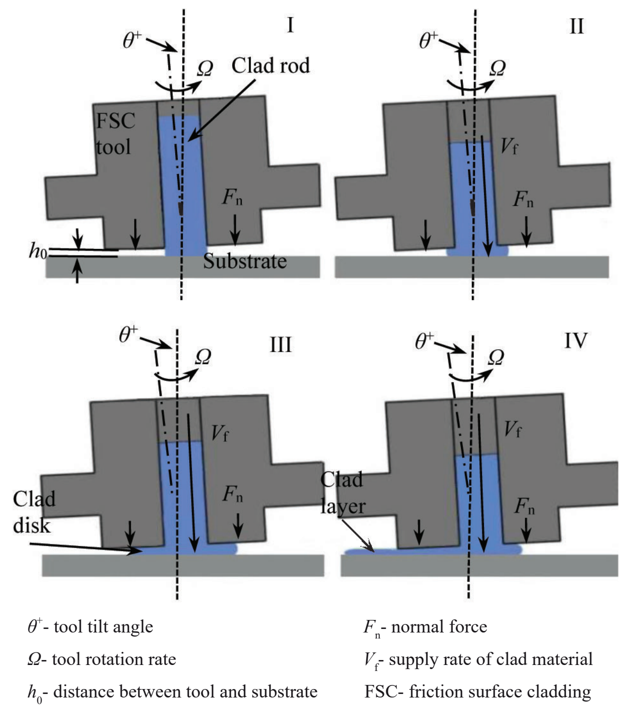

Fig.6 Schematic diagrams of coating preparation by friction stir welding[100]

improve the wear resistance of aluminum matrix. The friction surface welding or the combination method of friction surface welding and rotary ultrasonic machining are considered as the future research direction. The friction surface coating is suitable for the large aluminum alloy parts with good wear resistance and excellent mechanical properties. The enhancement in mechanical properties of aluminum alloys is important, which should be further researched.

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铝合金耐磨性能改善方法综述

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摘 要：铝合金是航空航天领域应用最为广泛的高性能金属结构材料之一。然而，由于铝合金硬度低、耐磨性能较差，铝合金零件在使用过程中容易出现磨损或划伤。本文主要从表面涂层法和纳米颗粒增强铝基体法两个方面综述了改善铝合金耐磨性能的方法，对探索新的耐磨铝合金制备方法、改善铝合金综合力学性能具有重要的现实意义和科学价值。

关键词：耐磨性能；表面涂层；纳米颗粒强化；铝合金

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