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REVIEW OF MANUFACTURING AND REPAIR OF AIRCRAFT AND ENGINE PARTS BASED ON COLD SPRAYING TECHNOLOGY AND ADDITIVE MANUFACTURING TECHNOLOGY

Cold spray technology is a method of deposited metal coatings by high-speed particle impact, especially in the preparation of metal alloy materials (Cu alloys, Ti alloys, Al alloys, Ni-based alloys, Mg alloys, stainless steels, and high-temperature alloys, etc.) The performance is particularly outstanding. The sprayed materials have better mechanical properties, mechanical properties, and service life, such as tensile strength, fatigue strength, and corrosion resistance. Cold spray technology can prepare corrosion-resistant coatings and high-temperature coatings, Wear-resistant coatings, conductive coatings, and anti-oxidation coatings and other functional coatings. From the perspective of process technology and equipment design, cold spray technology can be applied to the field of additive manufacturing technology, which not only reflects the repair function but also the manufacturing function, and applies cold spray technology and repairs the parts produced by additive manufacturing – Selective Laser Melting technology. The defects and problems are of great significance. This article summarizes the repair process and technical characteristics of cold spray technology, and repairs and protects the Cu, Ti, Al, Ni, Mg, and stainless steel and other metals and their alloys from corrosion, fatigue, and wear. The maintenance is reviewed, and the application of combining cold spray technology with additive manufacturing – Selective Laser Melting technology is proposed. Many materials can be used in the field of cold spray technology and Additive Manufacturing – Selective Laser Melting technology. In the communication between the two, the combination of technology and method is of great significance; the influence of spraying parameters of cold spraying technology (such as powder particle shape, spraying angle, spraying distance, critical speed and temperature of particles and substrate, etc.) on spraying effect and efficiency are proposed. Finally, the development of cold spray technology: post-processing of parts, critical speed and numerical simulation are possible.

Keywords: *cold spraying; additive manufacturing; parameters; aviation; repair.*

1. Introduction to Cold Spray Technology

The cold spray system was accidentally discovered by scientists in the Institute of Theory and Applied Mechanics of the Novosibirsk Branch of the former Soviet Union during the wind tunnel experiment in the 1980s. This is a method of depositing metal coatings by hitting high-speed particles on a substrate. Cold Gas Dynamic Spray (CGDS), referred to as cold spray technology. The advantage of this technology is that it can avoid oxidation, participate in thermal stress or phase transition during high temperature deposition [1, 2]. Therefore, this technology can realize an effective technology for multifunctional material surface [3]. In recent decades, the number of papers and patents on cold spraying technology has increased rapidly, covering the research and application of cold spraying in various fields [4 - 6].

1.1. Features of cold spray technology

During the cold spraying process, the coating deposition process can be divided into two stages: the first stage is the deposition of an initial solid powder particle layer; in this stage, the solid powder particles are bonded to the substrate; the second stage is to deposit again on the basis of the original solid powder particle layer. The essence is the plastic deformation combination between the solid powder particles. It should be noted that the critical speeds of these two phases are usually different, unless Same material. Theoretically, higher solid powder particle speeds can improve the quality and efficiency of cold spray deposited coatings.

Figure 1 shows the results of deposition of aluminum powder particles with a diameter of 45 microns on aluminum at different speeds. The study found that solid powder particles deposited when the

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deposition speed exceeded a critical speed to form a better quality coating [7]. It is worth noting that the critical velocity of solid powder particles is not constant. There are many factors that affect the critical velocity, such as: material type, diameter and temperature of solid powder particles, etc. The method of reducing the critical velocity has to appropriately increase the diameter of solid powder particles. And temperature.

Figure 2 shows the relationship between the deposition rate and the deposition efficiency of three different materials [8, 9], where 1 and 4 are aluminum, 2 and 5 are copper, and 3 and 6 are nickel. The hollow and solid symbols are respectively It means that the gas temperature is 300K and 700K. It can be seen from the figure that the deposition efficiency varies with the increase of the speed at different gas temperatures. Increasing the particle velocity and temperature can appropriately increase the deposition efficiency.

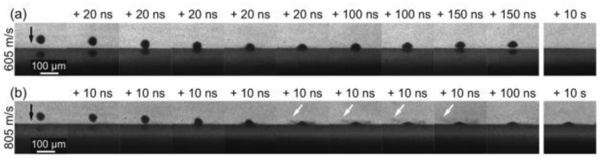


Fig. 1. Aluminum particles with a diameter of 45 µm hit the Al substrate at 605 m / s (top) and 805 m / s (bottom) speeds below and above the critical speed, respectively [7]

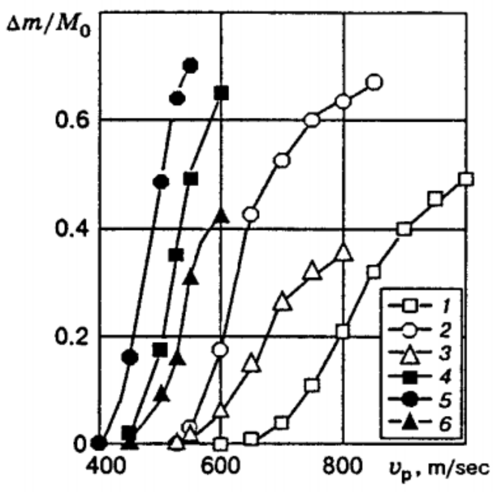


Fig. 2. Relationship between particle velocity and deposition efficiency (DE) of copper, nickel, and aluminum powders [8, 9]

Solid powder particles are usually atomized spherical. If there is a requirement for the diameter of solid powder particles in specific parts, one-to-one correspondence is required. Usually, the diameter range is 10 to 100 microns, mainly to ensure that the critical speed can be exceeded. Otherwise, the acceleration medium cannot accelerate the solid powder particles. In the current process of cold spray technology, the diameter of solid powder particles is usually 20-60 microns. For smaller solid powder particles, the diameter can be up to 100 microns, such as aluminum and zinc [10]. Spraying distance-the distance from the spray gun outlet to the surface of the substrate is 5-50 mm.

2. Additive Manufacturing Technology

2.1. Application and prospect of additive manufacturing technology in aviation

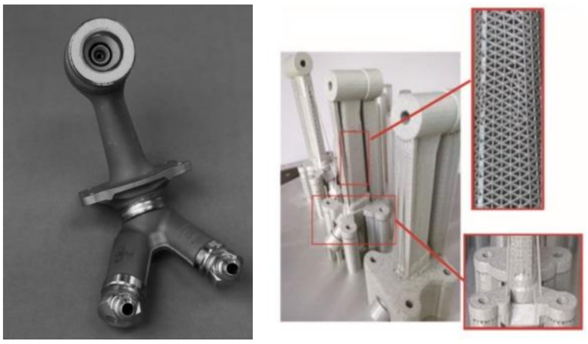
The additive manufacturing technologies currently applied in the aviation field are: Selective Laser Sintering SLS, Fused Deposition Modeling FDM, Selective Laser Melting SLM, Laser Metal Powder Deposition technology (Laser Metal powers Deposition LMD), laser solid forming technology (Leaser Solid Forming LSF), direct metal laser sintering (DMLS) and laser near net forming technology (Laser Engineered Net Shaping LENS), etc., such as: select Selective Laser Melting SLM (SLM) is a process method that can directly form metal parts. Selective Laser Melting technology (SLM) has typical advantages, such as: increase design freedom: bionic geometric structure optimization, easy to modify; high functionality: conformal cooling runner, lattice structure; reduce the number of parts: inherit multiple parts As a whole, reduce assembly; reduce tooling and assembly costs: near net forming; lightweight: improve fuel efficiency through the use of organic component design; optimize material utilization: use only the amount of material required for forming to reduce material waste and high production Strength alloy reduces the loss of tools; short production cycle, wide range of materials, high precision and other advantages. Common metal materials that can be printed using SLM technology, shown in Table 1.

Table 1

Printable metal materials

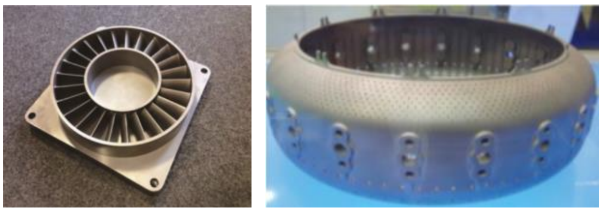
Materials	Common metal materials
Ti-Alloys	Ti6Al4V Gd.23*, Ti6Al4V Gd.23*
Co-Alloys	CoCr28Mo6
Ni-Alloys	IN625, IN718, IN939
Al-Alloys	AlSi10Mg, AlSi12, AlSi7Mg0.6, AlSi9Cu3
Cu-Alloys	CuSn10
Tool and stainless steel	1.4404/316L, Invar 36

GE applies SLM technology to the fuel nozzle of aero engine. As shown in Figure 3, the original nozzle physical map (a) and the nozzle physical printed by SLM technology (b) [11], mainly because SLM can achieve freedom Manufacturing technology advantages. This technology turns the original multiple nozzle parts into one, reducing the total weight by 13.5%, increasing the service life and durability by 4 times, and reducing the emissions by 15% [12]. Liang [13] studied the preparation of Ti-6Al-4V titanium alloy materials by SLM technology. Wang [14] and Zhao [15] showed the turbine disk and engine combustion chamber manufactured by SLM technology, as shown in Figure 4. Zou [16] studied the preparation of AlSi7Mg alloy using SLM technology. Ti-6Al-4V titanium alloy and AlSi7Mg alloy materials are widely used in aviation.



(a) (b)

Fig. 3. Leap engine fuel nozzle physical map (a) and nozzle physical print (b) by SLM technology [11]



(a) (b)

Fig. 4. Turbine disk formed by EOS (a) and combustion chamber (b) [14, 15]

The Cold Spray is probably the most suitable for repairing or manufacturing aircraft engine parts because it works in the same way as SLM technology, which can be used to repair turbine and compressor blades without changing their highly complex underlying crystal structure [17].

The advantages of additive manufacturing technology are obvious. GE expects that direct metal additive parts will account for 50% of aero engine parts in the future, which will reduce the weight of each large aero engine developed by GE by at least 454KG. The following can be directly applied to the engine parts of the manufacturing technology for prediction and statistics, supercharged stage / high pressure gas turbine parts: blades, guide vanes and stator guide vanes; combustion chamber components: combustion chamber liners and fuel manifolds; high / low pressure Turbine components: rotor blades, guide blades, and seal rings; fan components: metal edging and integral leaf discs; casing components: high-pressure compressor casing, main combustion chamber casing, high-pressure turbine casing, and low-pressure turbine casing; mounting components: Adjustable stator blade bushings, heat shields, pipes and brackets.

2.2. Application of cold spraying technology in the field of additive manufacturing

At present, metal materials that can be directly applied to cold spray technology: aluminum, copper, titanium, magnesium, zinc, nickel, iron, and Tc are used to manufacture parts. With the further development of cold spray technology, more and more researchers have begun to pay attention to the remanufacturing function of cold spray technology. Cold spray technology is evolving from a surface spray technology to an emerging additive manufacturing technology [18], In the field of cold spray technology, the repair application of the Ti-6Al-4V alloy described above is very extensive.

At the end of the 20th century, foreign researchers tried to use cold spraying technology to manufacture metal components, and found that it has great potential in the preparation of titanium alloy components [19]. JAHEDI et al. [20] used cold spraying technology to prepare titanium alloy parts, compared with other preparation processes As a result, it was found that the cold spraying technology for preparing titanium alloy parts has high efficiency, low oxygen content, and excellent mechanical properties, and can be used for near net forming of titanium alloys. Among them, the thickness of Cu blocks exceeds 5 mm, and the tensile strength is 200 MPa, reaching the strength of as-cast materials [21].

In principle, cold spray technology is a popular name for additive manufacturing technology-cold spray additive manufacturing technology (CSAM), so it also greatly broadens the scope of application of cold spray technology, cold spray additive manufacturing technology (CSAM) Continuing all the advantages of cold spray technology, compared with other additive manufacturing technology advantages, the most important advantages are: repair, short production cycle, unaffected product size, high flexibility and parts to be repaired. The applicability of maintenance, it is worth noting that this technology is particularly suitable for highly reflective metal materials, such as aluminum and copper, so it has obvious advantages over laser-based additive manufacturing technology. However, this

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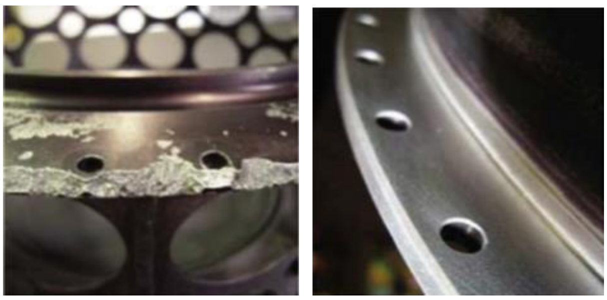
technology also has disadvantages: the surface of parts manufactured by cold spray additive manufacturing technology (CSAM) is rough and requires post-processing; in addition, the deposited layer of cold spray additive manufacturing technology (CSAM) is in the processing state, Its mechanical properties are not good, and it is often necessary to improve the mechanical properties of the parts by post-heat treatment [22].

2.3. Research on the repair of additive manufacturing parts by cold spraying technology

At present, there are very few studies on the repair and maintenance of defects in direct additive manufacturing aircraft parts through cold spraying technology. There are many materials that can be used in cold spray technology and direct additive manufacturing, such as copper, titanium, magnesium, aluminum and their alloys. There are many methods for direct additive manufacturing of aircraft components, but not all aircraft components through additive manufacturing tend to have perfect performance. We can explore the use of cold spray technology to repair defects in aircraft components manufactured by additive manufacturing. Copper alloy additive manufacturing aviation parts will produce pores, cracks, precipitates, and insufficient chemical composition, etc. [23], which will greatly affect the mechanical properties of the parts. The cold spraying technology can precisely affect the parts with pores and cracks. Make repairs. Using laser additive manufacturing technology to prepare complex structures and high-performance magnesium-aluminum alloy parts [24], Villafuerte et al. [25] used cold spray technology to repair the corrosion areas of magnesium-aluminum alloy parts of an engine, as shown in Figure 5. For [25, 26], it can be seen from the figure that the edge area of the repaired component is significantly improved, and no corrosion occurs.



(a) (b)

Fig. 5. Repair of corrosive parts of magnesium aluminum alloy by cold spraying technology [25, 26]: a – before the repair; b – after the repair

3. Surface repair of damaged parts by cold spray technology

3.1. Repair process of cold spray technology

The standard repair process of damaged parts using cold spray technology is mainly divided into four steps:

a) pre-processing of damaged parts of parts by cold spraying technology;

b) select the materials to be sprayed and spray-deposit the repaired parts on the damaged parts;

c) post-processing parts that have been repaired by cold spray deposition;

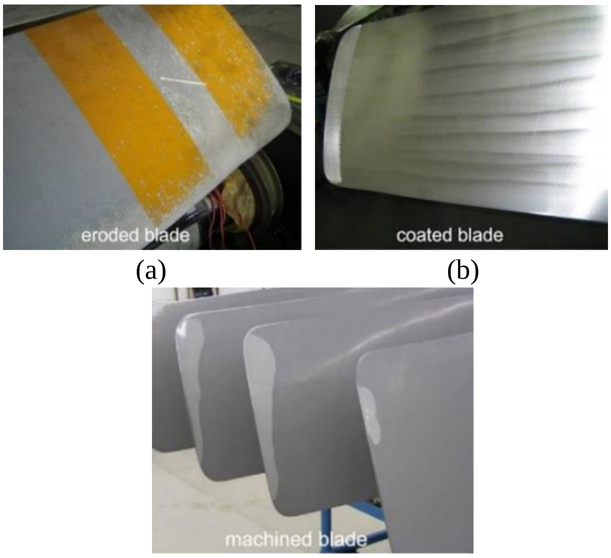
d) performance tests will be performed on the parts that have been repaired through cold spray technology.

3.2. Repair of corroded or corroded parts by cold spray technology

Analysis of aeronautical machinery parts. During the work of mechanical parts, the surface is prone to serious defects such as severe corrosion, erosion, chemical corrosion and wear, resulting in excessive size or reduced service life; economic loss by choosing to replace damaged parts It is relatively large, if it is replaced by cold spraying technology to repair its damaged parts, it will have good economics.

Cold spraying technology has obvious advantages in the repair of parts, and it is gradually popularized in the aviation field for the repair and application of broken and damaged parts. Scientists at the GE Global Research Lab (GRC) and Bari University of Technology in Italy have developed a method for cold spraying metal powders on repair parts (Scientists at the GE Global Research labs (GRC) and the Polytechnic University of Bari, Italy has developed a method of Cold Spraying metal powder onto repair parts.). For example, the U.S. military technology research laboratory applied cold spraying technology to repair and repair military helicopter aluminum alloy mast supports in the early 21st century. The results show that the cold spray technology is used to spray aluminum coatings on the mast supports made of aluminum alloy. The tensile strength and fatigue strength properties have not decreased, and the repaired substrate has more excellent corrosion resistance [27, 28].

The main reason for the occurrence of corrosion, erosion, chemical corrosion and wear of aviation parts is that they are subject to high-speed shocks and rotation at high speeds, especially the hot-end parts of carrier-based engines. Due to the influence of the marine environment, they have been exposed to high air humidity for a long time It can serve in complex environments such as harsh in saline and alkali, not only subject to erosion and wear, but also to the test of corrosion. In a rotorcraft powered by a turboprop engine, corrosion of its propeller blades often occurs, mainly due to the impact of dust, debris and ice particles / water droplets from the external environment on high-speed rotating propeller blades, especially in aircraft. During take-off and landing, the low-level gravel debris will have a serious impact on the surface of the aircraft's propeller blades, and the damaged surface will corrode extremely easily in a humid environment with the increase of time. In the past, the repair method of propeller blades was to cut the damaged parts. If repair was performed by cold spraying technology, the damaged parts were cut and the sprayed materials were post-processed to restore the propeller blades to the original size. Parameters to ensure the integrity and balance of aircraft power. The restoration of propeller blades has passed various tests of the airworthiness of the World Civil Aviation Administration. At present, the use of cold spraying technology to repair propeller blades has been widely used, as shown in Figure 6 Process of spraying technology repair [29].



(a) (b)

(c)

Fig. 6. The repair process of a certain type of propeller using cold spraying technology [29]:
a – eroded blade; b – coated blade;
a – machined blade

3.3. Cold spraying technology for repair and performance of different metal alloy parts

1. Cu.

Copper is widely used as a raw material in the field of cold spraying technology. The main reason is that copper has good ductility, so it can be used as one of the materials with higher quality of cold spray coating. The copper coating is prepared by the cold spray technology process. The copper powder particles can form a very dense and uniform coating on the substrate, and then the copper coating (the interface between the surface particles) is heat-treated. The research shows that the average tensile strength of the untreated copper coating is 124.9 Mpa, the average tensile strength of the copper coating after annealing is 167.7 Mpa, and the average tensile strength of the copper coating after cold spraying and annealing is increased by 34.3 % [30]. Generally, the hardness of copper alloy coatings prepared by cold spray technology is higher than that of pure copper coatings [31]. The main reasons can be attributed to two points. First, when the cold spray technology is used to prepare the coating, some crystals appear. The grains at the particle interface are refined; secondly, atomic diffusion during heat treatment causes the interface between the sprayed particles to disappear. Eason et al. [32] used cold spraying technology to prepare copper blocks on copper substrates to a thickness of 25 mm. Huang et al. [33] sprayed the copper coating on the aluminum alloy substrate using the cold spraying technique, and measured the relationship between the bond strength of the coating and the substrate and the particle velocity, as shown in Figure 7. In the cold spraying process, increasing the copper powder particle speed can produce high-strength copper blocks and even large components, as shown in Figure 8 to prepare copper flanges [34].

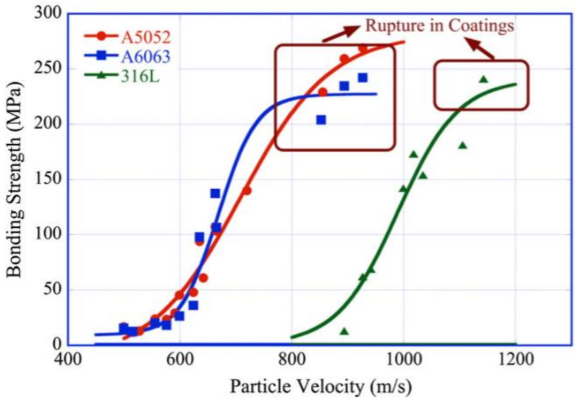


Fig. 7. Relationship between bond strength and copper powder particle velocity [33]

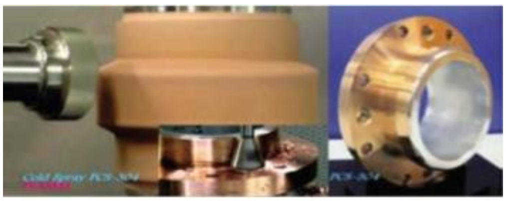


Fig. 8 Preparation of copper flanges by cold spraying technology [34]

In the spraying process, not only the speed of the powder particles will affect the quality and efficiency of

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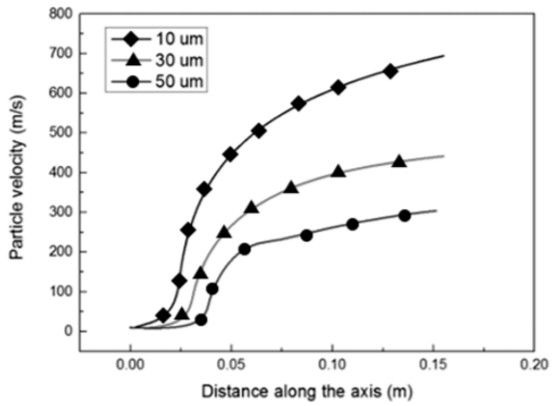
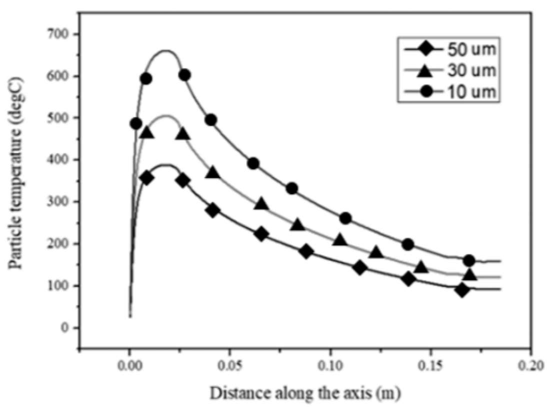
the deposition, but also the size and temperature of the powder will also affect its deposition. Zhang [35] et al. studied the relationship between the speed, diameter and temperature of copper-based composite powder particles with different diameters during the spray coating process by simulating the deposition of copper-based composite materials. As shown in Figure 9, the velocity and temperature of copper-based composite powder particles with different diameters change along the axis; it can be seen from the figure that as the diameter of the particles increases, the velocity of the sprayed powder particles decreases, the temperature decreases, and obvious diameters occur. Grain effect.



(a)



(b)

Fig. 9. Velocity(a) and temperature(b) changes of copper-based composite powder particles with different diameters along the axis [35]

2. Ti.

Titanium and titanium alloys have many advantages, such as low density, high strength-to-weight ratio, and excellent corrosion resistance, so they are widely used in aerospace, chemical and biological manufacturing fields.

Many researchers have studied the microstructure and mechanical properties of pure titanium coatings or Ti-6Al-4V coatings prepared by the cold spraying process. At the same time, pure titanium itself has strong active properties and the unique reaction of titanium alloy materials with the surrounding air, so it is difficult to obtain a dense pure titanium or Ti-6Al-4V coating, as shown in Fig. 10 Microstructure at the cross section of pure titanium or Ti-6Al-4V coatings prepared by the cold spraying process [36]. As shown in Fig. 11, the fragments of bimetal Ti-6Al-4V / aluminum and titanium / copper plates prepared by the cold spraying process are machined and milled after spraying [37], and as shown in Fig. 12 are the cold spraying process The production of pure titanium parts and pure titanium hemisphere parts with the help of molds [38].

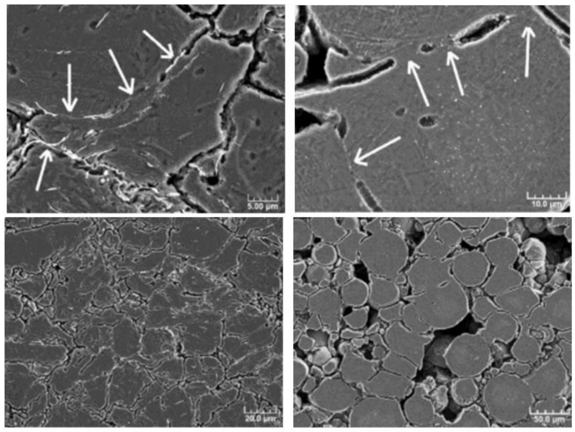


Fig. 10. Microstructure of titanium and Ti-6Al-4V coatings sprayed in the etched state [36]

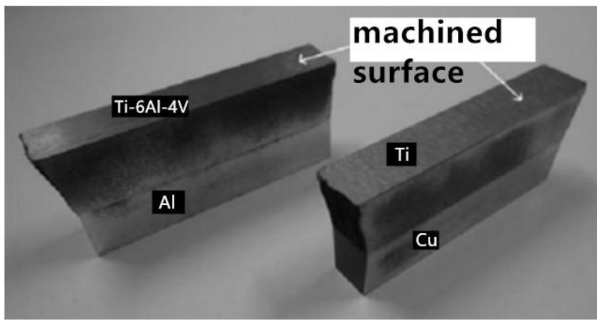
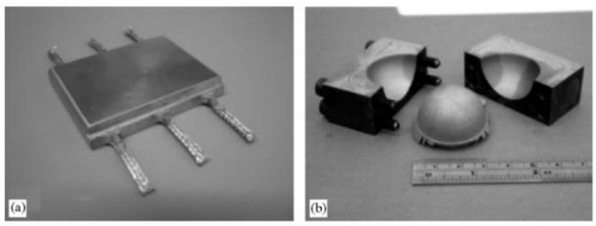


Fig. 11. The bimetal Ti-6Al-4V / aluminum and titanium / copper sheet prepared by the cold spraying process is machined and milled after spraying [37]



(a) (b)

Fig. 12. Using cold spray technology to produce pure titanium parts (a) and pure titanium hemisphere parts (b) with the help of a mold [38]

3. Al.

Aluminum is a material often used in cold spray technology, so many researchers have studied the deposition of aluminum and aluminum alloy coatings. At present, most of them are through studying the microstructure and corrosion resistance of aluminum alloys. Few literatures are about the mechanical properties of pure aluminum and aluminum alloy coatings made by cold spraying technology.

Compared with copper, aluminum powder is easier to deposit on the substrate, but the density of the aluminum coating is lower than that of the copper coating, mainly due to the lower density of aluminum. Figure 13 shows a typical cross-section of a pure aluminum coating obtained by the cold spraying process [39]. Figure 14 shows a typical cross-section of an aluminum 7075 alloy coating obtained by the cold spraying process [40].

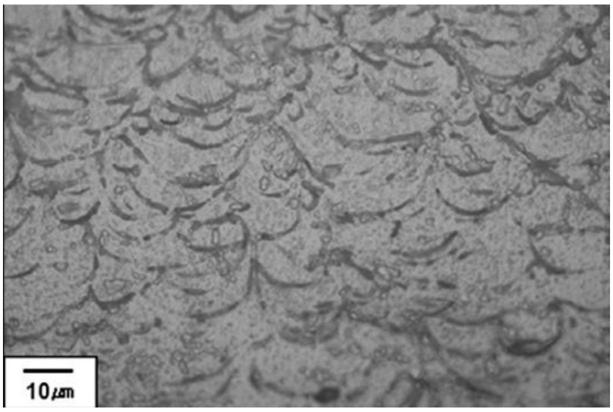


Fig. 13. Typical cross section of a pure aluminum coating [39]

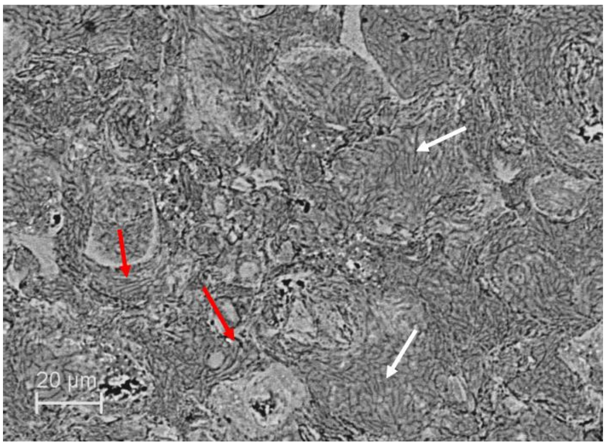
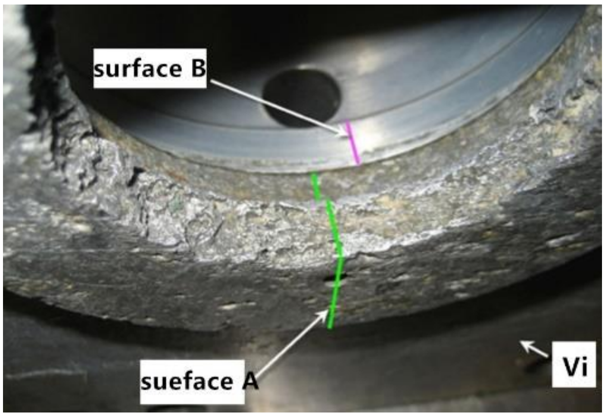


Fig. 14. Typical cross section of an aluminum 7075 alloy coating [40]

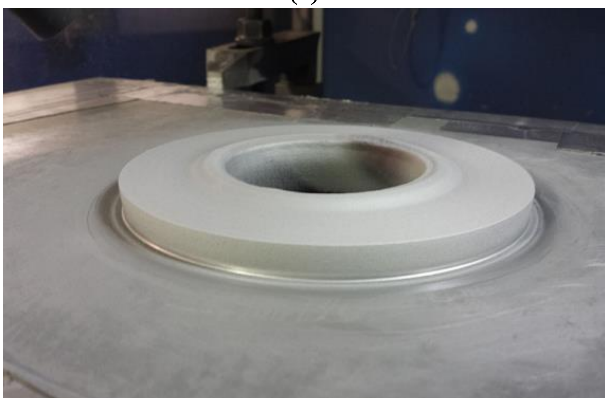
Aluminum and aluminum alloys are widely used in aerospace, marine, and automotive machinery fields. They have the advantages of low density, high tensile strength, corrosion resistance, and easy forming. As shown in Figure 15 (a), the aluminum mast support of a rotorcraft helicopter [41]. At present, the rotor mast support frame cannot be repaired once it fails. The main form of failure of the mast support frame is usually a: under the snap ring groove. Corrosion pits on the lip; b: mechanical damage on the upper lip of the snap ring groove and mechanical damage to the gear. As shown in Fig. 15 (b), the corrosion damage near the lower lip of the snap ring groove parts is near [41]. The area near the lower lip of the snap ring groove parts of the aluminum mast support frame of a rotorcraft is sprayed with aluminum alloy by cold spraying. The coating is deposited and finally the repaired parts are post-processed. As shown in Figure 16 (c) [41], the snap ring groove parts are repaired by cold spraying technology to repair the corrosion points.

(a) (b) (c)

Fig. 15. Aluminum mast support of a rotorcraft helicopter (a), corrosion damage area near the lower lip of the snap ring groove part (b) and snap ring groove parts (c) after the corrosion point is repaired by cold spray technology [41]



(a)



(b)

Fig. 16. Before (a) and after (b) repair of the aluminum alloy valve controller [42]

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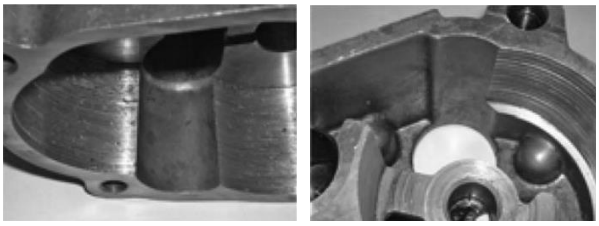
Cold spraying technology has been widely used in marine ships. For example, after corrosion of the aluminum alloy valve controller of ocean-going ships, internal holes will be formed on the surface. The damaged parts are repaired by cold spraying technology. Compared with other maintenance methods, the cold spraying technology is characterized by There will be thermal effects, as shown in Figure 16, the corrosion of the aluminum alloy valve controller (a) and the aluminum alloy valve controller (b) [42] that passed various tests after repair. The results prove that the control performance of aluminum alloy valve is good.

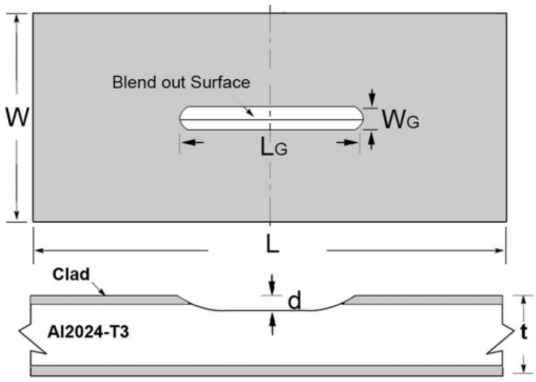
In the field of automotive machinery, cold spraying technology is used to spray corroded Caterpillar-3116 engines and Caterpillar-3116 fuel pump housings to spray aluminum alloy coatings, thereby achieving repair of corroded parts. Shown in Figure 17 is the Caterpillar-3116 engine and Caterpillar-3116 fuel pump housing [43]. The repaired Caterpillar-3116 engine and Caterpillar-3116 fuel pump housing are normally used in the later period without failure.



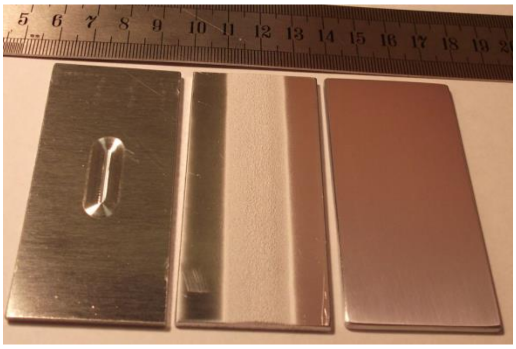
(a) (b)

Fig. 17. Caterpillar-3116 engine (a) and Caterpillar-3116 fuel pump housing (b) [43]

The skins of civil airliners and military aircraft are mainly made of aluminum alloy materials, and some parts are usually further protected by aluminum cladding. During the high-speed flight of the aircraft, due to the collision of dust or debris in the external environment, the aircraft skin is extremely prone to scratches, and the scratches formed by the scratches are easily eroded in a wet environment. The protective material (usually the aluminum cladding) is completely eroded, which in turn corrodes the next layer of aluminum alloy. If this layer of aluminum alloy structure is severely corroded, it will give the aircraft a fatal blow, affect flight safety, and reduce the use of aircraft skins. Life, while also increasing subsequent maintenance costs. In order to avoid the above situation, the aluminum cladding structure of the aircraft skin needs to be protected or repaired to prevent further corrosion of the aluminum alloy structure of the next layer, so as to reduce the maintenance cost and improve the economy. The methods currently used on the market to repair damaged aircraft skin include: Flame Spraying and High-velocity Oxy-fuel spraying (HOVF), all of which belong to the thermal spraying technology. In terms of the above, the above methods have common characteristics in the spraying process, that is, defects such as high porosity, easy oxidation and phase change during the deposition of the aircraft skin surface. If a collision occurs in the later stage, the raw materials in the high temperature spraying state may affect the aluminum alloy structure under the aircraft skin causes damage, which reduces the mechanical properties of the aircraft skin. Using the cold spraying technique to repair can avoid the defects mentioned above, which has the advantage that the substrate will not be damaged during the spraying process [44 - 46]. As shown in Figure 18 is a schematic diagram of the repair process of damaged aluminum alloy panel (a) and the aluminum cladding (b) of the aircraft skin aluminum sheet metal repaired by cold spraying technology [47]. It can be seen from the processing schematic diagram and the finished drawing that the aluminum alloy is completely filled to cover the damaged part of the aircraft skin, and the repaired part is not significantly different from the aluminum clad part. The performance test of the repaired parts shows that the hardness of the coating is significantly increased after the deposition, and the fatigue resistance of the repaired parts is also improved. The corrosion test results show that: Damaged layers on the alloy surface can provide better protection, but corrosion will exist at the edges of the aluminum cladding [47].



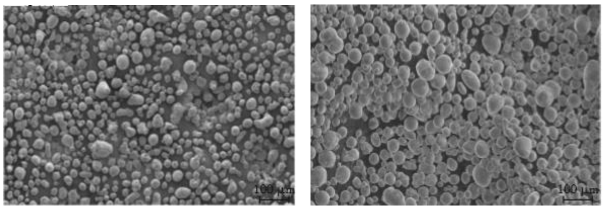
（a）



(b)

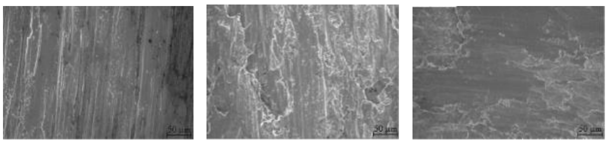
Fig. 18. Schematic diagram of repair process of damaged aluminum alloy panel (a) and aluminum cladding for repairing aircraft skin aluminum sheet metal by cold spraying technology (b) [47]

Using cold spray technology to spray and deposit the substrate, the uniformity of the coating and the compactness of the structure are also two very important assessment indicators. The diameter of the aluminum powder is an important factor affecting the above. Jia [48] et al. studied the spraying of pure aluminum coating on the surface of AZ31 magnesium alloy by cold spraying technology. The spraying powder was commercial aluminum powder. Two aluminum powders with diameters of 25 mm and 40 mm were used for spraying research. The micro-morphology of the aluminum powder deposition coating is shown in Figure 19 [48]. It can be seen from the figure that the particle size distribution of the two spray powders is very uniform. GCr15 steel balls were used for grinding of AZ31 Mg alloy, coating 1 (deposited with 25mm Al powder) and coating 2 (deposited with 40mm Al powder). The friction results are shown in Figure 20 [48]. It can be seen from the figure that the coating deposited by the aluminum powder with a smaller particle size has higher hardness, lower volume wear, and better wear resistance.



(a) (b)

Fig. 19 Micro-morphology of 25mm (a) and 40mm (b) aluminum powder deposited coatings with diameter particles [48]



(a) (b) (c)

Fig. 20. Wear of AZ31 Mg alloy (a), coating 1 (b) (25mm aluminum powder) and coating 2 (c) (40 mm aluminum powder) [48]

4. Ni.

Ultra-high nickel-based alloy materials are used very frequently in the aerospace field, especially in ultra-high temperature conditions, they can also show good mechanical properties and corrosion resistance. When the aircraft is in the normal flight process, many parts made of ultra-high nickel-based alloys need to bear large mechanical and thermal loads. Therefore, these parts will inevitably undergo severe wear and corrosion. There will be some safety hazards during use, and the service life of these parts will be shortened. For example, the barrel of the steering actuator under the nose of the Boeing 737 is made of nickel-based alloy materials. When the landing gear of the passenger plane is lowered, these parts will be in a complex environment such as humidity and high pressure. Corrosion and other conditions often occur, which eventually lead to corrosion of the front landing gear of passenger aircraft. The surface of the barrel of the steering actuator under the nose of the Boeing 737 is spray-deposited with a nickel alloy by cold spraying technology, so as to repair the corroded parts. As shown in Figure 21, the front landing gear is corroded. (a) and the case of post-treatment by deposit protection by cold spraying technology (b), spraying the barrel of the steering actuator under the nose of a Boeing 737 repaired with nickel alloy by cold spraying technology, the previously corroded surface It becomes smooth without any pits and cracks [49].

(a) (b)

Fig. 21. Corrosion of the front landing gear (a) and post-treatment of it by deposit protection using cold spray technology (b) [49]

Wei [50] et al. Studied the deposition of magnesium alloy surface with nickel powder by cold spraying technology. The results show that in-situ shot blasting assisted cold spraying can obtain a relatively dense nickel coating, and high-speed nickel powder particles penetrate into the AZ31B substrate. The coating adhesion is higher than 65.4 Mpa. Marios [51] et al. Studied the addition of nickel 718 powder to the nickel powder during the cold spraying process to enhance the cavitation resistance of the nickel coating. The results show that the addition of nickel 718 powder can reduce the overall mass loss by 80 %. By studying the particle size distribution of nickel powder and nickel 718 powder, as shown in Figure 22, the particle size distribution of nickel powder and nickel 718 powder and the parameters of nickel powder [51] and nickel 718 powder shown in Table 2, combined with the chart, we can know that nickel 718 Compared with nickel powder, the average diameter of nickel 718 powder is slightly larger, about 14 %.

5. Mg.

Magnesium and magnesium alloys have more advantages than other metals, high rigidity, low density, good thermal conductivity and superior machinability.

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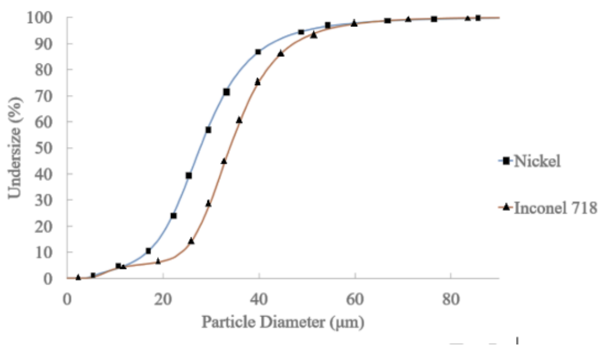


Fig. 22. Particle size distribution of nickel powder and Ni 718 powder [51]

Table 2

Parameters of nickel powder and nickel 718 powder

Parameters \ Material	Nickel powder	Ni718 powder
Average diameter / micron	29.1	33.9
Median diameter / micron	27.7	34.6

Therefore, magnesium and magnesium alloys have been widely used in manufacturing gearboxes of rotor helicopters. From the perspective of chemical analysis, the electrochemical properties of magnesium are relatively lively, second only to iron. When magnesium and other metals are extremely easy to form galvanic cells in a humid environment, magnesium will easily corrode with the anion reaction of other metal materials as electrodes, so Magnesium is used as a material to make rotor helicopter gear transmissions often suffer from electrochemical corrosion, which shortens the service life of rotor helicopter gear transmissions, long maintenance time of gear transmissions, and additional maintenance and repair costs, reducing economics.

The gearboxes of rotary helicopters equipped by many national forces are now mostly made of magnesium metal. Figure 23 shows the gearbox of a rotorcraft [52]. Corrosion over extended periods of time is more severe than regular maintenance [53 - 56]. Due to corrosion, the rotorcraft requires long-term maintenance, the parts are large, it is not easy to disassemble, and the workload and cost of maintenance are increased. As shown in Figure 24, the corrosion of magnesium components of a rotorcraft [57 - 59]. As shown in Figure 25, a key part of a rotorcraft is made of a magnesium material. From Figure 25 (a), it can be found that severe corrosion has occurred in this part, and the corrosion part is repaired by cold spraying technology. This is shown in Figure 25 (b) [60].

6. Stainless steel.

Stainless steel has good mechanical and mechanical properties. Many mechanical parts are made of stainless steel, such as brackets. Stainless steel coatings are commonly used in the protection of machinery, and their economic effectiveness is mainly reflected in wear and corrosion protection. Therefore, cold spray coating technology is likely to be a suitable alternative to conventional bulk materials [61]. Generally, it is very difficult to produce a dense coating with stainless steel as the spray material. Accelerating the powder particles to ultra-high speed, using high-pressure gas and high-temperature or helium spraying, it is easier to achieve dense coatings produced by using stainless steel as the spraying material [62]. Researchers use stainless steel powder as a spraying material, and study the deposition behavior and mechanical properties of stainless steel coatings in consideration of parameters such as the size of the deposited powder particles, post-annealing treatment, the speed of the deposited particles, and the gas temperature.

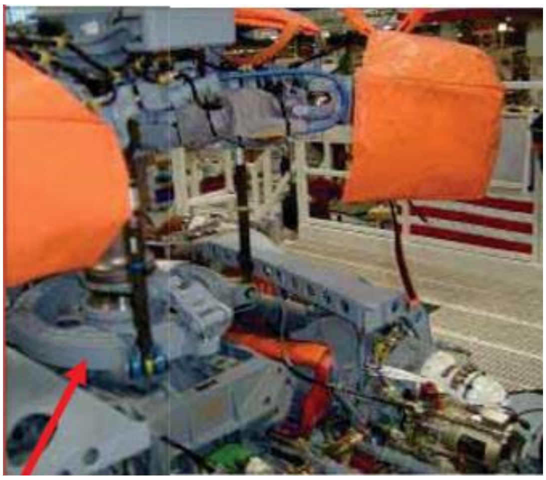
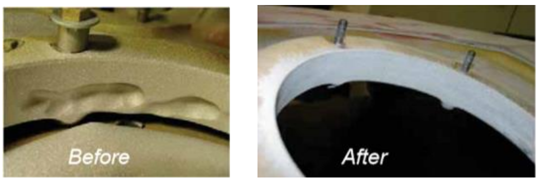


Fig. 23. Magnesium gearbox of a rotor helicopter [52]

Fig. 24. Corrosion of magnesium components in a rotorcraft [57 - 59]



(a) (b)

Fig. 25. Corrosion of magnesium parts of a rotorcraft helicopter (a) and repaired by cold spray technology (b) [60]

7. Superalloys.

Superalloys are more common at high temperatures. During spraying by cold spray technology, although in a high-temperature gas environment, high-temperature alloys that are not easily deformed also undergo plastic deformation when the cold spray particles impact the substrate, resulting in the inability to form a dense deposit coating. Therefore, such a deposit would be similar to high-density, high-quality powder compacts—low strength and no toughness. Therefore, in order to study to obtain better physical and mechanical properties of superalloys sprayed by cold spraying technology, at present, researchers have studied the coatings that are cold sprayed and then further heat treated.

4. Current problems and future outlook

Cold spray technology plays a vital role in aerospace, automotive, marine, energy, medical and other spray technology areas. In principle, the analysis of cold spray technology belongs to the category of additive manufacturing and has great potential. It can not only repair damaged parts but also manufacture related parts. From the analysis of the advantages of cold spray technology, it can better retain all the properties of the material to be deposited and also ensure that the mechanical properties of the sprayed substrate are not affected. From the birth of cold spraying technology to the present, coupled with continuous exploration and innovation by scientific researchers, its technical characteristics and features have been gradually verified and successfully applied in various fields. Although the advantages of cold spray technology are particularly outstanding, there are some disadvantages and challenges:

1. Cold spraying technology has been used in many fields to improve the strength properties, corrosion properties and fatigue properties of substrates, but processed parts need to be processed afterwards, so this should be another focus area for future research.

2. The spray parameters of cold spray technology (such as: powder particle shape, collision angle, spray distance, critical speed, and temperature of particles and substrate, etc.) are very important reference indicators; for example: the effect of powder particle shape on speed is the same Under working conditions, non-spherical particles are easier to accelerate than spherical particles, and non-spherical particles have better acceleration; the collision angle (angle with the substrate normal) will also affect the spraying effect, When incident at 0 °, 10 °, 20 °, 30 ° and 40 ° respectively, as the incident angle increases, the bonding strength of the particles and the substrate gradually weakens, which ultimately affects the deposition effect; the powder particles and the substrate will affect the deposition mechanism. The temperature of the powder hits the substrate, as shown in Table 3, the relationship between the compression ratio and the temperature of the powder particles. Increasing the temperature of the powder particles can accelerate the deformation of the powder particles, which is beneficial to the deposition on the substrate; The acceleration of the powder particles can significantly increase the degree of deformation of the particles and the substrate, thereby reducing the porosity of the deposited coating. Later, the theoretical calculation, numerical simulation and experimental operation were combined to finally formulate a plan with better deposition performance.

Table 3

Relationship between compression rate
and powder particle temperature

Y \ X	Compressional ratio		
	Cu/Cu	Fe/Fe	Ni/Ni
100	0.485	0.482	0.483
200	0.504	0.478	0.496
300	0.531	0.510	0.509
400	0.559	0.554	0.516
500	0.596	0.600	0.535
600	0.638	0.644	0.543
700	0.653	0.682	0.568
800	0.697	0.709	0.592

X – Compressional ratio;
Y – Particle initial temperature (°C)

3. Additive manufacturing technology continues to mature and improve, more and more widely used in the aviation field, such as Selective laser melting technology (SLM). SLM technology has typical advantages, such as: increase design freedom, high functionality, reduce the number of parts, reduce tooling and assembly costs, lightweight; optimize material utilization: use only the amount of material required for forming to reduce material waste and high production Strength alloy reduces the loss of tools; short production cycle, wide range of materials, high precision and other advantages.

Aerospace components manufactured by using SLM technology will also have corrosion, erosion and wear during normal operation. Cold spray technology can precisely repair and protect the above-listed defective or damaged components in order to ensure that the aviation components have better mechanical properties and longer service life, the exploration in this field is very urgent at present.

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ОГЛЯД ВИГОТОВЛЕННЯ ТА РЕМОНТУ ДЕТАЛЕЙ ЛІТАКІВ ТА ДВИГУНІВ НА ОСНОВІ ТЕХНОЛОГІЇ ХОЛОДНОГО НАПИЛЮВАННЯ ТА ТЕХНОЛОГІЇ АДИТИВНОГО ВИРОБНИЦТВА

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Технологія холодного газодинамічного напилювання – це метод нанесення металевих покриттів шляхом високошвидкісної взаємодії частинок порошку (сплави міді, титану, алюмінію, нікелю, магнію, металокерамічні суміші та інші) з підкладкою. Отримані покриття мають механічні властивості близькі до властивостей металів, з яких отримані порошки для напилювання. Серед них міцність на розрив, втомна міцність, стійкість до корозії, коефіцієнт температурного розширення та інші фізико-механічні характеристики. Технологія холодного газодинамічного напилювання дозволяє отримувати антикорозійні, зносостійкі, теплопровідні та інші функціональні покриття. Перспективним напрямком технології газодинамічного напилювання є отримання покриттів на деталях, отриманих з використанням адитивних технологій виробництва, наприклад селективного лазерного плавління. Крім того, холодне газодинамічне напилювання може бути не тільки використано для ремонту будь-яких поверхневих дефектів виробництва або експлуатації таких деталей, але й безпосередньо нарощування певних ділянок і поверхонь. У даній статті виконано аналіз робіт в області ремонту й захисту деталей з мідних, титанових, алюмінієвих, нікелевих і магнієвих сплавів, сталей та інших металів з корозійними пошкодженнями, зносом та іншими дефектами з використанням технології холодного газодинамічного напилювання. Авторами статті пропонується застосування технології холодного газодинамічного напилювання покриттів на деталі, отримані адитивним виробництвом – селективним лазерним плавлінням. Проаналізовано матеріали, які можуть бути використані для напилювання та виробництва деталей авіаційної техніки селективним лазерним плавлінням. Виділено основні технологічні параметри процесу холодного газодинамічного напилювання, зокрема, температура і швидкість частинок, розмір і форма частинок напилюваного порошку, що впливають на фізико-механічні характеристики покриттів, такі як адгезійна міцність, мікротвердість, пористість, корозійна- й зносостійкість та інші, а також впливають на коефіцієнт використання порошку.

Ключові слова: Холодне газодинамічне напилювання; адитивне виробництво; технологічні параметри; характеристики покриттів.

ОБЗОР ИЗГОТОВЛЕНИЯ И РЕМОНТА ДЕТАЛЕЙ САМОЛЕТОВ И ДВИГАТЕЛЕЙ С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИЙ ХОЛОДНОГО НАПЫЛЕНИЯ И АДДИТИВНОГО ПРОИЗВОДСТВА

Кунь Тань, С. Е. Маркович, Веньцзе Ху, А. В. Шоринов, Юронг ван

Технология холодного напыления – это метод нанесения металлических покрытий путем высокоскоростного воздействия частиц порошков (сплавы меди, титана, алюминия, никеля, магния, металлокерамические смеси и др.) с подложкой. Напыляемые покрытия имеют механические свойства близкие к свойствам металлов, из которых получены порошки для напыления. Среди них прочность на разрыв, усталостная прочность, устойчивость к коррозии и другие физико-механические характеристики. Технология холодного напыления позволяет получать антикоррозийные, износостойкие, теплопроводящие и другие функциональные покрытия. Перспективным направлением технологии холодного газодинамического напыления является напыление на детали, полученные с использованием аддитивных технологий

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производства, к примеру селективное лазерное плавление. Кроме того, газодинамическое напыление может быть не только использовано для ремонта каких-либо поверхностных дефектов производства или эксплуатации таких деталей, но и непосредственно наращивания определенных участков и поверхностей. В данной статье выполнен анализ работ в области ремонта и защиты деталей из медных, титановых, алюминиевых, никелевых и магниевых сплавов, сталей и других металлов с коррозионными повреждениями, износом и другими дефектами с использованием технологии холодного газодинамического напыления. Авторами статьи предлагается применение технологии холодного напыления покрытий на детали, полученные аддитивным производством – селективным лазерным плавлением. Проанализированы материалы, которые могут быть использованы для напыления и производства деталей авиационной техники селективным лазерным плавлением. Выделены основные технологические параметры процесса холодного газодинамического напыления, в частности, температура и скорость частиц, размер и форма частиц напыляемого порошка, оказывающие влияние на физико-механические характеристики покрытий, такие как адгезионная прочность, микротвердость, пористость, коррозионная- и износостойкость и другие, а также влияющие на коэффициент использования порошка.

Ключевые слова: Холодное газодинамическое напыление; аддитивное производство; технологические параметры; характеристики покрытий

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