On the Characteristics of Cold Spray Technology and Its Application in Aerospace Industries

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Abstract. Cold spraying technology is an advanced spraying technology developed based on the principles of aerodynamics. It is mainly used to deposit and repair the surface of metal alloy parts to ensure that the parts have better mechanical properties and service life. Compared with traditional thermal spraying technology, cold spraying technology has many advantages, such as low spraying temperature, low oxygen content and low porosity, and it is not easy to cause oxidation, burning, phase change and other phenomena during spraying. This article reviews the principles, technical parameters, and characteristics of cold spray technology, focusing on the effects of powder particle size and shape, particle and substrate temperature, critical speed, spray gun, collision angle, and spray distance on coating quality and deposition efficiency. In addition, the current research and application status of cold spray technology in the preparation of anti-corrosion coatings, high temperature resistant coatings, high temperature oxidation and wear resistant coatings are discussed, and the development prospects of cold spray technology are prospected.

Keywords. Cold spray, coating, critical speed, spray angle.

1. Technical Parameters and Technical Characteristics of Cold Spray

The technical parameters of cold spraying include the size and shape of the powder particles, the temperature of the particles and the substrate, the critical speed, the spray gun, the collision angle and the spraying distance \cite{1-3} etc. The above technical parameters will all produce the coating quality and deposition efficiency influences.

1.1. Size and Shape of Powder Particles

Different metal powders sizes and shapes will also affect the quality of the deposit. Zhao \cite{4} and other scholars studied by studying the maximum contact area of powder particles with diameters of 10, 20 and 30 microns after impacting the substrate. When the speed is within a certain range, by changing the powder particles in an irregular base at the speed of spraying on the material, the contact area of the powder particles and the substrate will change. When the speed is too large, this effect will reach saturation, and the contact area will not increase with the increase of speed. H Fukanuma \cite{5}, PATTISON J \cite{6} and other scholars found that because the traction coefficient of airflow to non-spherical particles is larger than that of spherical particles, the cross-sectional area and drag coefficient of powder particles will seriously affect the drag of particles the drag force is greater than...
that of spherical particles and irregular particles. Therefore, the speed of non-spherical particles is significantly higher than that of spherical particles due to acceleration under equal working conditions. Scholars such as Jodoin B [7] also found that non-spherical particles have a larger drag coefficient (CD) than spherical particles. Therefore, the drag force of non-spherical particles is greater, and the particles can obtain higher Speed, so it is of great significance to reduce the critical speed and improve the deposition efficiency. Zhao [4] and other scholars studied the comparison of plastic deformation and temperature distribution of aluminum and magnesium alloy powder particles of different sizes and shapes, as shown in table 1. Plastic deformation and temperature distribution of spherical powder particles after impact on the substrate both show a pair distribution, and the plastic deformation and temperature distribution of the ellipsoidal particles after impact on the substrate show different changes due to the impact directions of the major and minor axes of the ellipse. The degree of deformation of magnesium alloy powder particles is more intense, mainly because the specific heat and heat conduction of magnesium alloy are less than that of aluminum alloy, and the plasticity parameter is related. By studying particles of different sizes and shapes, it is concluded that particles with small differences in diameter and shape should be selected as much as possible for spraying, so as to ensure that the mechanical properties and mechanical properties of the substrate surface coating areas will not be too different.

| Shape     | Size [\mu m] | Plastic deformation (along the long axis) | Temperature distribution (along the long axis) | Plastic deformation (along the short axis) | Temperature distribution (along the short axis) |
|-----------|--------------|------------------------------------------|-----------------------------------------------|-------------------------------------------|-----------------------------------------------|
| Ball a / b / c | 10 /20/30    | Symmetrical distribution                  | Symmetrical distribution                        | Symmetrical distribution                  | Symmetrical distribution                        |
| Ellipsoid a | 9*9*12.35    | Symmetrical distribution                  | Symmetrical distribution                        | Asymmetric distribution                    | Asymmetric distribution                        |
| Ellipsoid b | 8.17*8.17*15 | Symmetrical distribution                  | Symmetrical distribution                        | Asymmetric distribution                    | Asymmetric distribution                        |

Conclusion: The shape and size of the powder particles are also important factors affecting the coating. First, choosing the spherical shape and equal diameter particles for spraying can effectively make the particles uniform and symmetrical in the plastic deformation and temperature distribution, thereby ensuring the substrate the uniformity of each area of the upper coating meets the performance requirements of the coating.

1.2. Speed
When the speed reaches a certain value, the powder particles are attached to the substrate to form a coating. This speed is called the critical speed. The critical speed can be obtained through experimental testing and numerical simulation, National Aerospace University in Ukraine has been committed to using simulation software to study the critical speed. Generally, the critical speed is regarded as the lower limit of the speed that can be deposited, so in the deposition process, the particle speed must be greater than the critical speed to achieve the deposition of powder particles on the substrate. When the speed of the powder particles is lower than the critical speed, the powder particles cannot be deposited on the substrate but rebound, leaving an impact on the substrate crater. The collision and combination of powder particles and substrate during cold spraying mainly depend on the kinetic energy of the particles. At the same speed, the kinetic energy of particles with smaller particle sizes is also smaller, and the plastic energy consumption of the substrate and particles during collision is less. In the spray deposition process, the powder particles can be driven by the acceleration medium to obtain supersonic speed in the Laval nozzle. The speed of the powder particles affects the
deposition efficiency. Figure 1 shows the relationship between the particle speed of copper, nickel and aluminum powder and the deposition efficiency (DE) [8-9], it can be seen from the figure 1 that the deposition efficiency changes with the increase of speed at different gas temperatures. Increasing the particle speed and temperature can appropriately increase the deposition efficiency. As shown in figure 2, Copper flanges were prepared by increasing the particle speed using cold spray technology [10]. Zhao [11] and other scholars also found that, as shown in figure 3, the plastic strain and temperature distribution of multi-particles deposited on a constant temperature substrate (25 ℃) at different speeds, which accelerates the powder particles, can significantly increase the particle and substrate the degree of deformation, thereby reducing the porosity of the deposited coating.

**Figure 1.** The relationship between the particle speed of Copper, Nickel and Aluminum powder and the deposition efficiency (DE) [8-9].

**Figure 2.** Preparation of copper flanges by cold spray technology [10].
Conclusion: Through research, it is found that the speed of particles will affect the deposition effect on the substrate. If the deposition speed is too low, the sprayed particles will not be able to deposit smoothly on the substrate; if the deposition speed is too high, the particles will also be sputtered, which will result in the particles not being deposited on the substrate and waste materials. Different spraying materials need to choose their appropriate deposition speed to achieve the unity of functionality and economy.

1.3. Spray Angle

Yang [12] found that the spray angle will affect the supersonic flow field structure and particle acceleration behavior inside and outside the nozzle. When the spray direction is not perpendicular to the surface of the substrate, Bow Shock in front of the substrate presents an irregular hemispherical shape. The intensity of the front Bow Shock will be weakened due to Oblique Shock generated on the surface of the substrate. As the spray angle decreases, the strength of Bow Shock will gradually weaken, and the impact speed of the particles will increase accordingly.

Wang [13] found that Copper powder particles with an initial velocity of 500 m/s were incident at an angle of 0 °, 10 °, 20 °, 30 °, and 40 ° to the normal of the substrate, and the incident time was 70 ns the screen shot of the screen, as shown in figure 4, at the same time, different cross-sections of the spray angle simulation diagram. From the simulation results, it can be seen that as the incident angle increases, the pit depth gradually decreases, and the particle deposition effect decreases, as shown in table 2. Ding [14] and Li [15] and other studies found that through the combination of test experiments and numerical simulation, as shown in figure 5, the experiment of impacting the copper substrate with a 20um copper powder particle velocity of 400 m/s at a 20 ° tilt angle. The cross-sectional diagram (a), the numerical simulation results (b) under the same conditions, and the experimental results and numerical simulation results are in good agreement through comparative observation. From the
analysis, it can be seen that the effect of cold spray deposition with angular oblique collisions is worse than the ideal vertical collision. With the increase of the incident angle, the depth of the pits gradually decreases, and the bonding strength between the particles and the substrate gradually weakens. When the incident angle is greater than a certain critical value, the particles will not be embedded in the substrate but will detach.

Figure 4. Simulated images of spraying cross-sections at different incident angles at the same time [13].

Figure 5. Experimental cross-sectional view (a) and numerical simulation results (b) of a copper substrate striking at a 20 ° inclination angle [14].

Table 2. Depth and depth change rate of particles deposited on the substrate under different incident angles at an initial velocity of 500 m/s.

| Spray angle | Depth [μm] | Depth change rate |
|-------------|------------|-------------------|
| 0°          | 7.995      | 0%                |
| 10°         | 7.897      | -1.25%            |
| 20°         | 7.406      | -7.37%            |
| 30°         | 6.744      | -15.65%           |
| 40°         | 5.735      | -28.27%           |

Conclusion: Generally, when the particles are deposited perpendicular to the surface of the substrate, the depth of the deposition has the best effect. As the incident angle increases, the depth will gradually decrease, resulting in a weakening of the coating effect.

1.4. The Effect of Particle and Substrate Temperature on the Deposition Mechanism

Scholars such as King PC, Ning X J, Fukumoto M and Shin S [16-19] studied that pre-heat treatment of powder particles or sprayed substrates can enhance the bonding strength, increase the deposition efficiency and reduce the critical speed. It can be seen that it is very important to study the influence of the temperature of the cold spray particles and the substrate on the deposition mechanism.

Feng [20] and other scholars found that when the particle impact velocity is 375 m/s, preheating the
powder particles and the substrate will help reduce the porosity and enhance the combination of the coating. Yin et al. [21] studied the impact of copper powder particles at 25 °C, 200 °C, 400 °C, and 600 °C on the copper substrate, as shown in figure 6 (a); they would be 100 °C, 300 °C, and 500, respectively. Iron powder particles of °C and 700 °C impact the iron substrate, as shown in figure 6 (b); nickel powder particles of 100 °C, 300 °C, 500 °C, and 700 °C, respectively, impact the nickel substrate, as shown in figure 6 (c). It can be seen from the figure that as the temperature of the particles increases, the degree of deformation of the particles gradually increases, the metal sputtering generated around the particles becomes more and more obvious, and the temperature of the particles after deposition also shows an upward trend. The parameter compression ratio is introduced here, as shown in table 3 is the curve of the compression ratio of three different materials with the temperature of the powder particles; from the figure further illustrates that increasing the temperature of the powder particles can promote the deformation of the powder particles, which is beneficial to the base wood deposition.

Figure 6. Temperature changes and plastic strain distribution of copper powder particles at different temperatures impacting copper substrate (a), Iron powder particles impacting Iron substrate (b), Nickel powder particles impacting Nickel substrate (c) [21].
Table 3. The relationship between the compressional ratio of three different particles and the initial temperature of powder particles.

| P/S T[℃] | Cu/Cu [600 m/s] | Fe/Fe [700 m/s] | Ni/Ni [800 m/s] |
|----------|-----------------|-----------------|-----------------|
| 100      | 0.487           | 0.431           | 0.488           |
| 200      | 0.503           | 0.472           | 0.497           |
| 300      | 0.536           | 0.517           | 0.514           |
| 400      | 0.559           | 0.558           | 0.525           |
| 500      | 0.591           | 0.601           | 0.542           |
| 600      | 0.638           | 0.63            | 0.547           |
| 700      | 0.657           | 0.683           | 0.573           |
| 800      | 0.694           | 0.704           | 0.591           |

Note: P/S: particle/substance

Conclusion: The study found that increasing the preheating temperature of copper ions will reduce the microhardness of the coating after deposition, as shown in table 4. Therefore, preheating can soften the copper particles, which is conducive to more severe plastic deformation of the copper particles, which is beneficial to the particles in deposition on the substrate.

Table 4. The relationship between Cu particle preheating temperature and coating microhardness.

| Preheating temperature [℃] | Microhardness [HV] |
|----------------------------|---------------------|
| 25                         | 127                 |
| 100                        | 124.8               |
| 200                        | 122.1               |
| 300                        | 116.2               |

1.5. Spraying Distance
The spraying distance plays a crucial role in the formation of the coating. The spraying distance also affects the speed change of the powder particles, so the appropriate spraying distance can make the powder particles obtain the appropriate speed to achieve the best spraying on the substrate Sediment. Wang et al. [22] scholars proposed and analyzed the optimal distance between nozzle substrate, as shown in figure 7. It can be seen from the figure 7 that by using the effect of Copper particles with different diameters on the impact velocity, it is concluded that there is an optimal spray distance between the spray gun outlet and the substrate is 16mm. When the spray distance is 16 mm, the weakened the intensity of Bow Shock has the smallest effect on the powder particles, thereby achieving a high impact velocity. Feng et al. [23] studied the use of low-pressure cold spray technology to prepare a Cu-Al₂O₃ composite coating on a LY12 aluminum alloy substrate with 90% Cu + 10% Al₂O₃ powder material, and set the spraying distance to 5, 15, 25 mm. The mechanical properties of the coating are shown in figure 8, the mechanical properties of the Copper coating on the Aluminum substrate. From figure 8, when the spraying distance is 15 mm, the prepared coating has the best mechanical properties. The author also studied the cross-sectional micro-topography of the coatings prepared at different spraying distances, as shown in figure 9. It can be seen from the figure that when the spray distance is 15 mm, the copper particles in the coating are deformed the most; when the spray distance is 5 mm, the copper particles are deformed to a lesser extent; when the spray distance is 25 mm, the copper particles in the coating are deformed The smallest, due to the principle of processing deformation hardening, the more severe deformation of the powder particles during the spraying process, the higher the hardness of the formed coating. According to the research of Borchers [24], the more severe the deformation of particles in cold spraying is, the higher the bonding strength of the coating. Scholars such as Zhang et al. [25] deposited pure Aluminum powder particles with a particle size of 25-48 microns on the base material of 45-gauge steel. By studying the effect of the spraying distance on the Al coating, the results showed that the spraying distance was 30 mm, as shown in figure 10. The deposition rate as shown in table 5 and Micro-Hardness of the layer are high, and the bonding effect with the substrate is good. The reason for the deterioration of the coating performance at other distances is that the powder particles fall at an unstable speed or particle scattering occurs. Therefore, when selecting the appropriate spraying distance, it is necessary to
comprehensively consider the speed of powder particles and particle scattering.

**Figure 7.** Using differently experienced copper particles to study the effect of spacing on impact velocity [22].

**Figure 8.** Mechanical properties of copper coating on aluminum substrate [23].
Figure 9. Micromorphology of the section of the coating prepared under different spraying distance [23].

Figure 10. The relationship between Al particles with diameters of 25 μm, 35 μm and 48 μm at different spraying distances and particle impact speed.

Table 5. The deposition rate of Al particles at different spraying distances.

| Spraying distance/mm | 10   | 20   | 30   | 40   |
|----------------------|------|------|------|------|
| Deposition rate      | 6.08%| 6.67%| 8.28%| 5.86%|

Conclusion: The study found that as the spraying distance increases, the collision speed also needs to increase; the spraying speed and spraying distance determine the mechanical and mechanical properties of the coating; if the spraying distance is too large, the particles will be scattered during the spraying process. If the spraying distance is too small, it will cause insufficient particle acceleration; therefore, it is very important to choose a suitable spraying distance. For example, the best spraying distance for Aluminum particles is 30 mm.

2. Application Status of Cold Spray Technology

Cold spray technology has the characteristics of low deposition temperature, wide selection of materials and low porosity, suitable for the preparation of composite coatings metal alloy coatings. It can be used to prepare large thickness coatings, high powder utilization, safety, environmental protection and high cost [26-27]. Cold spraying technology is to deposit powder particles by plastic deformation in a low temperature state. In this process, it will not be affected by heat. This process
does not need to worry about oxidation, grain growth, composition segregation and phase change, and the deposited layer the structure and physical properties of the material can be well preserved [28-29]. The materials that can be used for cold spraying are shown in table 6 [30-35]. During the spraying process, the deposited coating undergoes a shrinking process of cooling from the molten state, so the porosity of the deposited coating is extremely low, and the density can reach more than 98% [36], while also strengthening the coating and the substrate Bonding strength; therefore, some coatings with high thermal conductivity, high electrical conductivity and corrosion resistance can be prepared [37]. Because the entire process of cold spraying is achieved at a low temperature, the residual stress in this process is low and all are compressive stresses, which can be used to prepare thick and large coatings [38]; At present, copper, aluminum, titanium and their alloys have achieved results and sprayed with a thickness of 5 mm. As shown in table 6, the materials that can be used for cold spray.

| Materials   | Specific materials                        |
|-------------|-------------------------------------------|
| Metal       | Al, Zn, Cu, Ni, Ca, Ti, Ag, Co, Fe, Nb, W |
| High melting point metal | Mo, Ta                                   |
| Alloy       | Ni-Al, Al-Fe, Al-Cu, Cu-W, Al 7075, Al A357, Ti-6Al-4V |
| Ceramic     | Al2O3, Cr2O3, SiC, WC, TiO2, Cr3C2-NiCr, WC-Co, TiN, |
| Polymer     | UHMWPE, HDPE, PA-12, PFA                 |

2.1. Preparation of Anti-Corrosion Coating

Electrochemical corrosion usually occurs in aviation parts, mainly because the potential difference between different metals forms a micro-primary cell effect, which leads to corrosion of the surface of metal parts. The anti-corrosion coating prepared by cold spray technology can effectively protect these parts from electrochemical corrosion during work. According to the research report on the preparation of anti-corrosion coatings by cold spraying, the anti-corrosion coatings are divided into metal coatings, composite coatings and non-metal coatings, as shown in table 7.

| Anti-corrosion coatings | The type of coatings                                                                 | Advantages                                                                 |
|------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Al and Al alloy coatings| Al-Zn, Al-CoNiCrAlY, Al_{88}Ni_{6}La_{6}, Al_{96}Ni_{6}La_{6}Cu_{2}, Al_{90}0.5Y_{4.4}Ni_{4.3}Co_{0.9}Sc_{0.35} | Uniform density, low porosity, good corrosion resistance                   |
| Ni and Ni alloy coatings| Ni-Zn-Al_{2}O_{3}, Ni-Cr, Ni-50Cr, Ni-20Cr, Ni-20Cr-TiC, Ni-20Cr-TiC-Re, Ni-30%Cu, Ni-Ti | Maintain good corrosion resistance in strong acid or alkali environment     |
| Cu and Cu alloy coatings| Cu-Ni, Cu-30%Cu_{2}O                                                              | Has good anti-fouling and anti-corrosion performance                      |
| Composite coatings     | WC-25Co, Al-Al_{2}O_{3}, 7075Al-B4C and 7075Al-SiC, Ni-Al_{2}O_{3}, Polyethylene coating, UHMWPE | Strong resistance to electrochemical corrosion                              |
| Non-metallic coatings  | IC531 inorganic Zn silicate coating                                                | The surface is anti-corrosion and anti-air corrosion is better            |

At present, the methods for preparing aluminum coatings and composite coatings on magnesium and Mg alloy substrates by cold spray technology are generally composed of three types: pure aluminum coating, aluminum alloy coating and ceramic particle reinforced aluminum-based composite coating [39]. Tao [40] uses AZ91D Mg alloy as the base material, BRIAN S [41] uses ZE41A-T5 Mg alloy as the base material, DIAB M [42] uses AZ31B Mg alloy as the base material, all
uses cold spray technology to prepare pure aluminum coating. Research on the corrosion resistance of coatings; BRIAN S [43] et al. prepared AA5356, AA4047 and Al-5wt.% Mg alloy coatings on the surface of Mg alloys by cold spraying technology, and measured the galvanic corrosion rate of different coatings through experiments. As shown in figure 11, the purity of HP Al is 99.95 wt.%, and the purity of CP Al is 99.5 wt.%; The test results show that the corrosion rate of Al-5wt.% Mg alloy coating is about 0.155 mA/cm², slightly higher than Pure aluminum coating-magnesium alloy substrate and Mg alloy coating-magnesium alloy substrate, but it is obviously lower than the galvanic corrosion rate of aluminum coating-magnesium alloy substrate and aluminum alloy coating-magnesium alloy substrate.

![Figure 11. Galvanic corrosion current of different coatings and Mg substrates [42].](image)

Yu et al. [43] studied the preparation of AA5083 aluminum alloy coating and AA5083/20vol.% $\text{Al}_2\text{O}_3$ aluminum-based composite coating on the surface of ZM5 Mg alloy. The results show that the coating is dense and the coating hardness is high, which can significantly increase the ZM5 magnesium Corrosion resistance of alloy surface. Shi et al. [44] studied the deposition of aluminum-zinc coatings on high-strength rigid substrates. Long-term exposure experiments showed that no corrosion occurred on the surface of aluminum-zinc coatings, thus achieving a good effect on high-strength steel substrates Protective effects. Dong et al. [45] studied the deposition of aluminum coatings on ship parts and the formation of dense corrosion products on the surface of aluminum coatings to hinder the diffusion of corrosive media in seawater and reduce the corrosion rate. Gu et al. [46] studied the use of cold spray technology to deposit Al coatings. The results show that cold sprayed coatings are more uniform and dense than hot sprayed coatings, and have low porosity and better corrosion resistance.

While using cold spray technology to prepare pure Al and Al alloy coatings, adding some ceramic particles to prepare aluminum-based composite coatings can maintain the excellent corrosion resistance of aluminum coatings [47-49]. Wang et al. [50] and Kumar et al. [51] conducted in-depth analysis and research in the preparation of AA5056-SiC and Al-SiC composite coatings using cold spray technology. Spencer et al. [52] used cold spray technology to study the effect of ceramic particle content on the corrosion resistance of composite coatings. The research results show that the composite coating containing $\text{Al}_2\text{O}_3$ particles has better corrosion resistance than AZ91E alloy, but the effect of $\text{Al}_2\text{O}_3$ content on corrosion resistance is not obvious, as shown in figure 12.
2.2. Preparation of High Temperature Resistant Coating and High Temperature Oxidation Resistance

For the preparation of Cu and Cu alloy coatings, Xu [53] et al. studied the preparation of pure copper coatings on the surface of 6061 aluminum alloy specimens. The results showed that no significant oxidation occurred on the pure copper coatings. Li [54] et al. studied the preparation of MCrAlY coatings on high-temperature alloy substrates using cold spraying technology, which were oxidized in air at 1000 °C for 200 hours. The coatings did not change significantly, indicating good resistance to high-temperature oxidation. Li, Zhang, Sheng, Liu, SIDELEV D V, Richer P etc [55-61]. Many scholars studied the successful preparation of MCrAlY coatings on nickel-based superalloys and other substrates by cold spray technology. The results show that the MCrAlY coating has a wide range of substrates, and the MCrAlY coating on the substrate has very good high temperature oxidation resistance. The porosity of the coatings prepared on different substrates is relatively low, such as 921A ship steel plate and Al6061 aluminum alloy, and high-temperature alloys Inconel 738 and GH49. Li et al. [62] studied cold-sprayed MCrAlY coatings, and the results showed that the internal oxide content of the coatings was much lower than that prepared by thermal spraying process. The continuous dense $\text{Al}_2\text{O}_3$ produced by vacuum pretreatment showed that MCrAlY prepared by cold spraying technology the coating has good resistance to high temperature oxidation. Zhang et al. [63-67] scholars also studied cold spray MCrAlY coatings, and their research results are consistent with the results of Li et al. [62] scholars. Scholars such as Lee et al. [68] used cold spray technology to study the intermetallic compounds such as Al-Ni and Fe-Al, which have good high temperature resistance.

Commonly used high temperature resistant coating materials include Ni-based, Co-based alloys, MCrAlY alloys, oxide ceramics, etc. At present, they are mainly prepared by thermal spraying process [69]. In a low temperature environment, the cold spray technology produces large plastic deformation on the substrate through sprayed particles, which can provide a new idea for the preparation of low oxygen content, high density and high temperature resistant coatings. Zhang et al. [70] scholars prepared NiCoCrAlY coating by cold spray technology. The results show that the porosity of cold spray NiCoCrAlY coating is less than 0.92%, and the oxygen content is only 0.25%. The coating did not fall off after oxidizing at 1050 °C for 400 h. Xie et al. [71] scholars used cold spray to prepare NiAl coatings and performed densification treatment at high temperature. It was found that after the densified NiAl coatings were oxidized at 1020 °C for 200 h, no significant changes occurred in the coatings.

2.3. Preparation of Wear-Resistant Coating

The wear resistance of aviation components is also a very important indicator. It has a wide range of applications in aerospace and other industrial fields. Due to the shortcomings of active chemical nature, low hardness, wear resistance, corrosion resistance and high temperature resistance of Mg alloy, its further application is seriously restricted, and the surface treatment process of Mg alloy is actively explored to effectively improve the wear resistance and corrosion resistance of Mg alloy comprehensive performance is of great significance to promote the application of Mg alloy in the field.
of lightweight military and civilian high-end equipment [72-74].

The researchers used cold spray technology to study the coatings of many alloy systems to further improve the wear resistance of the Mg alloy surface, such as: aluminum-based composite coating [75], zinc-aluminum alloy coating [76], stainless steel coating Layer [77], tungsten carbide cobalt coating [78] and copper-tungsten composite coating [79] alloy composite coating; as shown in table 8.

**Table 8. Wear-resistant coatings of different metals.**

| Wear-resistant coating | Coating/substrate                  | Particle size | HV       | Bonding strength [Mpa] |
|------------------------|-----------------------------------|---------------|----------|------------------------|
| Al coating             | Al/AZ31 Mg alloy                  | 25 mm         | 72HV0.04 | 15                     |
|                        | 420 stainless steel/AZ80 Mg alloy | 19.85 µm      | 600.3HV0.05 | 44±8                   |
| Stainless steel coating| 316L/ AZ80 Mg alloy               | 20.00 µm      | 320.1HV0.05 | \                      |
|                        | WC-170Co/ AZ80 Mg alloy           | 10-30 µm      | 615 ± 62HV | 57 ± 11                |
|                        | Al-5wt.%Mg/ Mg alloy              | 18-45 µm      | 124 HV100g | 60                     |
|                        | Zn-Al2O3/ AZ31B Mg alloy          | Zn:10 µm      | 74 HV100g | \                      |
|                        |                                   | Al2O3:20 µm   | \        | \                      |
|                        |                                   | Ni:10 µm      | \        | \                      |
| Zn-based coating       | Zn-Al2O3-Ni/ AZ31B Mg alloy       | Al2O3:20 µm   | 132 HV100g | \                      |
|                        |                                   | Ni:10 µm      | \        | \                      |

Shockley et al. [75] found that the shape of the ceramic particles and the content of Al-Al2O3 in the Al-Al2O3 composite coating have an important effect on the wear resistance of the coating. Four different volume fraction coatings were studied: 10% polygon A coating of Al2O3 particles (ANG10), a coating containing 22% polygonal Al2O3 particles (ANG22), a coating containing 3% spherical Al2O3 particles (SPH3) and a coating of 11% spherical Al2O3 particles (SPH11). The research results show that: the composite coating containing 22% polygonal Al2O3 particles has the lowest wear rate, and as the wear time increases, the wear rate remains basically unchanged, as shown in figures 13 and 14.

![Figure 13](image-url). The relationship between the wear rate and wear cycle of four different volume fraction coatings at different speeds [75].
Dai et al. [77] used cold spray technology to spray 420 stainless steel wear-resistant coating on the surface of AZ80 magnesium alloy and compared with 38CrSi steel. The results show that the wear resistance of 420 stainless steel coating is significantly better than 38CrSi steel. Chen et al. [80] studied the preparation of 420/WC-17Co coating on the surface of AZ80 magnesium alloy by cold spray technology. Finally, the microhardness tester and universal material testing machine were used to determine the microhardness and bonding strength of the coating. The results show that the cold spray 420/WC-17Co coating can significantly improve the wear resistance and corrosion resistance of the magnesium alloy surface without significant thermal effects. Dai et al. [81] used cold spray technology to spray 316L and 420 stainless steel coatings on the surface of AZ80 magnesium alloy. By comparison, the hardness of 420 coating is higher than that of 316L coating, and 420 coating shows better performance than 316L coating. Wear resistance.

Appropriate addition of some ceramic particles to prepare aluminum-based composite coating can make the coating have higher hardness, strength and wear resistance. Scholars such as Spencer [52] used cold spray technology to study the effect of ceramic particle content on the friction and wear properties and hardness of composite coatings. As the content of $Al_2O_3$ ceramic powder increased, the hardness of the coating increased and the wear rate decreased rapidly, as shown in figure 15.

**Figure 14.** Surface morphology of four different volume fraction coatings after friction and wear experiments at different speeds (sliding cycles) [75].

**Figure 15.** Relationship between $Al_2O_3$ content and hardness (a) and the effect of wear resistance (b) [52].
3. Conclusion
Cold spraying technology is a new type of surface spraying process, which has irreplaceable advantages compared with traditional thermal spraying technology, such as uniform and dense coating, low porosity, low oxide content, high hardness, and low thermal stress and does not change the technical advantages of powder particles, such as the organizational structure, and has great potential application value. It has been widely concerned by scholars from various countries and been applied to industry. Cold spray technology can prepare ceramics, nano-structured powders and composite coatings. Currently, coating products are applied in many fields such as automotive, medical, chemical, aviation, aerospace and other military industries. Although the advantages of cold spray technology are particularly outstanding, there are some disadvantages and challenges:

(1) The shape and size of the powder particles are also important factors affecting the coating. First, choosing the spherical shape and equal diameter particles for spraying can effectively make the particles uniform and symmetrical in the plastic deformation and temperature distribution, thereby ensuring the substrate the uniformity of each area of the upper coating meets the performance requirements of the coating.

(2) Through research, it is found that the speed of particles will affect the deposition effect on the substrate. If the deposition speed is too low, the sprayed particles will not be able to deposit smoothly on the substrate; if the deposition speed is too high, the particles will also be sputtered, which will result in the particles not being deposited on the substrate and waste materials. Different spraying materials need to choose their appropriate deposition speed to achieve the unity of functionality and economy.

(3) When the particles are deposited perpendicular to the surface of the substrate, the depth of the deposition has the best effect. As the incident angle increases, the depth will gradually decrease, resulting in a weakening of the coating effect.

(4) Increasing the preheating temperature of copper ions will reduce the microhardness of the coating after deposition. Therefore, preheating can soften the copper particles, which is conducive to more severe plastic deformation of the copper particles, which is beneficial to the particles in Deposition on the substrate.

(5) As the spraying distance increases, the collision speed also needs to increase; the spraying speed and spraying distance determine the mechanical and mechanical properties of the coating; if the spraying distance is too large, the particles will be scattered during the spraying process. If the spraying distance is too small, it will cause insufficient particle acceleration; therefore, it is very important to choose a suitable spraying distance. For example, the best spraying distance for aluminum particles is 30mm.

(6) Using Aluminum powder as the spraying material, there is a gap between the Aluminum coating and the substrate after spraying. Therefore, reducing the gap between the Aluminum coating and the substrate can effectively improve or eliminate the residual stress; currently in the application of cold spray technology. There are relatively few studies on the residual stress of the coating after spraying.

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