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REVIEW

Current Implementation Status of Cold Spray Technology: A Short Review

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Abstract In recent years, cold spray technology has attracted more and more attentions. After more than 30 years of rapid development, research focus of cold spray technology is gradually shifting from fundamental and theoretical studies to application developments, some of which have been industrialized and mass-produced. In this paper, the characteristics of cold spray technology, cold spray materials perspectives and cold spray system developments were briefly introduced. Besides, the recent developments of cold spray applications in different fields including aerospace, biomedical, energy, electronics, semiconductor fields were discussed. Although cold spray technology is in the early stages of implementation, it has demonstrated a great potential to reduce costs and improve performance. World-wide awareness of ongoing and planned cold spray programs is critical to expand its applications and benefits.

Keywords application status · cold spray · materials perspectives · research progress · system developments

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Introduction

In the mid-1980s, when the Soviet Union scientist Anatolii Papyrin and his team studied the model of two-phase flow (gas + solid particles) in a wind tunnel, they found that when the speed of the solid particles was greater than a certain critical value, the substrate would no longer be eroded and particles started to adhere (Ref 1). Inspired by this phenomenon, Anatolii Papyrin and his team first proposed in 1990 that cold gas dynamic spray (referred to as 'cold spray') could be used as a new coating process and successfully deposited a variety of pure metals, metal alloys and composite materials on different substrates, proving the possibility of cold spray technology in engineering applications (Ref 1). Compared with the traditional thermal spray processes, the most notable feature of cold spray is its low process temperature and less thermal impact on the feedstock/substrate materials. The typical benefits of cold spray over thermal spray are minimized materials degradation, wide sprayable materials range, high deposition efficiency/rate and high adhesion strength, unlimited workpiece size, thick deposits, etc. (Ref 2, 3). Cold spray is particularly suitable for preparing certain materials, for example, metals or materials (such as intermetallic compounds) that must avoid oxidation and heat impact during spray, amorphous materials that are easy to crystallize, and nanomaterials that have grain growth issue when heated (Ref 4, 5). In the past 30 years, cold spray technology has attracted widespread international attention. Countries such as the USA, Canada, Germany, France, Japan, Australia, Singapore and China have carried out related cold spray fundamental studies and application developments. After entering the twenty-first century, cold spray research has experienced more rapid development. The research focus of cold spray gradually shifts from fundamental studies to engineering applications and industrial developments, especially after 2010, large-scale industrialized products made by cold spray gradually developed. To date, cold spray technology has been successfully applied in surface repair, surface enhancement, functional coating and additive manufacturing in many fields including aerospace, weapon, energy and power, electronic power, medical equipment (Ref 6). In this paper, we briefly introduce the current state-of-the-art knowledge of the cold spray technology, including cold spray materials perspectives, cold spray system developments and recent developments of cold spray applications in different fields including aerospace, biomedical, energy, electronics, semiconductor fields, etc.

Materials Perspectives

Cold spray has been reported to deposit most metals, metallic glasses, cermets (metal/ceramic composites), some ceramics and polymers, as well as powder mixtures onto a variety of substrate materials including metals, ceramics and polymers. Table 1 gives a brief overview of different types of typical material systems investigated in cold spray. More comprehensive overview of cold-sprayed material systems and their applications can be found in the literature (Ref 4, 5). Materials hardness is often treated as a key metric determining the cold sprayability: very broadly, for metals with hardness less than 300 HV, cold spray can produce excellent deposit with no thickness limitations; for metals with hardness between 300 and 400 HV, cold spray gives out acceptable deposit performance but may require post-processing, e.g., heat treatment or HIP; for metals with hardness greater than 400 HV, cold spray can be used as a method to produce porous-structure materials. For metal matrix composites, if prepared from mechanically mixed feedstocks, a ductile metallic component is needed exhibiting the 'cushion' effect to help retain the brittle component, and the composition yield varies depending on the specific material systems (Ref 7). Ceramics and polymers can be deposited by cold spray, but the coating density and adhesion strength are relatively low. For substrate selection, generally, materials having similar hardness or deformability with the powder can generate better coating adhesion (Ref 8).

Al-, Cu-, Ti- and Ni-based superalloys are important types of widely studied engineering materials in cold spray literature. Aluminum and its alloys have the characteristics of low density, high ductility, good corrosion resistance, excellent thermal and electrical conductivity and they are widely used in industry. Cold-sprayed aluminum and its alloy coatings can be used for repairing industrial parts to save a lot of cost and therefore have received extensive attention from academia and industry. Although aluminum and its alloys have relatively low strength and melting point, they have good plasticity, high deformability and low critical velocity during cold spraying, so they are materials theoretically easy to spray. However, due to the low density of aluminum, the motion state of in-flight particles is easily affected by the bow

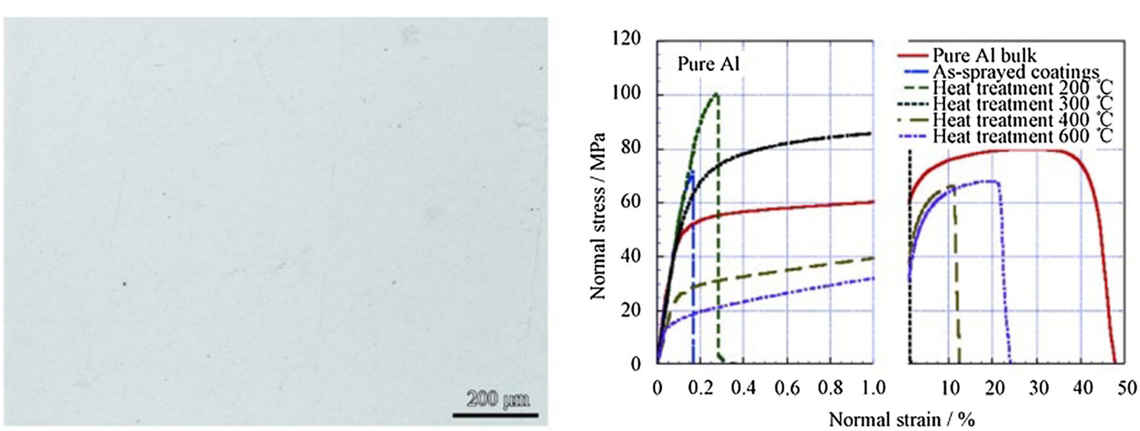
Table 1 A brief overview of different types of typical materials used in cold spray

Type	Special material
Pure metals	Al, Ag, Sn, Cu, Ti, Ni, Fe, Nb, Ta, Cr
Alloys	Al: $AlSi_7Mg$, NiAlW, NiAl, A380, 2024, 6061, 7075
	Fe: 304L, 316L, $FeNi_{50}$
	Ag: AgCuTi, AgPdIn,
	Cu: CrZrCu, CuSn, CuZn, CuAlFe, CuSnP
	Ti: Ti6Al4V
	Ni: IN718, IN625, IN738
	Co: CoCrMo, CoCrW, CoNiCrAlY
	Sn: SnBi, SnSbCu
Mixtures	Al: $Al+Al_2O_3$, Al+BN, Al+Fe+Mn, Al+Ti, Al+SiC
	Ag: Ag+W, $Ag+SiO_2$, Ag+graphene
	Cu: Cu+SiC, Cu+W, Cu+Ti, Cu+316L, Cu+WC/H13
	Fe: Fe+316L, $Fe+Al_2O_3$, Fe+Al
Ceramics	TiO_2, WC, WC-Co, HA, TiN
Polymers	UHMWPE, HDPE, PEEK

shock wave near the substrate. Also, the surface of the aluminum powder can easily get oxidized, and there are still challenges to overcome the effect of oxide layer and prepare high-density deposits. In addition, aluminum is a relatively active metal, which is prone to nozzle clogging and thus difficult to spray stably for a long time. Figure 1 shows the metallographic and mechanical properties of cold-sprayed pure aluminum prepared after optimizing spraying parameters and nozzle design (Ref 9). The prepared pure aluminum deposit is very dense, and the porosity is less than 0.5%. The tensile strength (about 70 MPa) of the as-sprayed pure aluminum exceeds that of the bulk. However, the plasticity is poor (the elongation is about 0.2%), and the fracture mainly occurs at the particle–particle interfaces. The properties of pure aluminum coatings can be further improved by heat treatment. The tensile strength and the elongation is increased to 100 MPa and 0.3%, respectively, after heat treatment at 200 °C. This can be ascribed to the atomic diffusion between particles, thereby improving the cohesive strength between particles and the tensile strength of the coating. With further increase of the heat treatment temperature, the plasticity increases and the elongation can exceed 20% after heat treatment at 600 °C, but the corresponding tensile strength decreases (Ref 9). This is because the increase of the heat treatment temperature promotes the grain growth and recrystallization of the coating material.

In addition to pure aluminum, cold-sprayed aluminum alloys also have excellent properties and have attracted many researchers' attention. Al-Si alloys have high strength, low thermal expansion and excellent anti-friction properties. Studies found that during cold spray of Al-Si alloys, due to the thermal effect of the high-temperature gas, Al-Si alloy coatings not only exist α-Al phase but also fine silicon particle reinforcement phase, thus exhibit the improved strength (Ref 10). Al-Sn binary alloys have excellent anti-stick properties and low modulus, which are often used as sliding bearing materials in automobile industries. Cold-sprayed Al-Sn binary alloy coatings have the characteristics of low porosity, high deposition rate and excellent mechanical properties (Ref 11). High-strength Al-Cu alloys are widely used in aerospace and automotive fields. Adding different alloying elements (such as Mg, Fe, Ag, Ni) to Al-Cu alloys can form different intermetallic compounds (such as Al_2Cu, Al_2CuMg, Al_9FeNi), which can further improve the mechanical strength. Studies found that the cold-sprayed AA2618 Al-Cu alloy coating (Al-Cu-Mg-Fe-Ni) is very dense and has intermetallic compound Al_2CuMg at the grain boundary and Al9FeNi precipitates distributed within the grain (Ref 12).

Copper and its alloys have excellent thermal conductivity, electrical conductivity, ductility, corrosion resistance and wear resistance, and are widely used in electric power, electronics, energy, machinery and other fields. They are often used as the model material in cold spray studies considering its ease to deposition. Figure 2(a) shows the metallographic photographs of cold-sprayed pure copper. The coating is very dense and has almost no pores (Ref 9). Figure 2(b) shows the stress–strain curves of the deposit under different heat treatment conditions. Similarly, the tensile strength of the as-sprayed copper exceeds that of the bulk, which is almost 300 MPa, but the plasticity is poor (the elongation is about 0.4%). With the increase of the heat treatment temperature, the plasticity increases and the strength decreases. In addition, it is worth noting that the functional properties of cold-sprayed copper coatings are excellent and their electrical conductivity can approach 100% of the bulk in the as-sprayed state (as shown in Fig. 2c). Figure 2(d) shows the bonding strengths of cold-sprayed copper coatings deposited on different substrates. The bonding strengths on AA5052, AA6063 and 316L substrates all exceed 200 MPa, but the higher the yield



(a) Microstructure of cold sprayed Al coatings

(b) Tensile strengths of cold sprayed Al coatings

Fig. 1 Microstructure and tensile strengths of cold-sprayed Al coatings (Ref 9). Reprinted with permission from Elsevier

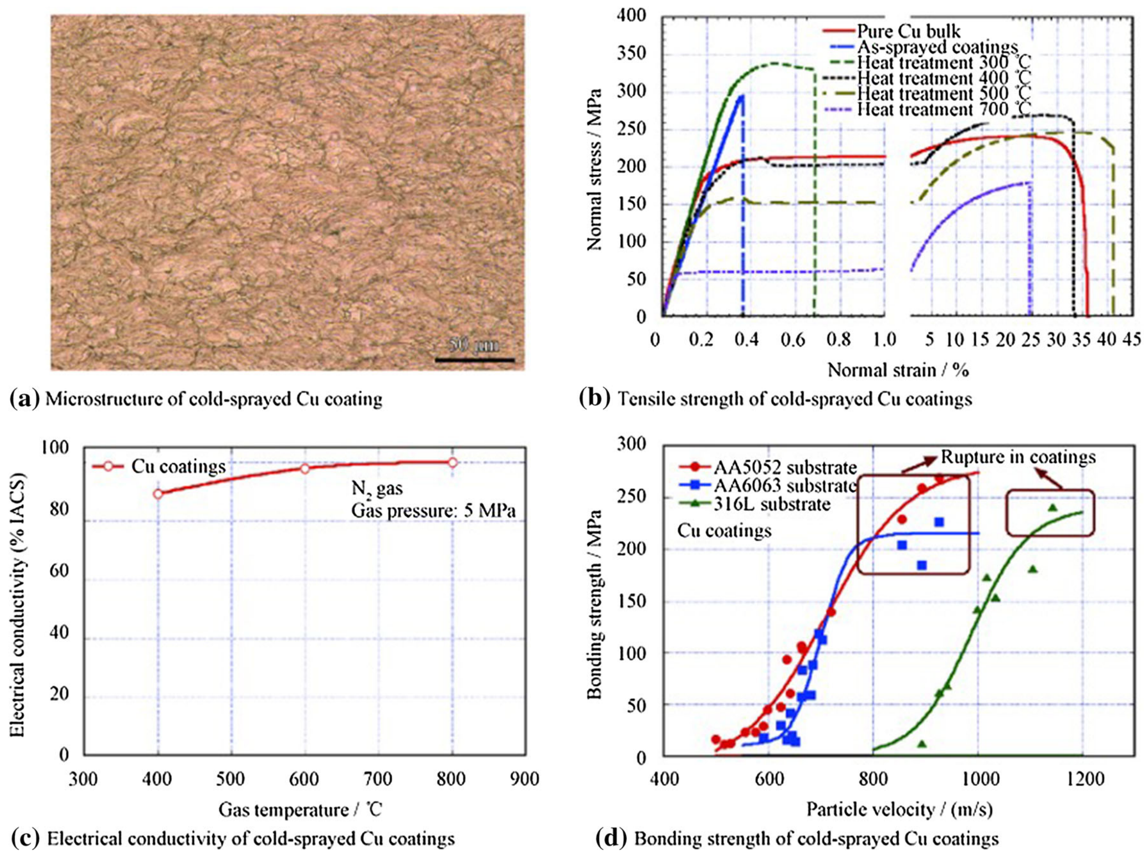


Fig. 2 Microstructure and properties of cold-sprayed Cu coatings (Ref 9). Reprinted with permission from Elsevier

strength of the substrate, the higher the particle velocity is required for effective bonding. With the increase of the particle velocity, high adhesion strength of the copper coating can be produced on different substrate materials (Ref 13). In addition, the study found that due to the severe plastic deformation and dynamic recrystallization of copper particles during cold spray, there are a large number of nanoscale grains (Ref 14) and nanoscale twins in the copper coating (Ref 15).

Due to the characteristics of low density, high strength, good corrosion resistance and good biocompatibility, titanium and its alloys are widely used in aviation, aerospace, petroleum, chemical, medical, construction, automobile, sports equipment and other fields. In cold spray, the critical velocities required for the deposition of titanium and its alloys are high. To obtain dense titanium alloy coatings, high-pressure cold spray system and higher parameters are required (for example: nitrogen as carrier gas, gas temperature 800 $\sim$ 1100 °C, gas pressure 4 $\sim$ 5 MPa (Ref 16-18)). In addition, the use of helium as the carrier gas can accelerate the titanium alloy particles to higher velocity, so that particles can undergo severer plastic deformation and achieve stronger bonding strength. Researchers also reported the use of mixed feedstocks (Ti+Ti6Al4V) can contribute to relatively dense composite coating ($\sim$1.5% porosity) compared with spraying either Ti or Ti6Al4V alone. This observation suggests generating hard/soft impact interfaces during cold spray is beneficial and can lead to better coating performance (Ref 19). Coatings of titanium and its alloys with different porosity levels can be obtained by tailoring the process parameters: porous coatings can be used for biomedical applications, and dense coatings can be used for repairing aerospace parts and remanufacturing. Figure 3 shows the cross sections of the cold-sprayed titanium and titanium alloy coatings after optimizing the parameters. The titanium and its alloy coatings deposited by cold spray are relatively dense and have no obvious cracks. In addition, tensile tests showed that the bonding strength of the cold-sprayed Ti6Al4V coating and the Ti6Al4V substrate exceeded 90 MPa (Ref 17) and the bonding strength between Ti6Al4V particles exceeded 350 MPa (Ref 20).

Besides the mechanical properties, the residual stress in the cold-sprayed coating also affects the overall properties of the coating. It is generally believed that the residual stress in cold spraying is caused by two main factors, i.e. thermal mismatch and particle peening. Residual stress studies in the cold-sprayed Ti6Al4V coating show there

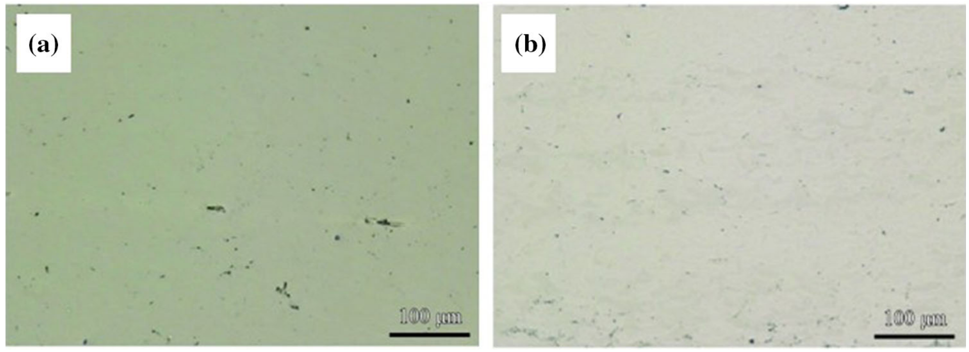


Fig. 3 Microstructures of cold-sprayed Ti (a) and Ti6Al4V (b) coatings (Ref 20). Reprinted with permission from Springer Nature

exists certain tensile stress on the coating surface but compressive stress near the coating–substrate interface (Ref 21). Moreover, different cold spray parameters and coating thickness will affect the distribution of residual stress in the coating. In addition, the anti-wear properties of cold-sprayed titanium and its alloy coatings are weak. Researchers found that the wear resistance of the coatings can be improved by post-treatment or preparation of titanium-based composite coatings.

Inconel 718 is a nickel-based superalloy contains Ni, Cr, Mo, Nb, Ti, and Al as the alloying elements. Through the formation of γ' and γ" strengthening phases and fine/stable carbides, Inconel 718 has high strength and good resistance to oxidation and gas corrosion under high temperature, thus it is widely used in aerospace parts with high working temperature. Compared with pure nickel which is an easy to spray material, Inconel 718 has a higher yield strength, poorer plasticity and higher strain hardening rate, therefore it is rather difficult to cold spray. Similar to titanium alloys, the critical velocity required for cold spray deposition of Inconel 718 is high. Researchers at Institute of New Materials, Guangdong Academy of Sciences, through the optimization of nozzle design and process parameters, reported that the porosity of cold-sprayed Inconel 718 superalloy coating can be reduced to below 0.3% (as shown in Figure 4a). As shown in Fig. 4(b), the tensile strength can reach 1200 MPa after heat treatment, and at the same time, the elongation can exceed 9%, which is the highest among the published literature. Figure 4(c) and (d) is the microhardness and bonding strength of cold sprayed Inconel 718 deposits before and after heat treatment. The microhardness of Inconel 718 in the as-sprayed state reaches about 590 $HV_{0.3}$, and after heat treatment, it reduces to about 400 $HV_{0.3}$. The bonding strength can reach 400 and 900 MPa before and after heat treatment, respectively (Ref 22). The tensile strength and bonding strength of the Inconel 718 coating after heat treatment have reached a level comparable to those of the as-cast Inconel 718. In addition, by studying the wear resistance of cold-sprayed Inconel 718 at room and high temperature, a dense and continuous $Ni_xFe_{2-x}O_4$ oxide film was formed on the worn surface of the Inconel 718 coating during high temperature friction, which is believed to improve the material's wear resistance (Ref 23). Thus, cold-sprayed Inconel 718 shows better wear resistance at high temperature than at normal temperature. Due to the excellent comprehensive properties of the cold-sprayed Inconel 718 coating, it is expected to be used for repairing nickel-based superalloy parts or as the surface enhancement coating of high-temperature parts.

Over the last few years, novel powder materials emerge which advance cold spray in various potential applications. Figure 5 lists a few examples of cold spray novel materials. Yin et al. (Ref 24) successfully deposited thick FeCoNiCrMn high entropy alloys (HEAs) with helium as the propulsive gas and produced dense coatings with no element segregation. High entropy alloys (HEAs) are new member of the metal alloy family discovered by Yeh et al. (Ref 25) in 2004 and have received intensive research efforts in recent years. They are constituted of five or more principal alloying elements in equimolar or near-equimolar ratio and thus exhibit their performances from multiple principal elements rather than a single element (Ref 25). Due to their unique phase structure, HEAs have superior mechanical properties, wear resistance, corrosion resistance, oxidation resistance and other benefits over conventional metal alloys (Ref 26). They have potential applications in many industrial sectors such as aerospace, shipbuilding, nuclear power. Dense HEA coatings can provide effective protection to underlying substrate materials against aggressive environments such as corrosion, wear and excessive heat (Ref 24). Chen et al. (Ref 27) used cold spray as an additive manufacturing technology to produce dense Invar 36 alloy and the low thermal expansion coefficient of Invar 36 alloy can give out high thermal and mechanical performances. Xie et al. (Ref 28) cold-sprayed nano-TiB_2-reinforced Al7075 composite powder and combined with post-heat treatment, and the deposit can realize simultaneous improvements in strength and ductility than the cold-sprayed Al7075 deposit. Yin et al. (Ref

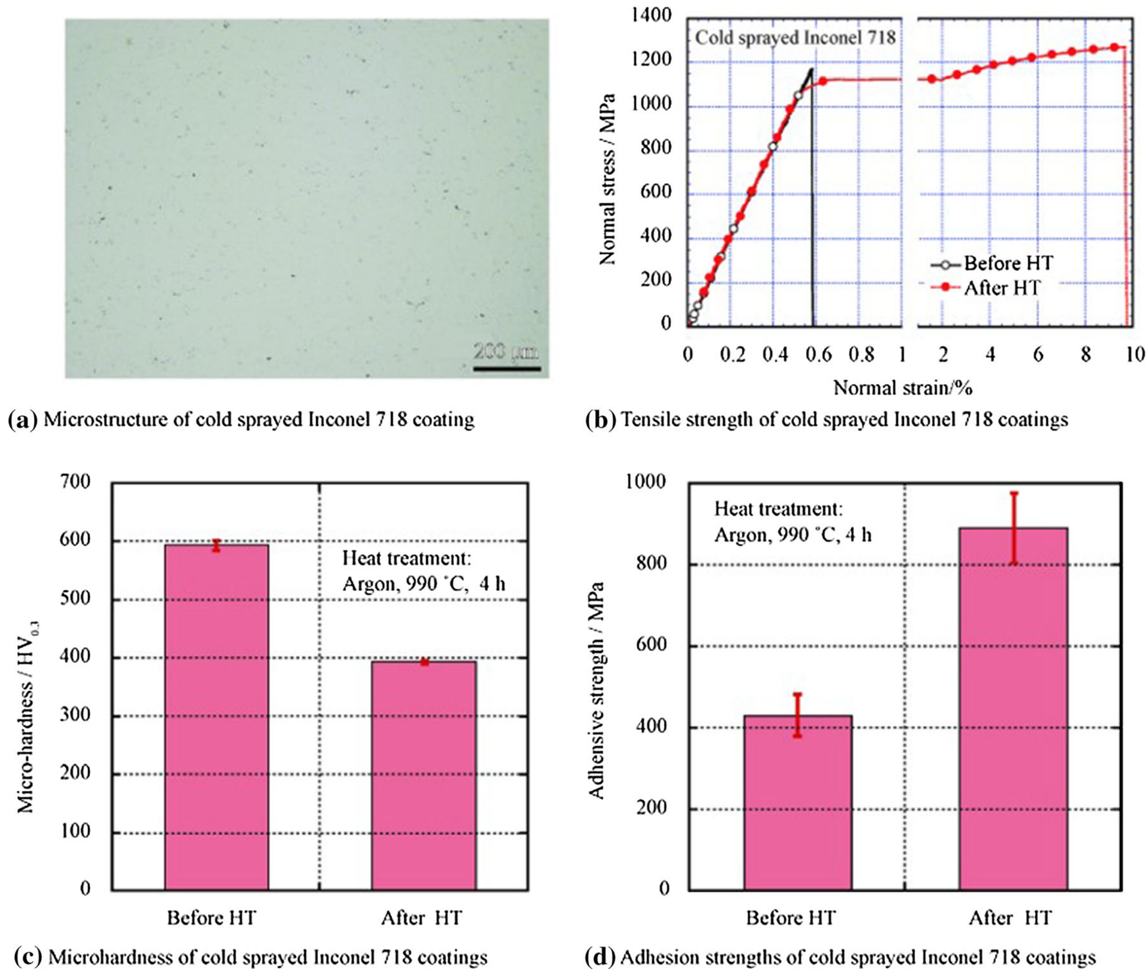


Fig. 4 Microstructure and properties of the cold-sprayed Inconel 718 coatings (Ref 22). Reprinted with permission from Elsevier

29) developed diamond-reinforced metal matrix composites (DMMCs) using core-shell-structured powders. The use of core-shell-structure (core-diamond, shell-metal) powders helps retain more intact diamond content, which potentially leads to better performance as wear-resistant coatings compared with that of mechanically blended powders.

Cold Spray System Developments

The Category of Cold Spray Systems

Basically, cold spray can be divided into two categories, i.e., low-pressure cold spray (LPCS, 5-10 bar) and high-pressure cold spray (HPCS, >10 bar). The schematic diagrams of different cold spray processes are displayed in Fig. 6 (Ref 30).

A comprehensive comparison between the HPCS and LPCS is listed in Table 2. In the LPCS, compressed air or nitrogen is usually used as the working gas. The gas pressure is 5-10 bar and gas temperature is 100–500 °C. The powder particles are injected from the expansion section of Laval nozzle through the siphon effect into the nozzle. The powder particles are usually accelerated to 300-600 m/s (Ref 31). The LPCS is suitable for materials with low melting point or low yield strength, for example, aluminum bronze (Ref 32), babbitt alloys (Ref 33, 34), magnesium alloys (Ref 35), etc. The friction and collision between the powder particles and the nozzle is reduced since powder particles do not pass through the throat of the nozzle, thus, the possibility of nozzle clogging and abrasion is reduced and the nozzle could have longer service life (Ref 36).

Different from the LPCS, nitrogen and helium are commonly used as carrier gases in HPCS. The gas is usually preheated to 200-1100 °C, and the pressure range is 30-50 bar or higher. The powder is usually injected from the convergent section of the Laval nozzle. To prevent the powder from flowing back into the powder feeder, the pressure of the powder feeder should be higher than the working gas pressure (Ref 37). The nozzle of the HPCS

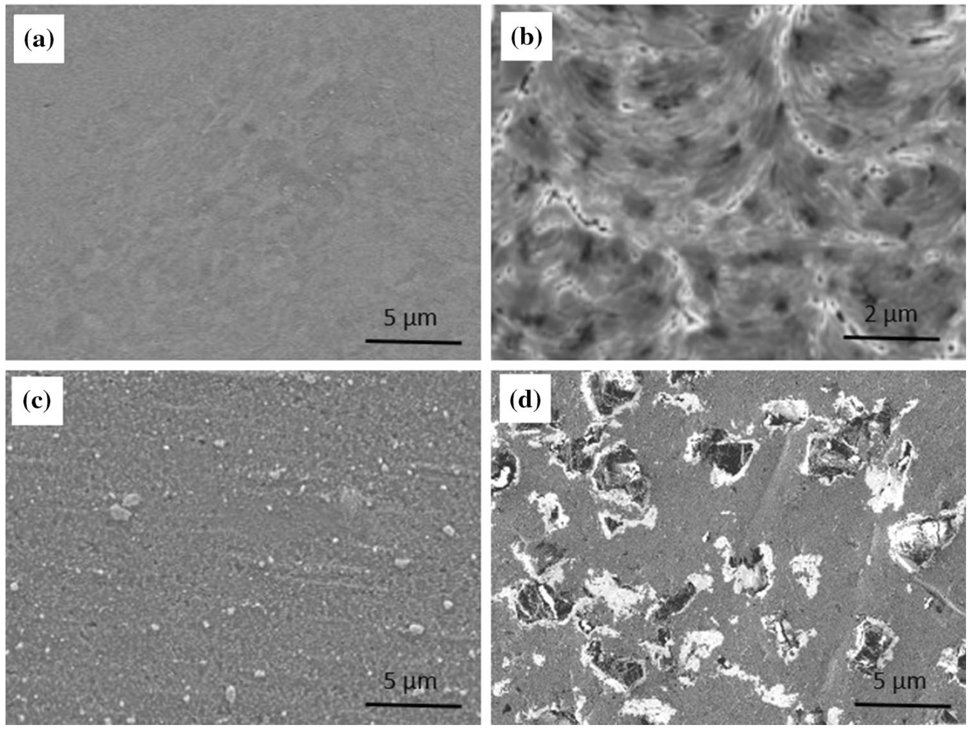


Fig. 5 Examples of novel materials reported in recent cold spray literature. (a) FeCoNiCrMn high entropy alloy (Ref 24), (b) Invar alloy (Ref 27), (c) nano-TiB_2/Al7075 composite (Ref 28), (d) Al/coated diamond (Ref 29). Reprinted with permission from Elsevier

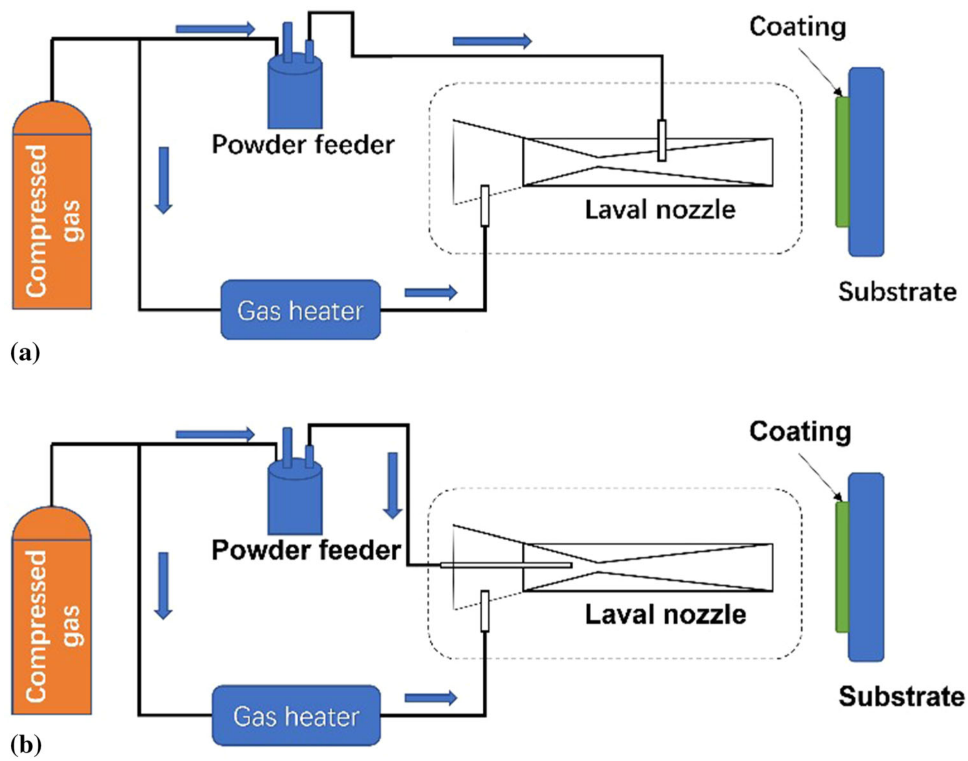


Fig. 6 Schematic diagram of the cold spray process. (a) Low-pressure cold spray, (b) high-pressure cold spray

system can be easily clogged, which is more obvious when the temperature increases. Therefore, water-cooling system is often used in the HPCS system. Besides, the nozzle throat of the HPCS system can be severely worn, which can occur during long-term spraying of hard particles. The noise of a HPCS system usually exceeds 100 decibels, so the equipment needs to be operated in a soundproof booth (Ref 38). Compared with downstream injection, the interaction time between the powder and the air flow in HPCS is longer, and the spray particles can achieve a higher

Table 2 Comparison between the HPCS and LPCS system

System parameters	HPCS system	LPCS system
Pressure	7-55 bar	6-15 bar
Preheating temperature	Up to 1100 °C	Usually less than 500 °C
Injection location	Upstream injection	Downstream injection
Propellant gas	Nitrogen, helium	Nitrogen, compressed air
Portability	Low	High
Whether water cooling	Yes	No
Powder characteristics	High melting point, high strength	Low melting point, low strength
Typical application	Additive manufacturing, wear-resistant coatings, corrosion-resistant coatings, repair	Repair, additive manufacturing, biomedical coatings

speed. The HPCS system has a better potential to deposit materials that are difficult to deform, such as steels, titanium, inconel, etc. (Ref 5).

From the operation mode, cold spray systems can be divided into two types: hand-held and robot-controlled. Most hand-held cold spray systems are low pressure cold spray systems. It can bring certain convenience to the operator to carry out cold spraying operations in a small space, and it is also suitable for repairing large-scale parts. The high-pressure cold spray system of VRC in the USA can also be hand-held, making it highly competitive (Ref 39). The cold spray system operated by the robot can keep the nozzle relatively stable and work for a long time during the spray process. Usually, the heater and the nozzle are integrated in the high-pressure spray system, which has a large weight and is not suitable for hand-held; the manipulator can ensure the relative position of the nozzle and the substrate during the spray process and ensure that the spray angle and distance remain unchanged. The nozzles of the low-pressure cold spray system can also be mounted on the manipulator, so that good stability same as the high-pressure cold spray system can be obtained. Another benefit of using a robot is that it can be planned in different paths to obtain the desired shape for additive manufacturing (Ref 40, 41).

In addition to the structure of the nozzle, the material of the nozzle is also a key factor to avoid nozzle clogging and ensure the long-term cold spray production. Different nozzle materials are suitable for different spray powders. Chemical reactions may occur and clog the nozzle, resulting in a decrease in the cold sprayed coating quality. The nozzle materials include polymer, ceramic, stainless steel, copper, etc. Ceramic nozzles are usually used for spraying high hardness, irregular powder materials because it has high wear resistance, but is not suitable for high ductility materials which can easily adhere on ceramic nozzles (Ref 42, 43). Stainless steel nozzles are prone to wear and corrosion, resulting in coatings that are susceptible to contamination by the nozzle material (Ref 44). The clogging probability of polymer (PBI) nozzles is low, but they are prone to wear when the working temperature is high (Ref 45-47). Different nozzle materials have different effects on the coating deposition efficiency, which may depend on the thermal diffusivity of the nozzle material and the interaction of powder particles with the nozzle inner wall during cold spray. Nozzles with higher thermal conductivity can reduce critical velocities of the powder material, resulting in higher deposition efficiencies (Ref 48, 49). The effect of nozzle material on cold spray performance and applicable materials needs further investigation in the future.

Commercial Cold Spray Systems

After more than 30 years of rapid development, several commercial cold spray systems have been developed worldwide, such as VRC in the USA, Impact Innovations in Germany, Plasma Giken in Japan, Centerline in Canada and Dycomet in Russia. The market for cold spray equipment is constantly expanding to meet the increasing needs of cold spray technology.

The U.S. Army Research Laboratory (ARL) in Adelphi, Maryland, USA, and the South Dakota School of Mines (SDSM&T) developed a new portable high-temperature and HPCS system in 2011, a hand-held HPCS system VRC Gen III (70 bar/650 °C) (Fig. 7a) (Ref 50). The typical feature of the VRC Gen III cold spray system is the flexible connection between the heater and the cold spray gun, which can effectively reduce the weight of the cold spray gun. VRC has carried out a lot of optimizations on the system insulation to reduce heat loss and improve heater efficiency. The system can be used for hand-held spraying, and it is able to work in the spraying workshop or on-site for repair (Ref 51).

Figure 7(b) shows the German Impact Innovations company HPCS, which has relatively rapid product development progress and has launched new generations of cold spray systems: EvoCSII 5/8 and EvoCSII 6/11. The maximum operating parameters of the EvoCSII 5/8 system are 50 bar/800 °C, and the maximum operating parameters of the EvoCSII 6/11 system are switchable: 50 bar/1100 °C and 60 bar/1000 °C (Ref 52). The EvoCSII system adopts a modular system structure, which can also be expanded later if needed. Each equipment contains two spray guns and four powder feeders and can preheat the powder to increase the temperature and deformability of the particles, thereby improving the deposition efficiency and the quality of the prepared coatings.

The PCS series cold spray system developed by Plasma Giken of Japan has been widely used globally. The PCS series cold spray system mainly includes the HPCS system PCS-800/1000 and the hand-held low pressure cold spray system PCS-100/E50. The maximum temperature and pressure of the cold spray system is 1100 °C and 7.0 MPa and the rate of powder feeding is 300 ~ 500 g/min (Ref 53). PCS-800/1000 series cold spray system is equipped with a water-cooling system. The heater and the spray gun are rigidly connected. They are large and heavy. The equipment is suitable for depositing materials that are difficult to cold spray, such as stainless steels, titanium alloys and superalloys. The PCS cold spray equipment is industrially mature and is widely used in different fields such as repair and additive manufacturing of aviation components (Ref 54), sputtering target manufacturing and repair, daily cooking utensils, new energy vehicles, etc.

The earliest cold spray system was developed by Obninsk Center for Powder Spraying Ltd. (OCPS) in Russia. Currently, DYMET 423 cold spray system can be used to deposit metal coatings of different materials such as Al, Zn and Ni. The maximum input compressed air pressure of the equipment is 1.2 MPa, the pressure and temperature of the working gas inside the DM45 spray gun is, respectively, 0.5 ~ 0.8 MPa, 200 ~ 600 °C, the maximum power is 3.3 kW, and the powder feeding rate is 6 ~ 48 g/min (Ref 55).

The SST cold spray system is developed by Canadian Centerline company, which adopts a downstream powder injection design. SST equipment can use nitrogen, helium or compressed air and its working pressure range is 4-35 bar and the maximum working temperature is 550 °C (Ref 56). The system is equipped with the latest SST-X powder feeding system, and the highest powder feeding rate can reach 120 g/min (Al powder). It has the characteristics of compact structure, convenient transportation and on-site spraying operation.

There are also several self-made in-house cold spray systems in the published literature. Design and manufacture of cold spray equipment requires certain interdisciplinary knowledge, including mechanical engineering, materials science and control engineering, and the stability and reliability of the self-made system may be lower than the commercial cold spray system. The self-made in-house cold spraying equipment is instead suitable to be used for fundamental studies. Usually, commercial cold spray systems use Laval nozzles with circular and elliptical outlets (Ref 57), and some self-made rectangular exit nozzles have been used in cold spray studies (Ref 58). Compared with elliptical or circular nozzles, rectangular nozzles can achieve higher particle velocities (Ref 59-61). Stenson et al. (Ref 62) also developed nozzles of different sizes from those provided by commercial cold spray, and micro-nozzles were used to verify the resolution of cold spray in additive manufacturing. The early CGT cold spray system (Ampfing, Germany) can only work at 30 bar pressure and 600 °C. Schmidt et al. (Ref 63) further improved the system to achieve spraying at the maximum temperature and pressure of 900 °C and 45 bar. Wang et al. (Ref 64) developed a vacuum cold spray system, which can realize cold spray deposition of nanoscale particles in a vacuum environment.

The Limitations of Current Cold Spray Systems

In the past ten years, both the HPCS and LPCS system are developing rapidly and have achieved certain success in the fields of coating, parts repair, additive manufacturing, electronic appliances, etc. However, there are still some limitations, mainly in the following aspects:

(1) If the weight and size of the cold spray gun can be reduced so that the cold spray system is portable, while the spray temperature and pressure and the control accuracy can be improved, these will bring significant benefits to practical applications.

(2) Issues such as nozzle clogging and wear are still typical obstacles, which could limit further industrial applications of cold spray technology. Effective measures from nozzle design, nozzle material selection, auxiliary cooling and other aspects are still urgently needed in the future cold spray system development.

(3) Inner-hole cold spray system is very important in the industry, which can be used to deposit coatings on inner tubes or holes. High-quality coating is still difficult to achieve by the current inner-hole cold spray systems. Nozzle design and optimization is a possible solution, which needs more efforts in the future.

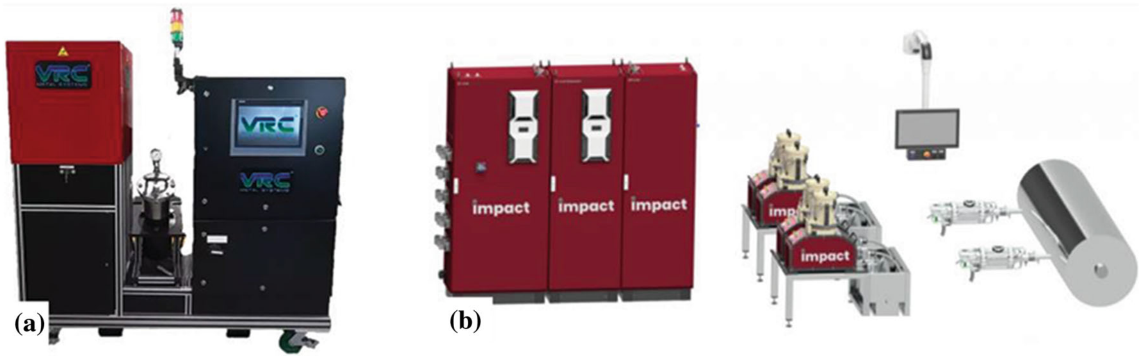


Fig. 7 (a) VRC Gen III (Ref 50) and (b) Impact Innovations EvoCSII 6/11 (Ref 52). Ref 50 reprinted with permission from VRC Metal Systems, LLC. Ref 52 reprinted with permission from Impact Innovations

Applications Status

Repair & Remanufacturing

To repair and remanufacture high value damaged metal components, traditional techniques such as arc welding, thermal spraying and laser deposition are still the most used repair techniques. However, these traditional processes are likely to cause severe defects due to excessive heat input and high temperatures, such as oxidation inclusions, thermal deformation and cracking, which could significantly limit their repair capabilities. On the other hand, some thin-walled components produced with complex shapes are impractical to be repaired by the above-mentioned techniques and are directly scrapped, resulting in a huge waste of resources and energies.

The unique solid state deposition characteristic of cold spray technology makes it possible to avoid the defects related to excessive heat input and high temperatures, and it has great potential to be used in the repair of aerospace, naval and automotive components. Cold spray technology has been favored by the U.S. Army Research Laboratory (ARL) and U.S. Department of Defense during the last two decades. For a long time, the U.S. Department of Defense has provided giant research funds for the cold spray technology research as a repair technique for damaged components (such as fighters, warships, tanks, vehicles, etc.). There are some cold spray repair examples as showing below.

Cold spray was used to restore the dimension and function of the A357 cast aluminum alloy component of the F/A-18E/F Super Hornet fighter (Ref 45). Cold spray technology was used to repair the components of the Seahawk helicopters, which could save 35-50% of the cost compared with that of manufacturing new components (Ref 45). Besides, ARL together with General Electric and Moog repaired the GE T700 Front Frame Housing using cold spray technology. The front frame is fabricated from cast C355 aluminum alloy and 6061 aluminum alloy was selected as the repair material. Figure 8 shows the T700 Front Frame from the time it was received with surface wear and corrosion damage to the finished end item after being cold sprayed, machined and anodized (Ref 65).

In addition, marine pump housing was repaired by cold spray technology, which has been reported by Stamey (Ref 66). The base material of the pump is a common tin-bronze alloy that is used in wear and marine applications where high strength, low speeds and heavy loads are required. The tin-bronze alloy is not easily weld repairable. Cold spray was selected as an excellent choice of repair of these components. Besides, a corroded component from a naval vessel was repaired by high pressure cold spray by Moog and placed back into inventory for future use (Ref 65). The component was fabricated from 6061 T651 aluminum and contained extensive corrosion damage such that it had to be removed from service. The cold spray repaired part is shown in Fig. 9 after finally being machined to dimension and subsequent to anodizing. The repaired actuator was then placed back into use, mitigating the long lead times and expense associated with the purchase of a new component.

In addition, some other manufacturing companies or research centers have developed cold spray technology to repair high-value damaged components, such as Boeing, GE, Pratt & Whitney, Honeywell, Airbus, Safran, Rolls-Royce, TWI, etc. However, the current cold spray repair applications mainly focus on non-structural repair. It is still very challenging to achieve structural repair by cold spray technology, and future efforts are needed to further improve the adhesion strength, cohesion strength and ductility of the cold-sprayed coatings. Appropriate in situ or post-process treatments on cold spray coatings should be further developed.

Biomedical

Cold spray is an emerging coating technique that offers unique coating characteristics that can be used in biomedical applications. Biocompatible metallic materials (Ti-based, Fe-based and Co-based alloys), polymers (UHMWPE, HDPE, PEEK) and some ceramics (HA, HA-graphene, TiO_2) have been successfully deposited by cold spray processing for tissue engineering and anti-bacterial applications.

For the metallic materials, cold spray can be used to fabricate biomedical structures that are stronger than similar materials made with conventional manufacturing processes. The structures' small size and porosity make them particularly well-suited for building biomedical components, such as replacement joints. As shown in Fig. 10, Moridi et al. (Ref 67) reported that the cold-sprayed porous titanium alloy structures have a porosity of more than 30%, an apparent Young's modulus of 51.7 ± 3.2 GPa and a compressive yield strength of 535 ± 35 MPa. The porous structures are beneficial for cell growing and reducing the likelihood of the implant loosening. Other attempts were done with tantalum (Ref 68), Co-Cr alloy (Ref 16), SS316L coatings (Ref 69) by cold spray, where it is observed good interface adhesion, low porosity, low corrosion rate and increase of hardness. Although in vivo tests are still pending, the results showed the potential to be suitable for development of a new class of metallic biomaterials.

Some polymers show excellent biocompatibility with human bodies, such as UHMWPE, HDPE, PEEK. However, they have poor integration with adjacent bone tissues upon implantation due to their hydrophilic properties (Ref 70). Ravi et al. (Ref 71) achieved UHMWPE and UHMWPE-Al_2O_3 composite coatings on the surface of polypropylene (PP) substrate by cold spray technique, which was 1 ~ 4 mm in thickness (Ref 71). The addition of Al_2O_3 ceramic particles can effectively improve the density, bond strength and wear resistance of the UHMWPE coating (Ref 72). King et al. (Ref 73) deposited Cu particles on the polyethylene (HDPE) substrates by cold spray technology. Studies have shown that the HA-coated PEEK prepared by cold spraying can promote the attachment of osteoblasts and can improve cell activity, ALP enzyme activity and calcium ion concentration.

Hydroxyapatite (also known as HAP) is another typical biomedical material, which has been widely used in dental and orthopedic implants, due to its chemical and crystallographic similarity with bone minerals. Noorakma et al. (Ref 74) prepared 20 ~ 30 μm HA coating on the surface of magnesium alloy AZ51 by cold spray technology, and the elastic modulus of the coating (around 9 GPa) is close to bone tissue. Liu et al. (Ref 75) used vacuum cold spray technology to deposit HA and HA-graphene composite coatings on the Ti surface. As a result, the HA and HA-graphene-coated titanium substrate showed improved adhesion and growing of osteoblasts. Cold spray technology could also be a novel approach to fabricate biocompatible composite coatings consisting of HAP and titanium, which could be used as surgical implants for load-bearing applications.

In addition to meeting the necessary mechanical properties and biocompatibility, antibacterial properties of cold-sprayed coatings are also attracting attentions. Sanpo et al. (Ref 76) found that the cold-sprayed HA-Ag/PEEK coatings have good biological activity and have obvious antibacterial effect against DH5α Escherichia coli. A research team at McGill University announced the cold-sprayed copper coating is highly effective at deactivating the COVID-19 virus, as well as bacteria, on high-touch metallic surfaces, which demonstrates the efficiency of the coating in deactivating 99.9 per cent of human coronavirus in 30 minutes (Ref 77). Cold spray technology can be rapidly activated and deployed to help reduce the spread of SARS-CoV-2 in public spaces, such as hospitals and public transit, which will benefit tremendously from this research. It was also found that the cold-sprayed ZnO/Ti composite coatings also have antibacterial effect against Escherichia coli. Besides, cold-sprayed copper coatings also have some antimicrobial properties against a variety of microorganisms.

For cold-sprayed biomedical coatings, extensive knowledge has been gained pertaining to fundamental issues about material selection, coating processing, dynamic coating formation, biological performances, and microstructure-property relations. While some of the biomedical coatings are still in the preclinical testing stage. Knowledge on in vitro and in vivo behaviors of cold-sprayed biomedical coatings at different levels is yet insufficient. Cold spray technique for fabricating advanced biomedical coatings and making biomedical devices needs further explore.

Electronic & Semiconductor

Cold spray coatings can be used for electronic and semiconductor production. There are a range of materials including tantalum, niobium, titanium, silver, copper and other pure materials available for electronic coatings applied to components used in the sputtering process. Many products commonly used today have a coating created through sputtering targets. These coatings include semiconductors, glass coating, solar cell coating and so on. Most modern electronics incorporate essential components which have been produced with tantalum sputtering targets. These include microchips, memory chips, print heads, flat panel displays as well as others. Sputtering targets are used

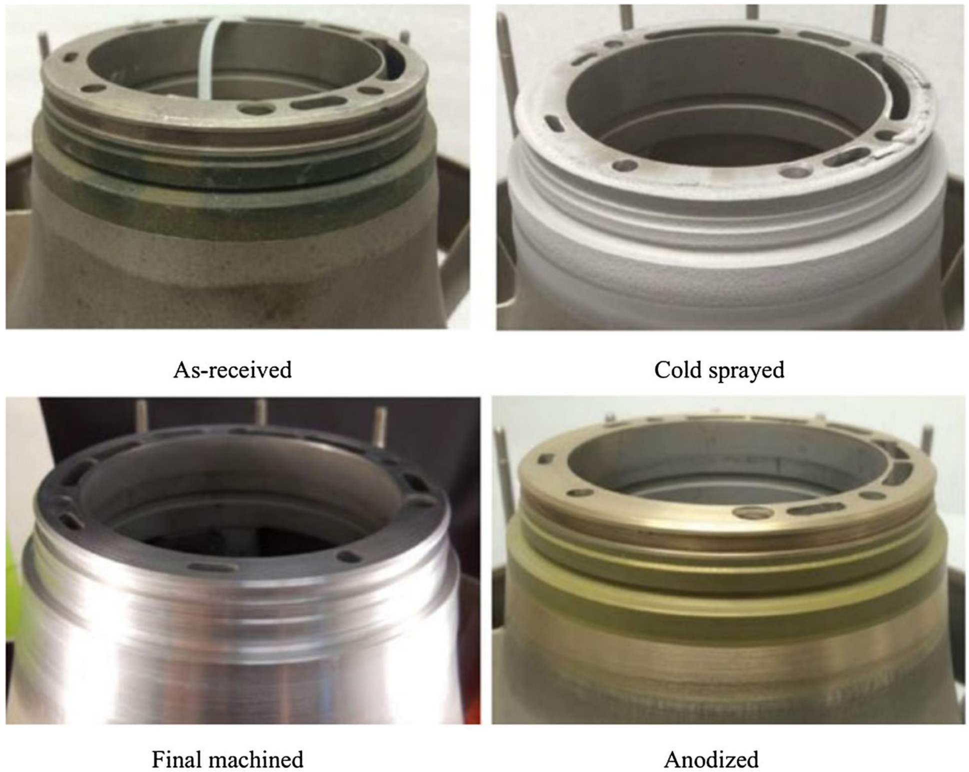


Fig. 8 Repair of the T700 Front Frame by cold spray technique (Ref 65)

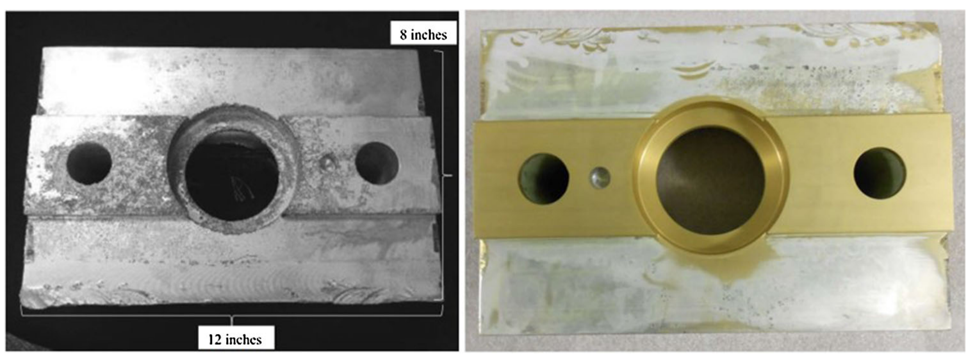


Fig. 9 Corroded vessel actuator before and after cold spray repair (Ref 65)

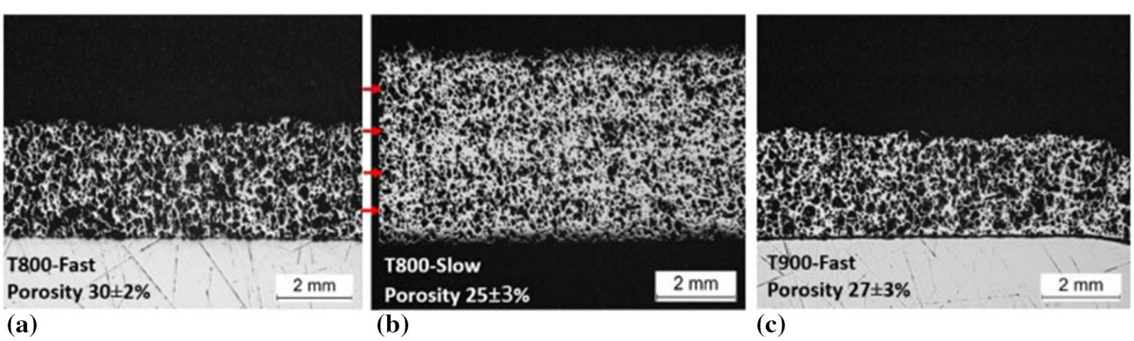


Fig. 10 Optical micrograph of cross sections of Ti materials printed by cold spray (Ref 67). Reprinted with permission from Elsevier

to produce low-radiation-coated glass—also known as Low-E glass—which is commonly used in building construction because of its ability to save energy, control light and for aesthetics. Demands for renewable energy are on the rise. Third generation, thin-film solar cells are prepared using sputter coating technology.

Figure 11 shows the large-scale silver alloy sputtering target prepared by cold spraying and post-process machining. Cold spraying can efficiently deposit and form silver coating, which is more than 16 mm in thickness. The production efficiency of cold spray is much higher than the traditional fabrication methods. Besides, the average grain size is smaller than that of casting materials. Therefore, large-scale metal sputtering targets directly formed by cold spray have been used in the electronics and information industries, such as integrated circuits, information storage, liquid crystal displays, laser memories, electronic control devices, glass coatings and other fields. However, the current challenge is how to effectively fabricate high purity and low oxidation sputtering targets by cold spray technology. Developing low oxidation metal powders and adapting new cold spray strategy are worth exploring in the future.

Power & Energy

Compared with traditional electroplating technology, cold spraying technology can not only effectively avoid environmental pollution problems, but more importantly, the characteristics of good coating performance and unlimited thickness make it particularly suitable for copper, silver coatings on the surface of printing rollers, electrodes, batteries, etc. Figure 12 shows a copper roller for gravure printing. The copper coating is prepared by cold spraying. After laser engraving, the pattern is clear and vivid, which fully meets the requirements of gravure printing. Compared with the original electroplating process, the cold spraying process has higher production efficiency, less environmental pollution and can meet the needs of thick coatings so that the printed products have a better three-dimensional effect.

Figure 13 shows the electrode used in the polysilicon reduction furnace. It is the core component of the equipment required for polysilicon production. The electrode material is usually pure copper. Although the impurity content in pure copper is very low, the electrode head is heated by the silicon core medium, resulting in trace impurities. It is easy to precipitate and be carried into the process gas, which ultimately affects the quality of polysilicon. To solve this problem, some manufacturers use electroplating/electroless silver plating as a protective coating. The purpose is to prevent the electrode conductivity while avoiding impurity pollution. However, its process stability is poor and the plating thickness is limited (tens to several hundred micrometers), environmental pollution and other problems cannot be solved well. The group at Institute of New Materials, Guangdong Academy of Sciences has used cold spray technology to prepare silver coatings to completely overcome the above problems. The combined strength of the prepared pure silver coating and the copper substrate exceeded 60 MPa, and the thickness is not limited. The purity of the silver coating can be kept the same as that of the powder (99.9%). The coating deposition efficiency is extremely high, the processing capacity is as high as 40 kg/h, and it is environmentally friendly and pollution-free.

Figure 14 shows the layout of a cold spray coating on a central processing unit (CPU) cooling unit fabricated by cold spray (Ref 78). The cold-sprayed Cu coatings on the heat sink could effectively improve the heat distribution and the performance of the CPU. Besides, cold spray copper coatings with ~300 μm in thickness were deposited on both sides of ceramic substrates for electronic power modules application (Ref 79). The advances of cold spray in recent years have extended its implementation in nuclear energy systems. Zr alloys have been widely used for light water reactors due to their high neutron transparency as well as excellent corrosion resistance and mechanical properties. However, Zr alloys experience severe oxidation and mechanical degradation in high-temperature steam. Cold spray technology is regarded as a promising approach to deposit Cr coatings on Zr alloys, which has been extensively investigated due to its high melting point and excellent oxidation resistance (Ref 80-84). Figure 15 shows the cold spray Cr-coated Zr-alloy cladding tube fabricated by Westinghouse Electric Company and the corresponding cross-sectional micrographs (Ref 80).

Another application example in nuclear energy system is the cold-sprayed Cu coatings on the used nuclear fuel container under development in Canada for the final storage of used nuclear fuel, as shown in Fig. 16. The container is comprised of a steel vessel and a Cu coating on the surface for corrosion protection. The Cu coatings are fabricated by electrodepositing and cold spraying. Since the Cu coating is not a structural part, the strength of the

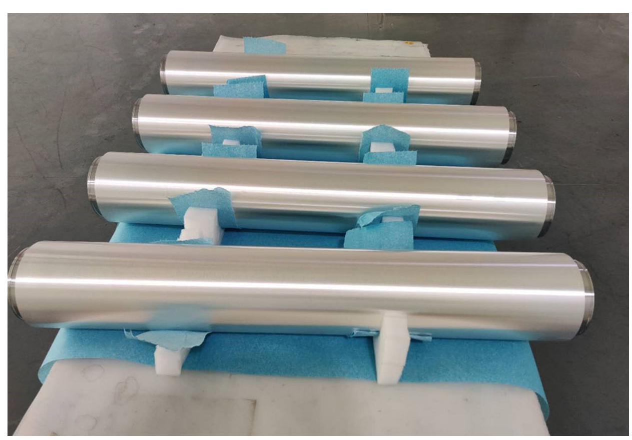


Fig. 11 Cold spray silver alloy coatings with post-process machining for sputtering target applications

copper is less important; however, the copper deposit still needs a minimum ductility. A low-temperature heat treatment is conducted locally to restore the ductility in the cold spray Cu layers. The Cu coatings could probably provide a solution for a long-term storage (up to 1 million years) of used nuclear fuel.

Additive Manufacturing

Cold spraying is not only a coating technology, but also an emerging solid state additive manufacturing technology. For example, NASA recently developed a combustion chamber and rocket nozzle by using cold spray additive manufacturing (CSAM) technology, as shown in Fig. 17. Their project team recently hot fire tested their lightweight combustion chamber and nozzle (Ref 86). Compared with the traditional electroplating method of fabricating the rocket nozzle and chamber, cold spray additive manufacturing can significantly reduce the lead time and improve the efficiency. Given that the coating thickness variation has to be minimized and the coating properties have to be uniformly tailored during CSAM process, advanced techniques are needed to allow for real-time coating quality monitoring in a non-destructive manner (Ref 87). Modern Artificial Intelligence (AI)-driven technologies are necessary to achieve intelligent coating quality inspection and characterization. Machine vision, data processing technologies and other computational tools are effective approaches for process optimization, monitoring and control. Besides, the optimization of the robotic spray path for complex structures is very important. A reliable analytical topological model and robot trajectory planning approach can be set up based on the simulation platform (Ref 40, 88). Machine learning technique has the capability to learn from the past data and predict the likelihood of a particular outcome, which has attracted many researchers' attention (Ref 89). However, application of machine learning algorithm in cold spray process is still in the early-stage development, which requires much more future efforts to meet the challenges.

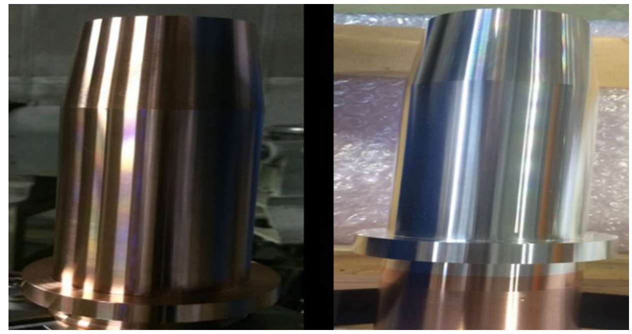


Fig. 13 Cold-sprayed silver coatings on the electrodes used for polysilicon manufacturing

Conclusions & Future Perspectives

This article briefly introduced the current industrial application status of cold spray technology. After more than 30 years of development, cold spray technology has been used to deposit a variety of metals, alloys and metal-based composite materials to form dense and thick coatings with high deposition efficiency, which could be used to repair damaged metal components and enhance the surface properties of the components. Cold spray has been applied in different industrial fields, such as aerospace, biomedical, electronic, semiconductor and power. The innovation potential of this research area is outstanding, and now a transition from laboratory-scale research to industrial applications is starting to emerge. There are some challenges for cold spray structural repair and cold spray additive manufacturing at this moment. Future efforts are still needed to further improve the application readiness of cold spray technology.

Based on the non-fusion principle and solid-state bonding mechanism, cold spray has its niche in the repair and restoration of damaged parts primarily from wear and corrosion. Cold spray has proved to be an effective geometry restoration technology and has the potential to repair, restore or enhance the damaged parts, which presents cost-saving advantage and increases the lifespan of numerous non-structural parts. However, there are some

Fig. 12 Cold-sprayed copper coatings on the printing roll

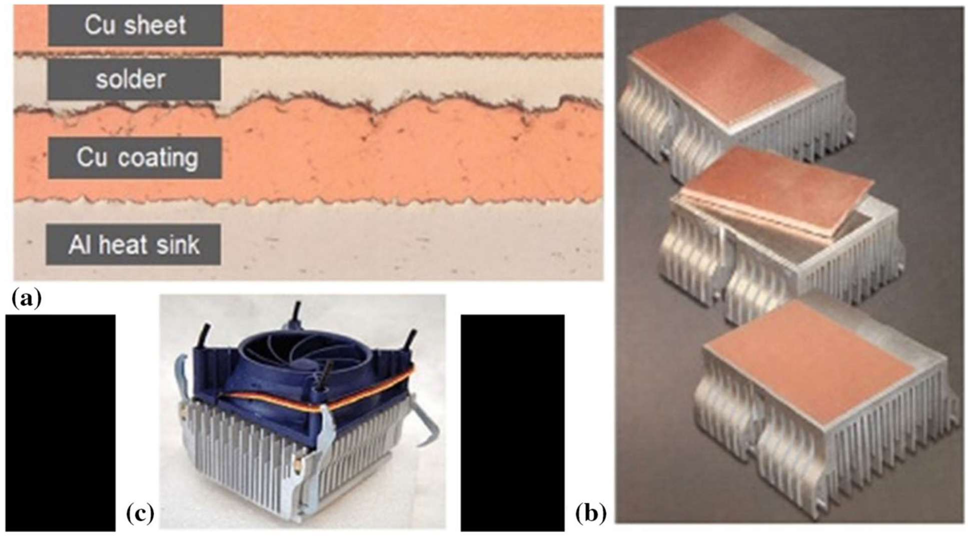


Fig. 14 Layout of cold spray copper coatings on heat sinks. (a) Layer layout in cross section, (b) assembly of heat sink and cold-sprayed coating and finally soldered plate for heat distribution, (c) verax P16Cu fan for CPU cooling (Ref 78). Reprinted with permission from Springer Nature

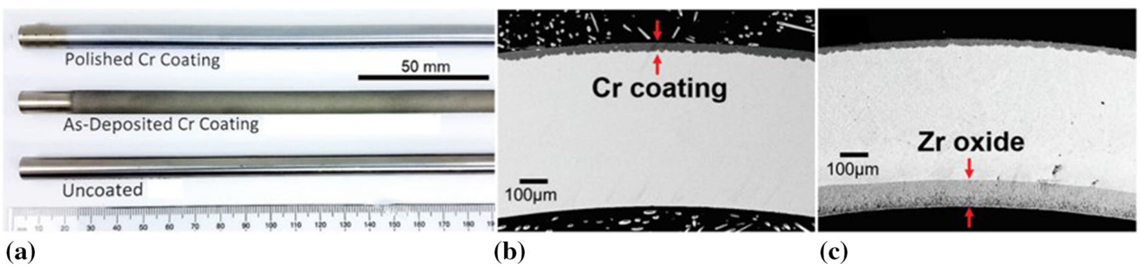


Fig. 15 (a) Photograph of cold spray Cr-coated Zr-alloy cladding tube. Cross-sectional micrograph for (b) as-fabricated coated cladding and (c) oxidized coated cladding at high temperatures (Ref 80). Reprinted with permission from Elsevier

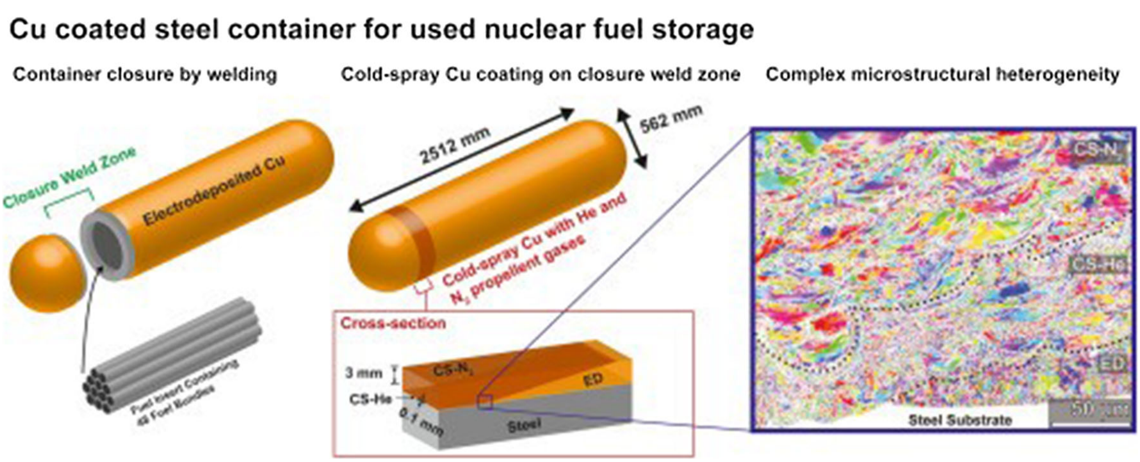


Fig. 16 Cold-sprayed Cu coatings for nuclear fuel storage (Ref 85). Reprinted with permission from Elsevier

challenges for cold spray structural repair applications. Current efforts on the use of cold spray for structural application are very limited. Some of the critical questions remain to ensure the applicability of cold spray repair for structural restoration. The strength of the cold-sprayed deposit is usually lower than the bulk material, and appropriate in situ or post-process treatments are needed to explore. Cold spray repair lacks a standard handbook and a database of properties at this moment, which needs further efforts to focus on this aspect.

Helium is the ideal gas candidate for cold spray to achieve a good quality of deposits. However, the drawback of using helium is its price, which is more than 40 times higher than nitrogen. In this regard, helium recovery system is a good option to recycle the helium gas. The current cold spray helium recovery system needs further

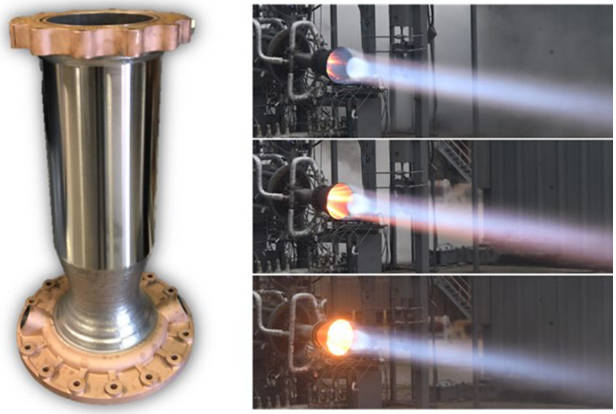


Fig. 17 Cold spray additive manufacturing of combustion chamber and rocket nozzle by NASA (Ref 86)

improvement in the gas collection and purification process; thus, the helium gas can reach a greater clean level.

Cold spray additive manufacturing opens up whole new opportunities for fabricating large-scale 3D metal materials in a solid-state approach, which has many unique advantages in keeping the materials properties unchanged and depositing large-scale freestanding parts within a short time. However, the resolution of cold spray deposition is limited due to the nozzle exit diameter. Another challenge for cold spray additive manufacturing is how to precisely control the toolpath and fabricate complex structures. Process monitoring and machine learning modules can be incorporated with cold spray process to better control the cold spray additive manufacturing process.

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