coatings

Review

Remarkable Potential of Cold Spray in Overlay Restoration for Power Plants: Key Challenges, Recent Developments, and Future Prospects

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Abstract: Cold spray has become a prominent deposition technology for coating, repair, and restoration in many industries, such as the aerospace, automotive, and power generation industries. It also has the potential to be used as an alternative overlay restoration for power plant components as it has minimal thermal distortion phase changes, as compared to conventional welding and thermal spray. This article aims to bridge the gap in the scientific literature by presenting a comprehensive review of cold spray in the context of power plant components. Firstly, this review examines the challenges of cold spray and subsequently elucidates effective mitigation strategies. Secondly, the review analyses the recent development of cold spray in the field of coating application. Moving forward, it investigates the integration of cold spray technology in repair applications, focusing on practical implementation and effectiveness. Finally, the review presents the overall impact of cold spray, its current outlook, and discusses future prospects. As such, the review will provide the community with a broad understanding of cold spray applications in the power plant sector.

Keywords: cold spray; energy; power plant; overlay restoration

1. Introduction

To date, numerous inventions in power plants have been designed, such as hydroelectric, coal-fired, and nuclear power stations. Strong economic growth, higher operating temperatures, and longer operation hours are why there is an increasing demand for electricity, thus pushing existing power plants beyond their normal capacity [1]. This increase in demand leads to rising equipment maintenance costs due to damage and defects that arise. There are various types of damage and defects in a power plant, such as erosion, corrosion, damage from foreign objects, and dimension defects [2]. Erosion occurs when a surface protective scale or coating is worn away by an aggressive chemical environment that is very acidic or highly alkaline, with high fluid surface velocities. Besides chemical erosion, there are two other types of corrosion. One is oxide corrosion, an electrochemical reaction that happens to metal when exposed to water and undergoes compositional changes. The other one is galvanic corrosion, which is damage caused and accelerated by an electrical response that occurs when two distinct metals are in contact with each other. Defects in shape or dimension are caused by production problems and are impacted by foreign objects. These problems can lead to expensive repairs, time-consuming maintenance, material losses, and subpar performance; if left untreated, failure will occur [3]. One of the ways to restore defective parts is through overlay restoration. Overlay restoration repairs defective parts, enhances desired properties that are not inherent in the base metal, or returns the component dimension to its original state [4].

Previously, overlay restoration was conducted using repair techniques such as weld overlay and thermal spraying. Weld overlays are deposited using submerged arc welding (SAW), tungsten inert gas welding (TIG), shielded metal arc welding (SMAW), and metal inert gas welding (MIG) [5]. Generally, weld overlay is a process of joining metals by depositing abrasive and corrosive-resistant materials. A critical purpose of weld overlay is to improve the properties of the surface or the base material of the parent workpiece. A study in 2012 by Takeuchi et al. [6] successfully used SAW for the overlay cladding of nuclear reactor pressure vessels. Another example of weld overlay was studied by Tashev et al. [7], where TIG weld overlay was carried out using nano-sized tin powder on carbon steel plates. As a result, the overlay restoration has improved the wear resistance by 210%. Welding has proven to strengthen wear resistance well, but the thermal shrinkage in welding can cause cracks [8]. Additionally, the total energy needed to heat and melt the filler wire is provided by the arc in TIG welding. Therefore, the rate of heating and melting is a constraint on the metal deposition rate. Besides weld overlay, high-velocity oxygen fuel spraying (HVOF) and high-velocity air fuel (HVAF) are the common thermal spraying techniques used in overlay restoration [9]. HVOF uses a fuel (either kerosene or hydrogen) and oxygen, which are ignited to deposit ceramic and metallic layers onto a metal surface to provide wear and corrosion resistance. In contrast, HVAF coating technology uses propane in a compressed air stream. Thakur and Arora [10] investigated the slurry behaviour and erosion of HVOF-sprayed WC-CoCr coatings and found that erosion resistance was improved.

Weld overlay and thermal spray are still relevant in overlay restoration. However, as these methods are high-temperature in nature (involve melting of materials), they cannot be used to repair/restore temperature-sensitive materials or change the properties of the parent material. As such, there is potential for cold spray to be used as an alternative for component repair and restoration. Cold spray is an effective new coating technology that can deposit a thick layer as a repair solution at a relatively lower temperature (material remains in solid state) [11]. This technology can be divided into two types: high-pressure cold spray (HPCS) and low-pressure cold spray (LPCS). For a conventional thermal spray process, procedures including dissolving the metal in a chemical bath and vapourising and melting processes were necessary. However, in cold spray technology, a wide range of materials can be deposited without the need for those processes [12]. The successful deposition of nickel alloy on a turbine blade in a power plant has been proven [13]. An increase in electricity demand means the need to increase power supply efficiency and improve performance. A turbine blade extracts energy from high-pressure and high-temperature gas from a combustor [14]. The efficiency can be increased by raising the temperature and the working environment up to 1400 °C [15]. Hard material with excellent properties is used to ensure that the material of the turbine blade can work under high temperatures. A common material used for turbine blades is nickel alloy because its properties are suitable for working under high temperatures and in high-pressure environments. Thus, it is vital to discover the type of cold spray powder that can be deposited onto hard material with high efficiency.

Furthermore, cold spray has been widely used in many industries, and many studies have been performed on the cold spray of hard materials but not specifically for power plant equipment due to the high risks involved. Thus, the industry tends to focus on quick and easily proven solutions, such as welding and thermal spray, even if they are costly [16]. Though cold spray has proven to be a superior coating technology, more studies need to be performed to justify the usage of cold spray, specifically in overlay restoration for hard materials on power plant equipment [15]. Koivuluoto et al. [17] analysed various nickel alloy cold spray powders and proved that nickel alloy microstructures have highly deformed and tightly bonded structures. The nickel-based alloy, Inconel 625 (IN625), was also deposited on cast iron for restoration and surface enhancement [18]. The coating is feasible, of high quality (dense and no delamination), and beneficial in terms of oxidation-reduction and surface enhancement (due to the higher hardness of IN625), thus providing possibilities to repair/restore grey cast iron components such as engine blocks and pump housings. Other than nickel, cold spraying was used to enhance the corrosion resistance of a magnesium (Mg) alloy surface using a titanium coating [19]. It was found that this coating helps to reduce the wear and corrosion rates of a Mg alloy. Wei et al. [20] investigated the corrosion enhancement effect of highly dense Ti-based coatings. The coating was shown to not be permeable during the entire 24 h immersion in 10 wt% HCl solution, thus providing excellent corrosion protection for the substrate. Singh et al. [21] investigated the difference in copper coatings using LPCS and laser cladding technology. The laser cladding technique is a welding technique that uses the same concept as arc welding methods. Their study shows that cold spraying techniques could produce a superior balance between strength, density, and thermal conductivity compared to the laser cladding technique. Chu et al. [22] studied the cold sprayability and corrosion properties of tantalum coatings. The results showed that angular tantalum powder exhibits the best overall performance (deposition efficiency, corrosion resistance, and cohesion strength) and cost-effectiveness. Cold-sprayed CoNiCrAlY coatings were also studied and can potentially be used as thermal barrier coatings (TBCs) for nickel-based super alloys [23]. With rapid heating, the coating porosity level was reduced and inter-particle bonding was enhanced. These examples prove that cold spray can be a good alternative as an overlay restoration method.

This review focuses on using cold spray technology for overlay restoration for power plants, which can help with the long-term reduction in maintenance costs [24]. In most cases, parts that cannot be welded are scrapped, but they can be salvaged if they can be repaired using cold spray. In this review, the recent development of cold spray for coating applications, i.e., the latest applications and improvements, was first discussed. Next, studies from 2017 onwards were collected and reviewed to recognise the limitations of the latest applications. Then, cold spray implementation in repair applications was reviewed to determine the difference between soft and hard materials used as cold spray powder. From this study, the difference between LPCS and HPCS can also be understood. The potential of cold spray in power plants for overlay restoration is then investigated to discover the feasibility of hard materials used in cold spray in overlay restoration. This review would provide a guide for those interested in cold spray as a cost-effective alternative, specifically in overlay restoration in power plants.

2. Cold Spray Technology

Cold spraying, also known as gas dynamic cold spraying, is a process of coating deposition using solid powder with a range of 1 to 50 μm. Anatolli Payprin developed the cold spray method in the mid-1980s [25]. This technology was discovered by a few researchers who work at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences in Novosibirsk, Siberia, during a study of the two-phase flow of gas and solid particles in a supersonic wind tunnel. They successfully deposited a wide range of materials, including pure metals, metal alloys, and metal–ceramic composites, on a wide range of substrate materials. This finding led to the discovery of metal particle behaviour that changes dramatically with a higher gas velocity [25–27]. At lower particle velocity, these particles will rebound and leave tiny abrasions on the solid components, creating a sandblasted-like surface [12]. The researchers continued to experiment with higher gas velocity, and as a result, the particle adhered to the surface instead of bouncing off. This particle speed is the critical velocity of the cold spraying process [28]. The essential components in cold spray techniques are a gas heater, powder feeder, pressurised gas, and nozzle. The schematic diagram of cold spray technology can be seen in Figure 1.

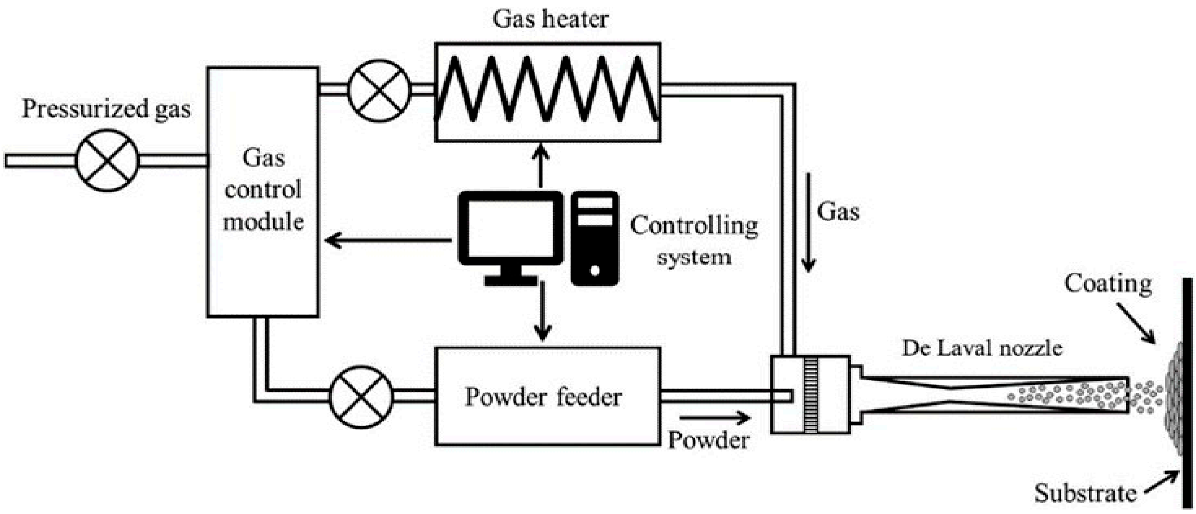

Figure 1. Schematic diagram of cold spray process (adapted from [29], with permission from © Elsevier).

Cold spray coating is a deposition method that employs very high velocities and ballistic impingement of powder particles on a base material at rates between 300 and 1200 m/s. [30]. A high-pressure jet is expanded through a converging and diverging nozzle to generate a super-sonic gas jet after being prepared to account for the adiabatic cooling brought on by expansion. The injection of powder particles into this gas jet is performed using a carrier gas. A high-velocity particle jet is produced by momentum transfer from a supersonic gas jet [30,31]. When these powder particles strike the substrate surface, they deform plastically and create interlinking splats, creating a covering [31]. A typical cold spray system consists of a gas heater, a powder hopper or powder feeder, a controlling system, a high-pressure gas delivery system, and a cold spray gun. The gas supply system may supply nitrogen or helium at rates of up to 170 m^3/hr at pressures of 15 to 50 bar, with temperatures up to 1373 K via an electric heater. The powder hopper delivers powdered coating material in size ranges of 5–45 microns, and a carrier gas then transports it to the gun [31,32]. The control console monitors the gas flow rates, pressures, powder feed rates, etc. Using customary work managing systems (robotic arms, scanning stages), the spray beam is scanned over the substrate surface. Since this process involves minimal heat interaction with the powdered material, temperature-sensitive materials like nanophase and amorphous materials, as well as oxygen-sensitive materials like titanium, copper, and aluminium, are suitable for cold spray. For cold spray technology, there are two major categories commonly referred to as HPCS and LPCS [7]. The comparison between the two systems is shown in Table 1.

Table 1. Comparison between HPCS and LPCS systems.

Parameters	Cold Spray System	
	HPCS	LPCS
Pressure (bar)	~60	5–17
Temperature (°C)	~1100	~550
Working gas	N2, He	Air, N2, He
Heating power (kW)	~40	3–5
Powder injection location	nozzle convergent section	near nozzle throat

2.1. High-Pressure Cold Spray (HPCS)

HPCS is a coating deposition process in which powder particles are delivered to the spray nozzle throat from a high-pressure gas supply. A typical HPCS operates with a max pressure and temperature of 60 bar and 1100 °C, respectively [33]. This system accelerates small solid particles with diameters between 5 and 100 µm to high speeds in a supersonic jet of hot gas, and typically, the velocity will be around 300 m/s to 1200 m/s or 1000 ft/s to 4000 ft/s [12]. The next step is to spray the powder onto the surface of a hard substrate such as metal, ceramic, or glass. The particles are heated adiabatically and deformed plastically at extremely high shear rates upon impact if the velocity is high enough and the material combination is suitable for the process, which causes the particles to flatten out and attach to the subsurface [34,35]. Although it happens on a smaller scale in this instance, the bonding mechanism is quite similar to the adiabatic shear instability found in explosive welding. Even though the gas initially has a high temperature, it quickly cools as it expands in the long, diverging section of the spray gun nozzle, keeping the spray particle temperatures below the melting point. This is why the gas is known as "Cold Spray". Figure 2 shows the schematic diagram of HPCS, where the difference from LPCS is that it uses a high-pressure powder feeder and a high-pressure gas supply.

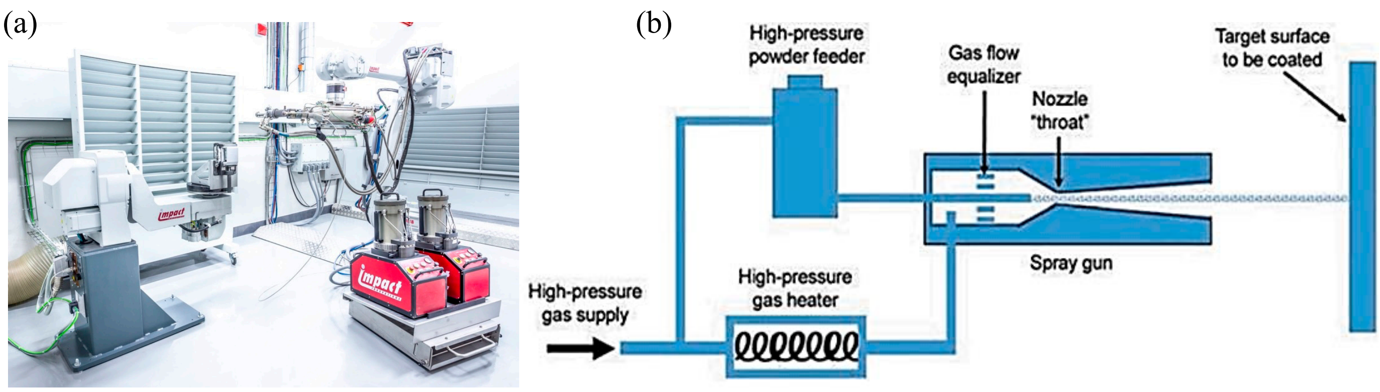

Figure 2. (**a**) Example of HPCS system from impact innovation [33], and (**b**) schematic diagram of HPCS system (adapted from [12], with permission from ASM International).

The system in HPCS employs very high particle velocities that enable this process to deposit a wide range of metals and composites. The impact velocity of the spray must surpass a critical velocity to generate hydrodynamic shear instability at the bond contact to accomplish good or high-efficiency bonding. The particles will bounce back and abrade the surface if the impact velocity is low. The minimal impact velocity required to produce the hydrodynamic shear instability in cold spray is known as the critical velocity ($Vcrit$) [34–36]. As the average particle velocity rises past $Vcrit$, the deposition efficiency rises considerably. By comparing with LPCS, the mass of material deposited to the mass sprayed onto the surface, deposition efficiency may be observed. The critical velocity varies considerably for various materials, and additional elements like spray particle temperatures, substrate temperatures, and particle sizes might also affect it. Figure 3 shows the changes in gas pressure, temperature, and velocity in the converging–diverging nozzle. The flow velocity in the diverging section of the nozzle becomes supersonic (Mach > 1), and the gas temperature falls as the flow velocity rises if the pressure decreases across the narrow throat of the nozzle above a critical minimum [12]. To achieve the highest spray particle velocities, solid particles are injected upstream of the nozzle throat, passing through the nozzle sonic and supersonic areas.

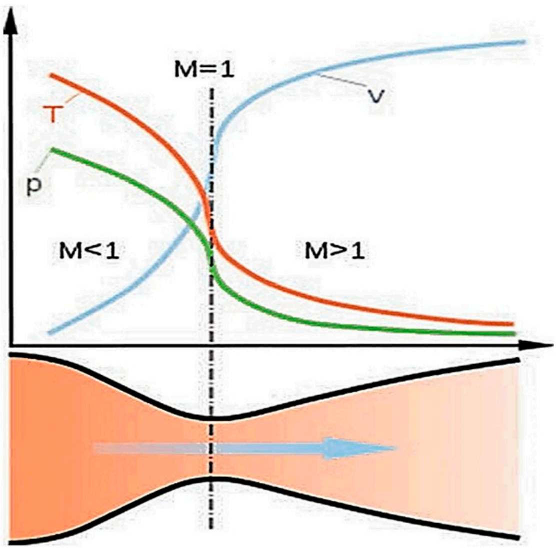

Figure 3. Notional diagram illustrating changes in gas velocity, temperature, and pressure flowing through a converging–diverging (de Laval) nozzle (adapted from [12], with permission from ASM International).

2.2. Low-Pressure Cold Spray (LPCS)

LPCS is a coating deposition that uses a low-pressure powder feeder to inject the spray powder downstream the nozzle throat directly into the diverging supersonic section of the nozzle [14]. LPCS system is lighter and less expensive compared to HPCS [14,35]. However, this process is limited to particular materials, while the HPCS process has a wide range of materials. A compressed gas with a pressure between 5 and 17 bar is the working gas in LPCS [36,37]. The utilised flow rate ranges from 0.5 to 2 m^3/min, and the heating power ranges from 3 to 5 kW. It is used to spray a powdered metal and ceramic mixture mechanically. Adding a ceramic component to the mixture results in high-quality coatings that use only a small amount of energy. The schematic diagram of the LPCS process in Figure 4 shares common or same features with HPCS in Figure 2, with some similarities.

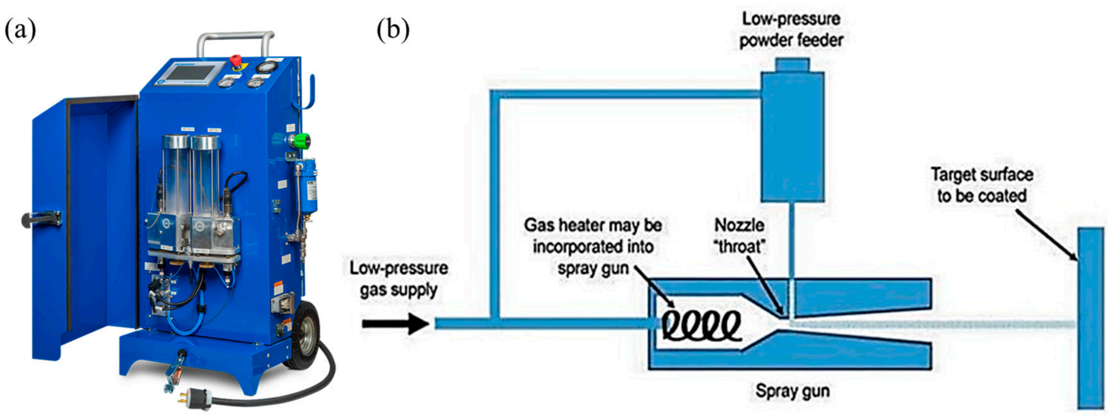

Figure 4. (**a**) Example of LPCS system from Centerline Supersonic Spray Technologies [37] and (**b**) the schematic diagram of low-pressure cold spray (LPCS) process (adapted from [12], with permission from ASM International).

In LPCS, compressed gas supply such as air and nitrogen at comparatively lower pressures is preheated to a temperature of up to 550 °C. The compressed air is then forced through a converging–diverging nozzle and accelerated to velocities ranging up to approximately 600 m/s or 2000 ft/s [12]. Compared to HPCS, LPCS systems are frequently incorporated into a handheld spray gun assembly with smaller and lighter electric gas heaters. Another significant distinction between LPCS and other processes is that in this method, powder feedstock is introduced directly into the diverging supersonic part of the nozzle just downstream of the nozzle throat [11]. Due to the significantly reduced gas pressures in this area, injecting the powder downstream of the nozzle throat dramatically decreases the powder-feeding apparatus complexity and cost [11,38,39]. However, injecting the particle downstream has limitations because the maximum achievable particle velocity is lower than HPCS. As a result, the range of materials that can be deposited using LPCS is limited. However, LPCS provides a less expensive technology with a safer working environment. The narrowness and small cross-section of particle jet can also be incredibly controlled. This makes it possible to employ stencils and deposit coatings in precise locations on a substrate. With LPCS, it is also possible to coat several components with different layer thicknesses [12,39].

3. Challenges of Cold Spray and Mitigation Strategies

The cold spray has been around for approximately 30 years in the restoration and repair areas and has undergone exciting and unprecedented development steps [40]. In fact, by concentrating on innovative solutions to remove current barriers that prevent the system from achieving its full potential, cold spray technology may be expanded to a much more comprehensive range of applications and achieve a higher degree of industrial adoption [41]. Numerous experiments have been conducted to enhance cold spray technique and increase deposition efficiency. After 30 years of research and development, cold spray technology has made many scientific and technological advancements, including new materials, fresh concepts, advanced cold spray apparatus configurations, new pre- and post-process treatment techniques, and new bonding methods as new applications [40]. However, there are still a few key challenges in the cold spray process: delamination, crack, and residual stress. To overcome these limitations, three strategies are generally undertaken: (i) heat treatment, (ii) surface roughness, and (iii) shot/hot peening. These methods serve as improvisations of the cold spray technique.

3.1. Heat Treatment

The deposited particles in cold spray experience oxidation or decomposition during the process [42]. It has relatively weak interfacial bonds and brittleness, which causes limitations in industrial applications and the fabrication of complex structural components [43–45]. One way to solve these problems is to conduct post-heat treatment [42,46]. To enhance the microstructure and mechanical properties of the deposits, a study has been conducted using standard heat treatment (HT), newly invented electric pulse processing (EPP), and friction stir process (FSP) [47]. EPP is a fast non-equilibrium process that applies high-density electron charges to generate coupling fields of electricity, heating, and strain to modify microstructure and mechanical properties [48]. It is a simpler method than traditional HT, saving time and energy. EPP has lately been used to alter the microstructure and mechanical properties of metals like zinc (Zn), copper (Cu), titanium (Ti), and aluminium (Al) and their alloys [49–51]. On the other hand, FSP uses intense and localised plastic deformation to alter the metal properties. This deformation is produced by forcibly inserting a non-consumable revolving tool into the workpiece and, in a stirring motion, pushing laterally through the workpiece. A study was conducted to investigate the effects of EPP, FSP, and HT on the microstructure evolution and mechanical properties of Cu deposit specimens in order to determine their predominant strengthening mechanisms [43]. The microstructure of the copper coatings after these processes is shown in Figure 5a–d. Overall, the microstructure of the cold spray deposits has a certain level of improvement, where most of the fine grains near the particle interface enlarge due to strong heat effects and significant atomic diffusion. The HT and EPP repaired the weak interfaces of the deposit, while FSP allowed for the total elimination of the negative effects of particle interfaces and grain refinement. As a result, the FSP-processed deposit showed the best mechanical properties result, with an increment of tensile strength and ductility by

261% (from 83 to 310 MPa) and 40% (1 to 40%), respectively. The primary factors enhancing the strength of the deposit processed through EPP are the enhanced bond interfaces and the presence of high-angle grain boundaries and twins. In contrast, for the deposit processed through FSP, the main strengthening mechanisms are attributed to improved interface bonds, superfine grains, and strain hardening.

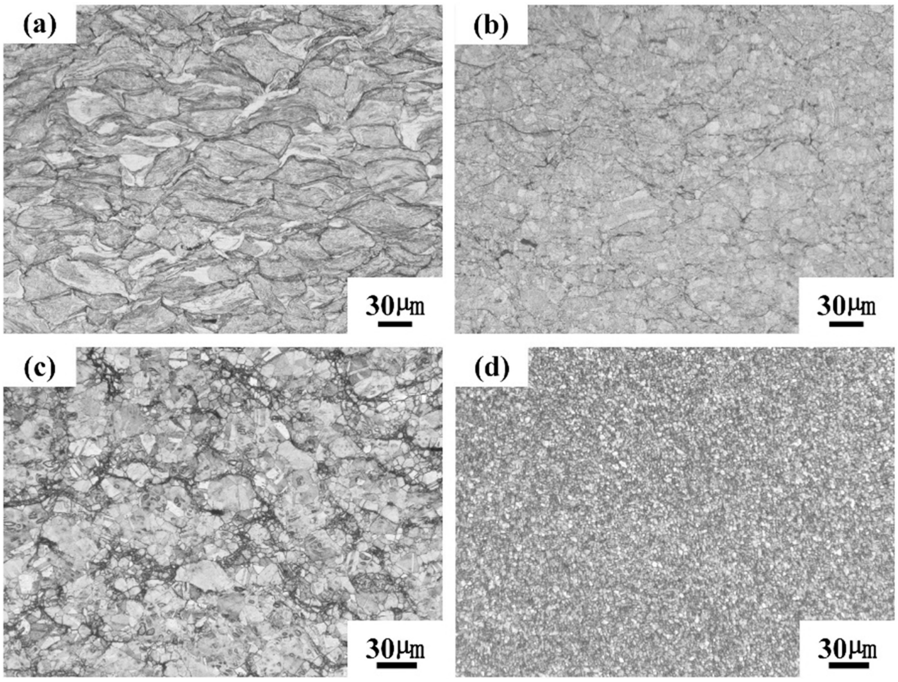

Figure 5. OM micrographs of deposits: (**a**) cold spraying, (**b**) after heat treatment, (**c**) after EPP, and (**d**) after FSP (adapted from [43], with permission from © Elsevier).

Generally, the cold spray deposits are post-processed using a conventional furnace heat treatment method, as they are established and cost-efficient [52,53]. Recently, eddy currents have been studied as a potential replacement for the conventional furnace method. However, some drawbacks include low efficiency and oxidation problems [53]. A hybrid strategy exists in addition to eddy current heat treatments to enhance the mechanical and microstructural characteristics of cold spray additively manufactured (CSAM) aluminium composite [54]. The cold-sprayed IN718 coatings' flexural strength and ductility were enhanced by the e-induction heat treatment, which uses eddy currents to produce heat in addition to electron migration. In cold spray, eddy current is an effective option for heat treatment. A hybrid approach was conducted by using three types of Al_2O_3/A380 composite deposits, mixing spherical, irregular, and spherical þ irregular shaped Al_2O_3 particulates with the original A380 alloy powder. Figure 6 shows the schematic for the steps of this process. This hybrid focuses on the composite deposit morphologies and the heat treatment that produces an appropriate tamping, in addition to the original A380 alloy powder [54,55].

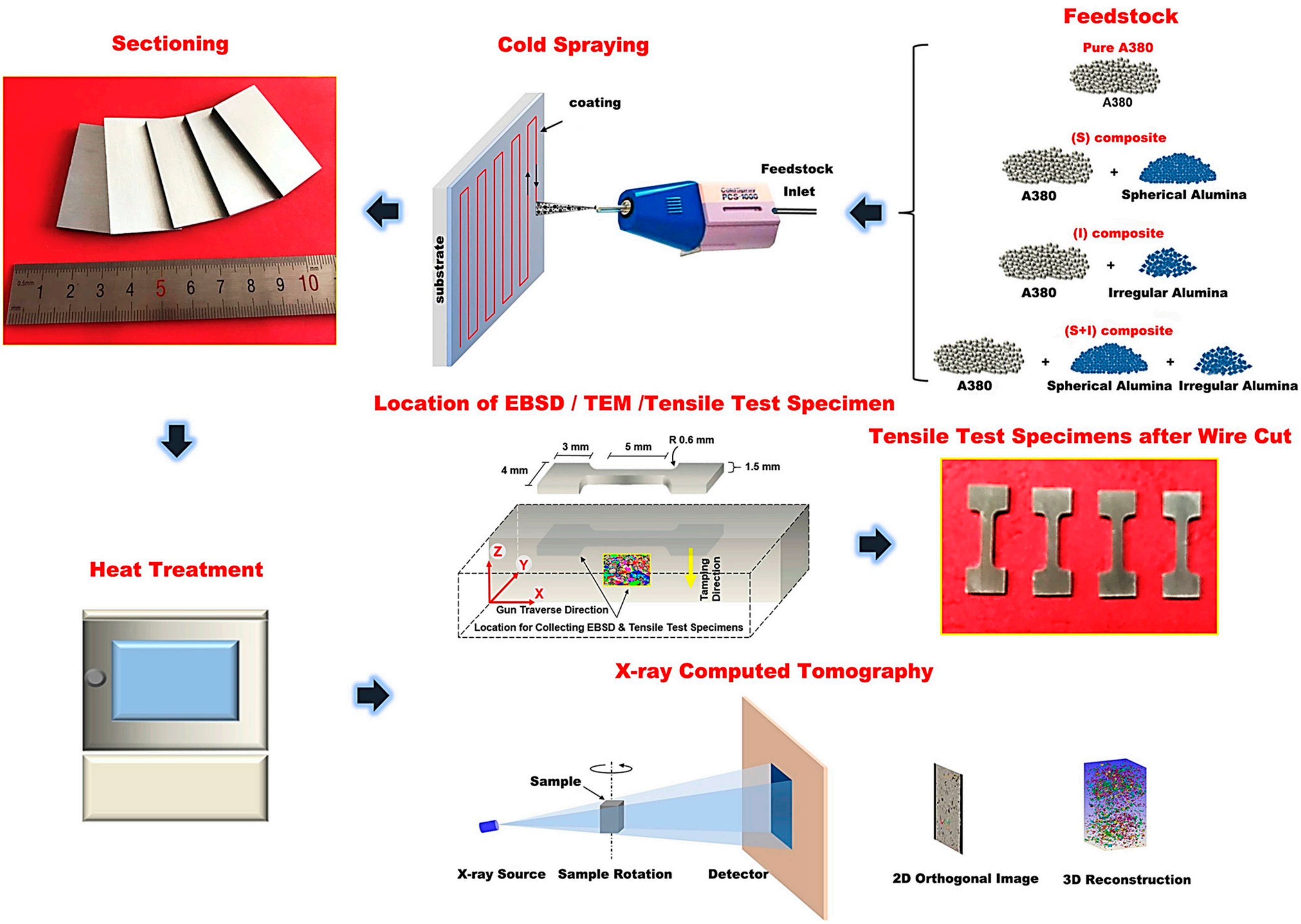

Figure 6. Schematic of the cold spray process, post-spray heat treatment, and the characterisation of the deposits (adapted from [54], with permission from © Elsevier).

Increasing material temperature through powder preheating, substrate heating, and laser-assisted cold spray (LACS) will also facilitate particle deformation [56–58]. However, there are certain limitations in using this mentioned approach, such as contamination or the high cost of the high-power laser setup. Thus, a study on improving tool steel powder cold spray by softening and heat treatment has been conducted. In this study, the technique was improved by adjusting the powder size and adding heat treatment, which led to the manufacture of dense materials [59]. Powder tempering and powder annealing are the two types of heat treatment employed. Under nitrogen gas, the annealing temperature was 875 °C, and the tempering temperature was 600 °C [59]. The outcome demonstrates the possibility of softening powder through heat treatment, and annealing heat treatments produced powder with a superior cold spray ability than tempering heat treatments due to a reduction in powder hardness of more than 60% [58,59]. According to earlier studies, heat treatment is a proven method to enhance the deposition of cold spray technology.

3.2. Substrate Surface Roughness

Delamination of thick coatings is one of the technical issues associated with the cold spraying technique [25,60]. One of the solutions is to improve the surface roughness. A study on the effect of surface roughness on several properties of cold-sprayed copper coating has been investigated [61]. The impact of surface roughness has been studied and characterised using various techniques, including scanning electron microscopy or energy dispersive spectroscopy, X-ray diffraction, optical microscopy, micro-hardness, nano-indentation, electrical and thermal conductivity measurements, and density and porosity analyses. This study discovered that the substrate surface roughness significantly influences the coating qualities. It demonstrates that for some powders such as Ti6Al4V, a mirror-finished or highly polished substrate surface has been proven superior in terms of coating properties in cold-spraying compared to the as-received or hot-rolled and semi-polished substrate surfaces because it promotes intimate conformal contact for the first layer of particles [62].

The surface roughness of cold spray Inconel 718 (IN718) was investigated by Singh et al. This study used two different grits to create two different roughness levels: F-36 grit and F-150 grit [63]. Different grits produce different surface roughness, which leads to different results. However, substrate preparation is independent of surface preparation and can influence the deposition efficiency only for the first few layers [64,65]. After the preparation of the substrates, IN718 substrates that were prepared with F-36 grit blast was 3.1 ± 0.2 μm, whereas the roughness obtained with F-150 grit blast was 1.3 ± 0.2 μm. Figure 7 shows the difference between F-36 and F-150 grit substrates. Figure 7a,b show that the coating thickness of the F-36 substrate is greater than F-150 due to the greater substrate roughness and, consequently, more surface area for the deposition of the powder. Figure 7c illustrates a wavy morphology at the substrate-coating contact, indicating that both the coating and substrate underwent deformation. In contrast, Figure 7d shows a comparatively low deformation of the substrate due to its flat morphology. In addition, these figures reveal that the F-36 substrate had a more pronounced substrate deposition than the F-150 substrate, which resulted in mechanical attachment between the particle and the substrate in the latter case. Therefore, substrate roughness has a substantial impact on particle deformation and deposition efficiency.

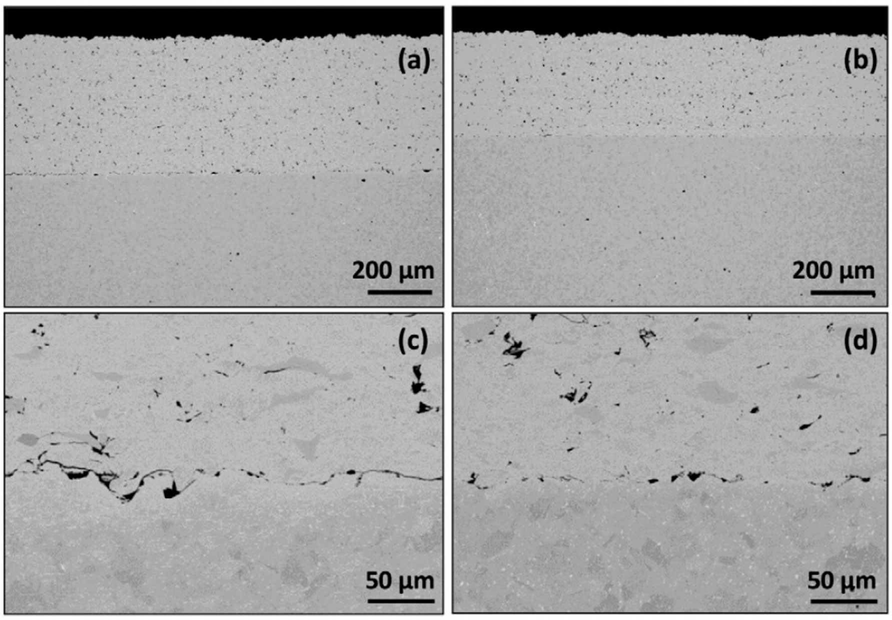

Figure 7. Cross-section of substrate prepared by grit blasting (**a**) with F-36 grid, (**b**) with F-150 grit, (**c**) interface between coating and substrate with F-36 grid, (**d**) interface between coating and substrate with F-150 substrate (adapted from [63], with permission from © Elsevier).

Cold spray is a suitable coating method for components that are heat-sensitive [66]. The primary issues with Ti6Al4V coatings for aerospace applications are their microstructure, porosity level, adhesion, and fatigue behaviour [67,68]. To determine how the substrate state affected the cold spray coating of Ti6Al4V, a study was conducted by Sun et al. [69]. Four different surface preparation techniques, including grinding, milling, sandblasting, and water-jet cutting, were used before the cold spray process. It was found that substrate samples with coatings applied to the ground surfaces had the most extended fatigue lives before failing. In contrast, samples with coatings on water-jet cut surfaces had the shortest lives before failure. It was clear that the spraying and substrate surface preparation conditions had a significant impact on the fatigue strength of the cold-sprayed Ti6Al4V coatings [69]. Despite the abundance of research performed on particle velocity, only a small number of studies focus on the significant impact that substrate hardness, surface roughness, and standoff distance have on particle deposition [70]. A study by Cetin et al. [71] on this issue also concentrated on the substrate's hardness and roughness. SiC emery sheets were used to modify the substrate surface roughness, obtained at various grits of 5, 10, 20, and 30 mm. As a result, increasing surface roughness led to an increase in substrate hardness, which benefits the coating attributes in terms of coating thickness, porosity concentration, and coating hardness. For the effect of substrate surface roughness on the coating surface roughness, Tan et al. [62] showed that the projected substrate surface roughness is minimal because the final as-sprayed coating surface consists of semi-spherical unmelted particles, which is at least two times the initial substrate surface roughness. For example, substrate surface roughnesses of R_a of 0.05 µm (polished surface) and 5.37 µm (water-jet cut surface) resulted in coating surface roughnesses of R_a 9.5 and 9.75 µm, respectively.

3.3. Surface Peening

The cold spray technique uses a high-speed gas jet to propel metal particles toward a substrate, where they bind instantly through mechanical interlocking or metallurgical bonding [72]. The cold spray approach is quick and results in little distortion or heat-impacted zone compared to more conventional repair methods like welding and thermal spraying. Due to its advantages, it is used for dimensional and shape restoration of components in the aerospace, automotive, and marine industries that suffer from wear and/or corrosion while in use [73]. A recent analysis has brought attention to the difficulties in generating dense titanium coatings equivalent to bulk material due to their high strength compared to most routinely sprayed metals [74]. In light of this, a study on the peening-based post-processing of cold-sprayed Ti6Al4V coatings had been carried out. Two mechanical peening methods, deep cold rolling (DCR) and controlled hammer peening (CHP), were employed to improve the cold-sprayed Ti6Al4V coating on the Ti6Al4V substrate. By introducing compressive residual stresses, DCR and CHP strengthen the bond between the coating and substrate, according to research performed by Maharjan et al. [75]. Additionally, the porosity is decreased by up to 71%.

The cold spray process typically introduces residual stress into the coated surface, which will eventually affect the efficiency of the bonding. Residual stresses are the key parameter for compact and well-adherent coatings. Research by Ghelichi et al. [76] described how two different types of aluminium coatings that were cold sprayed onto the metal substrate and another one that was given the air blast shot peening treatment changed the residual stress state (ABSP). The outcome demonstrated that further shot peening had adjusted residual tensions that were created during the coating process [76]. One type of substrate that can be used for cold spraying is magnesium. However, in the physiological environment with H_2 evolution, magnesium is known for having significant rates of corrosion, which has limited the clinical uses of its alloys [77]. Alloying, structure optimisation, and surface modification are a few methods that have been used to reduce the corrosion rates of Mg alloys [78,79]. Post-shot-peening processing, though, appears to be the most promising approach of all. To analyse the corrosion changes in the behaviour of Zn coatings before and after shot peening, the results were obtained by comparing the morphologies and phase structures after immersion in stimulated body fluid [80].

In most investigations, a shot-peening treatment improved the fatigue behaviour of metals. Additionally, shot peening may also affect residual stress and improve the bulk metallic materials' resistance to corrosion [81–83]. Shot peening treatment has a more significant tamping effect on cold-sprayed coatings than on bulk materials. Therefore, the shot peening technique can create exceptionally dense, corrosion-resistant cold spray coatings. Figure 8 shows the schematic illustration of the cold spraying and shot peening processes to obtain dense Al coatings on LA43M in a study by Lu et al. [84]. In this study, the cold-sprayed coatings were tamped with high-energy martensitic stainless steel particles, deforming the Al particles and eliminating any porosity. The samples with shot-peened aluminium exhibit improved corrosion resistance in the electrochemical test. The shot-peened Al coating successfully prevents corrosion of the LA43M alloy, and its long-term usage in severe environments matters most.

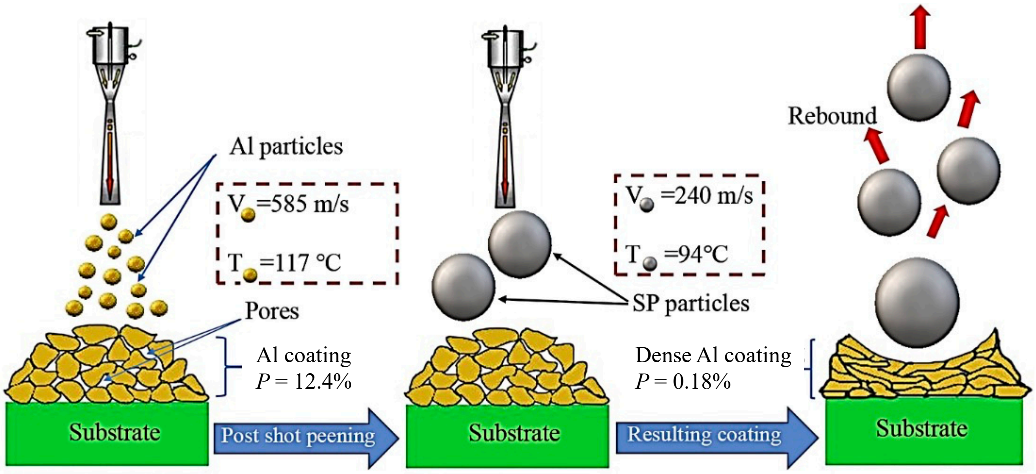

Figure 8. The schematic illustration of cold-spraying and shot-peening process (adapted from [84], with permission from © Elsevier).

4. Recent Development of Cold Spray for Coating Application

The cold spray has been widely used for coating, repairing, and overlying. As for coating, the cold spray has been used for decades [28,85]. There are a few other types of coating technology, such as HVOF coating, atmospheric plasma spray (APS), and HVAF [9]. HVOF is one of the thermal spraying techniques in which heated or melted materials are deposited onto the surface of the substrates. HVOF is usually used as a coating to protect from wear and corrosion. However, HVOF spray can be extremely difficult and complex as its function depends on various factors. HVOF is also a costly technique because of the amount of equipment needed [86]. Atmospheric plasma spray was initially used as a surface finish. APS is also a common coating technique used in various industries such as the aerospace, automotive, electronics, and biomedical industries. Equipment for APS is generally expensive to buy and use. Most importantly, the high temperature used in APS can cause carbide decomposition or excessive oxidation. Thus, it gives a carbide coating with lower hardness [87]. HVAF coating uses the combustion of propane in a compressed air stream. HVAF usually has a more uniform ductile coating and an average mechanical bond strength. However, HVAF consumes a large volume of air and is also costly. HVAF also has a low deposition efficiency and low flexibility [88]. Table 2 tabulates the latest cold spray implementation in repairing applications from 2017 to the present.

Currently, cold spray has been used prominently in coating technologies. A study by Moreno-Murguia et al. [89] used LPCS to deposit copper powder onto an aluminium substrate. In this study, they used different pressures in the cold spray process, which ranged from 5 to 8 bar. It was found that deposition efficiency was the best at 7 bar and decreased when pressure increased to 8 bar. Copper coatings can be deposited onto a PEEK resin composite substrate, as shown by Gillet et al. [90]. The main finding of this study is that alternating powder size for deposition is needed to obtain thick coatings. The alternating powders used were fine, medium, and large powders. A study on LPCS of tin bronze-alumina coating in artificial seawater has been performed to observe its microstructure, mechanical properties, and tribological behaviour. The increase in Al_2O_3 content in the powder composite resulted in the increase in composite coatings hardness from 154.7 HBW to 194.2 HBW in $CuSn_5–Al_2O_3$, the increase in coating bonding strength from 11.2 MPa to 32.5 MPa and the decrease in wear rate [91]. However, increasing Al_2O_3 content decreases deposition efficiency from 22.3% to 18.6%. In addition, Wang et al. [92]

simulated the deposition of Al powders onto 20 steel substrates at cold spray process parameters. Figure 9 shows that the temperature of the CS significantly influences the morphology of the particle when deposited onto the substrate.

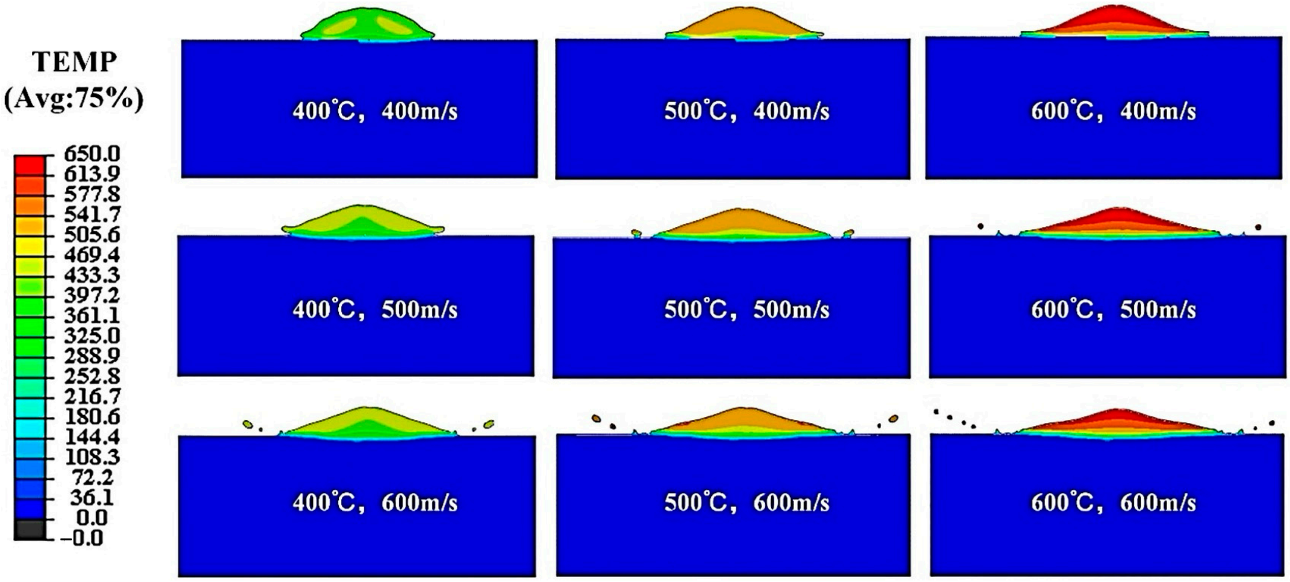

Figure 9. Contours of the temperature for Al/20 steel impact simulation under different conditions. (adapted from [92], with permission from © Elsevier).

In 2021, a study showed that LPCS was used on an ABS substrate by using TiO_2 powder [93]. This study showed that the coating is dependent on the nature of the substrate and the type of feedstock powder used. ABS is also thermally sensitive; thus, high-temperature gases can cause excessive heating. Various types of gases can be used as the gas supply. A study by Valente et al. [94] was conducted to compare the usage of nitrogen and helium gas. As a result, the use of helium as a process gas increases the track thickness by roughly 50% and 62%, concerning nitrogen at a working pressure of 12.5 bar and 14.5 bar. As for the deposition thickness, there is no commonly adopted commercial system with the same process condition that can be compared to nitrogen gas. Some studies have used air as a gas supply. Another study by Tianyu et al. used air as a gas supply to deposit copper and Al6061 powder onto the Al5052 substrate [95]. A study by Koray also used air as a gas supply, and Ni-Zn-Al_2O_3 powder was deposited onto a TZM (Mo-based alloy) substrate [96]. Low velocities and temperatures produced low jetting heights. Both studies needed to use relatively low temperatures to prevent substrate oxidation. Due to the wide range of materials that can be used in LPCS, Sn-Sb-Cu powder was also successfully deposited onto the C45 steel substrate [97]. Lastly, nickel–alumina powder was successfully deposited onto the S235JR mild steel substrate. This research studied a few coating powder types with different % of the material used. As a result, a coating with powder type 1 (Al_2O_3 + 70 wt% Ni) has a lower hardness compared to a coating with powder type 2 (Al_2O_3 + 80 wt% Ni) [98].

Other than LPCS, HPCS has also been utilised extensively for coating processes, particularly with hard materials. With HPCS, which offers exceptionally high particle velocities, various metals can be deposited, including many hard materials. Previously, in 2017, HPCS was previously used to deposit 7075Al powder onto the 7075-T6 substrate. The result showed that the ductility and strength had increased at low temperatures due to the precipitation of strengthening phases and their hardening effect [99]. Stainless steel 316 powder can also be deposited onto the same material substrate. Helium gas was used, but it limited the study due to its high cost and limited availability. However, this coating is a suitable method for repairing and maintaining pharmaceutical equipment [100]. Bhattiprolu et al. have investigated the influence of feedstock powder and CS process parameters on the microstructure and mechanical properties of Ti6Al4V cold spray depositions [101]. The study shows that particle velocity increases if the nozzle length is increasing, and as a result, low-porosity coatings have been produced with high adhesion strengths. The deposition quality also depends on the microstructure of the powder. A study in the year 2020 has proven that surface roughness is also an essential parameter in the cold spray process [61]. This study used copper powder and steel substrates with different types of surface roughness, which were mirror-finished (0.06 ± 0.01 µm) and semi-polished (0.50 ± 0.14 µm). The result showed that a mirror finish was better than a semi-polished finish to achieve more remarkable coating properties. However, the crack initiation from the multiple-splat boundaries can cause failure of the cold spray coating.

Besides that, IN625 has also been used as feedstock powder in HPCS processes. Figure 10 shows the hardness result by using three different types of powder: IN625 with helium gas, SS316 with helium gas, and CrC-NiCr with nitrogen gas [102]. It shows that IN625 had the highest hardness. IN625 porosity was 6.4 times higher than SS316, but IN625 had better erosion resistance, while CrC-NiCr had a greater hardness than SS316 but poorer erosion resistance. Thus, hardness alone is not a direct indicator of the cavitation erosion performance.

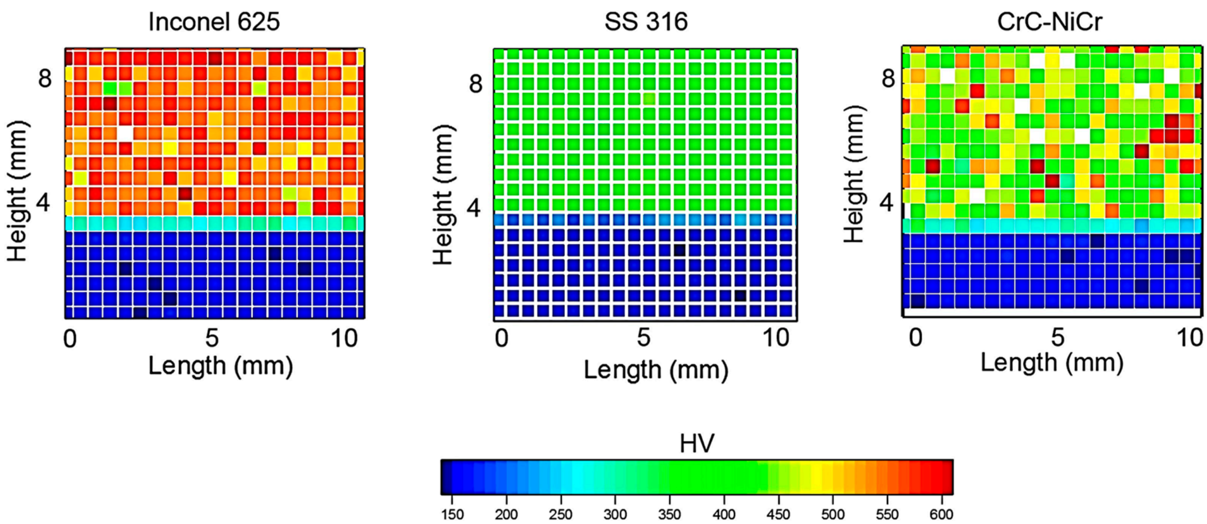

Figure 10. Hardness map of three different coatings onto SS316 substrate (adapted from [102], with permission from © Elsevier).

Furthermore, HPCS can also deposit soft material, such as Al alloy powder, onto an Al alloy 6082-T6 substrate. This study used nitrogen gas as the gas supply at 40, 50, and 60 bar with a temperature range of 350–500 °C [103]. HPCS at 500 °C and 60 bar yielded a low porosity level and a micro-hardness of 130 ± 5 HV0.05. Heat treatment improved the mechanical properties as well, and ultimate tensile strength was slightly increased. Other than aluminium, titanium is another soft material that can be used in HPCS. Boruah et al. studied the deposition of Ti6Al4V powder onto the Ti6Al4V substrate [104]. Residual stress increased due to thermal gradients from high deposition temperatures. The result showed that the highest tensile strength has been found at 346 MPa.

IN718 is the most widely utilised hard material in HPCS, particularly in aerospace and power plants. Zhang et al. compared HPCS and APS in their study to deposit IN718 powder onto IN718 substrate [105]. The result showed cold-sprayed IN718 coatings are superior in terms of lower porosity (0.2–0.5%), higher hardness (510.4–527.3 HV_{200g}), and compressive residual stresses (−30.5 ± 12.5 MPa). Both the coatings have comparable adhesion strengths of around 74 to 76 MPa. HPCS was used to deposit CoCrMo and Ti6Al4V powder onto a 6061-T651 aluminium alloy substrate in a study by Jiang et al. [102]. This study used nitrogen gas at 45 bar pressure at a 1000 °C temperature. The result showed that the porosity level was low and had a high coating bond. High impact energies of CoCrMo particles led to a higher average shear bonding strength and a higher wear resistance compared to the Ti6Al4V coating. Lastly, Al6061 powder has been successfully deposited onto the Al5005 substrate using HPCS with helium gas at 500 °C temperature and 30 bar [106]. In this study, it was found that the usage of inert gas in cold spray additive manufacturing (CSAM) might enhance or increase mechanical performance. Heat treatment after the cold spray process also helped to improve corrosion resistance, and sintering was also needed to improve strength and ductility. These recent studies show that cold spray is a promising coating technique, with a wide range of materials that can be used in either HPCS or LPCS.

Table 2. Recent development of cold spray for coating application.

No.	Powder and Substrate	Type of Cold Spray	Gas Supply	Temperature and Pressure	Surface Roughness	Main Findings	Limitations	Year	Ref.
				Aluminium- and copper-based coatings					
1	Aluminium, Al_2O_3 powder 20 steel substrate	LPCS	Air	400–500 °C 6 bar	-	The temperature has a significant influence on the morphology of the particles.	-	2021	[92]
2	Al6061 powder Al5005 substrate	HPCS (CSAM)	Helium	500 °C 30 bar	0.55 ± 0.05 µm	In the CSAM process, utilising inert gas as a carrier gas for metal powders may result in improved mechanical performance. Heating the sample increased its corrosion resistance in the deposition state.	Sintering is needed to improve the strength and ductility.	2021	[106]
3	7075 Al powder 7075-T6 substrate	HPCS	Helium	400 °C 28 bar	-	The improvement in strength and ductility with low-temperature HTs was brought on by the precipitation of strengthening phases and their influence on hardening.	-	2017	[99]
4	C355 Al alloy powder Aluminium alloy 6082-T6 substrate	HPCS	N_2	350–500 °C 40, 50, and 60 bar	-	Failure of cold spraying at 500 °C and 60 bar pressure resulted in a coating with porosity with a level of ~1% and a micro-hardness of 130 ± 5 $HV_{0{\cdot}05}$. Heat treatment of Al C355 coatings reduced porosity. Heat treatment at 225 °C enhances the ultimate tensile strength and ductility.	The drawbacks of porosity and weak interfacial adhesion restrict the use of CS technology for the structural restoration of Al alloy components.	2018	[103]

Table 2. *Cont.*

No.	Powder and Substrate	Type of Cold Spray	Gas Supply	Temperature and Pressure	Surface Roughness	Main Findings	Limitations	Year	Ref.
				Aluminium- and copper-based coatings					
5	Copper, Cu powder; Aluminium, Al Substrate	LPCS	Air	600 °C 5–8 bar	0.24 ± 0.03 µm	Pressure at 7 Bar has the highest efficiency. The deposition efficiency dropped (6–11%) when the pressure was increased to 8 bar.	Porosity and deposition efficiency can be affected by powder feed rate.	2022	[89]
6	Copper, Cu powder; Carbon Fibre + Peek resin composite substrate.	LPCS	N_2	330 °C 8 bar	-	A PEEK film thickness of approximately 50 µm is good enough to elaborate with coating.	Alternating powders (fine, medium, and large) are needed to reach a thick coating.	2019	[90]
7	Copper powder SS316L steel substrate	HPCS	N_2	600 °C 50 bar	Mirror finished (0.06 ± 0.01) Semi-polished (0.50 ± 0.14)	It was discovered that substrate surfaces with a mirror finish (fine polish) performed better compared to the hot-rolled and semi-polished substrate surfaces as obtained to achieve improved coating qualities when cold-spraying.	The breakdown of the coating was mostly caused by a crack that began at multiple-splat boundaries or junctions and then spread along those boundaries.	2020	[63]
8	Cu and Al6061 powder Al5052 substrate	LPCS	Air	400 °C 8–11 bar	-	For CSAM operations with higher particle velocity and temperature, the deposition layer is thinner with a long and sharp jetting structure due to significant particle plastic deformation.	There are challenges such as rendering high surface roughness, poor dimensional accuracy, and higher porosity level.	2022	[95]
				Composite coatings					
9	Ni-Zn-Al_2O_3 powder TZM (Mo-based alloy) substrate	LPCS	Air	300 °C 8 bar	0.2 µm	Ni-Zn-Al_2O_3 cold-sprayed coating layers can be employed as a protective coating on TZM alloy for high-temperature oxidation resistance.	The temperature used must be relatively low to prevent the TZM substrate from oxidizing.	2020	[96]

Table 2. *Cont.*

No.	Powder and Substrate	Type of Cold Spray	Gas Supply	Temperature and Pressure	Surface Roughness	Main Findings	Limitations	Year	Ref.
10	Sn-Sb-Cu powder C45 steel substrate	LPCS	N_2 and air	400 °C 5 bar	224 ± 12 μm	The low shear strength phase in the alumina-reinforced Sn-Sb-Cu-based composite coating is torn out and transferred to the wear flat on the counter body.	-	2020	[97]
11	Nickel–alumina powder S235JR mild steel substrate	LPCS	N_2	600 °C 9 bar	-	Coating with powder type 1 (Al_2O_3 + 70 wt% Ni) has lower hardness compared to coating with powder type 2 (Al_2O_3 + 80 wt% Ni).	-	2021	[98]
12	$CuSn_5$–Al_2O_3 Powder Aluminium alloy substrate	LPCS	Air	500 °C 8 bar	-	The hardness of the coating increased from 154.7 to 194.2 HBW with the increase in Al_2O_3 content. The coating bonding strength rises from 11.2 to 32.5 MPa. The wear rate of coatings decreases with the increase in Al_2O_3 content.	The deposition efficiency of the coatings dropped from 22.3% to 18.6%.	2020	[91]
Steel, Titanium, Nickel, Cobalt, Chromium-based coatings									
13	AISI316L powder Stainless steel 14001 substrate	LPCS	N_2 Helium	400–500 °C 8–15 bar	-	The stainless steel material is successfully deposited onto stainless steel substrates with nitrogen at 12.5 and 450 °C.	There is a need for further illustrations of how to deposit AISI316L samples with more complex geometries.	2020	[94]

Table 2. *Cont.*

No.	Powder and Substrate	Type of Cold Spray	Gas Supply	Temperature and Pressure	Surface Roughness	Main Findings	Limitations	Year	Ref.
14	316 L stainless steel powder and substrate	HPCS	N_2	850–1100 °C 40–50 bar	0.1 ± 0.05 µm	Industrial pharmaceutical equipment can be repaired and maintained using cold spray 316L SS coatings.	Helium has limited availability and is expensive.	2022	[100]
15	Ti6Al4V powders (gas atomised, plasma atomised powder, hydride de-hydride powder) Ti6Al4V substrates	HPCS	Helium	400, 425 and 500 °C 4.14 bar	-	For each type of powder, increasing the nozzle length led to a rise in particle velocities and low-porous coatings.	The microstructure of the powder influences the deposition quality.	2018	[101]
16	Ti6Al4V powder Ti6Al4V substrate	HPCS	N_2	1100 °C 50 bar	-	A high thermal gradient caused by using a higher deposition temperature (1100 °C) causes residual strains to increase. The highest tensile stress was found to be 349 MPa.	There are limited neutron data points to perform a good comparison with the contour result.	2019	[104]
17	IN718 powder IN718 substrate	HPCS	N_2	800 °C 40 bar	± 1.7 µm	While APS relies on the molten powders solidifying into a dense coating, CS primarily relies on the kinetic energy of the impacting softened powders to undergo plastic deformation and cling to the substrate surface coating.	-	2021	[105]

Table 2. *Cont.*

No.	Powder and Substrate	Type of Cold Spray	Gas Supply	Temperature and Pressure	Surface Roughness	Main Findings	Limitations	Year	Ref.
18	CoCrMo and Ti6Al4V powder 6061-T651 aluminium alloy substrate	HPCS	N_2	1000 °C 45 bar	15.8 ± 0.1 µm (Ti6Al4V) 23.2 ± 0.2 µm (CoCrMo)	The CoCrMo and Ti6Al4V coatings had low porosity levels and were firmly adhered to the substrates. Due to the high impact energies of the CoCrMo particles, CoCrMo has a greater average shear bonding strength. The CoCrMo coated samples had superior wear resistance than the Ti6Al4V coated samples and bare Al alloy substrates.	-	2017	[102]
19	TiO_2 ABS substrate	LPCS	N_2	300 °C	-	The type of feedstock powder utilised also affects the quality of the coatings produced.	The higher temperature of the gas supply caused extra heating of the thermally sensitive ABS.	2021	[93]
20	SS316, IN625, and CrC-NiCr powder SS 316 substrate	HPCS	Helium (SS316 and IN625) N_2 (CrC-NiCr)	800 °C 30 bar (SS316 and IN625) 40 bar (CrC-NiCr)	-	The porosity of IN625 is higher than SS316, but IN625 has better erosion resistance. CrC-NiCr has higher hardness than SS316, but SS316 has better erosion resistance.	-	2020	[102]

5. Cold Spray Implementation in Repair Application

Cold spray has been used for repair works in many industries, such as aerospace, marine, automotive, and various power plants. The general procedure to cold spray a selected component surface is shown in Figure 11. The surface of mechanical parts is usually prone to severe defects such as erosion, chemical erosion, corrosion, and wear, which worsens the service life and contributes to economic loss due to the need to replace new parts. In the aerospace industry, cold spray has contributed significantly to repairing damaged parts. In the early 21st century, a USA military technology research laboratory also used cold spray techniques to repair military helicopter aluminium alloy mast supports [107,108]. The result showed that the repaired substrates had better corrosion resistance, and the tensile and fatigue strength did not worsen. In Ukraine, cold spray had been used to repair eroded propeller blades and corroded rotorcraft helicopter gearboxes [109]. This review has listed a few materials that are suitable for repair. For instance, copper has good ductility, titanium has a low density in addition to high corrosion resistance, aluminium is easy to deposit, nickel-based material has good mechanical properties, magnesium has good thermal conductivity and superior machinability, and stainless steel is good in terms of wear and corrosion protection. The implementation of cold spray in repairing applications are listed in Table 3.

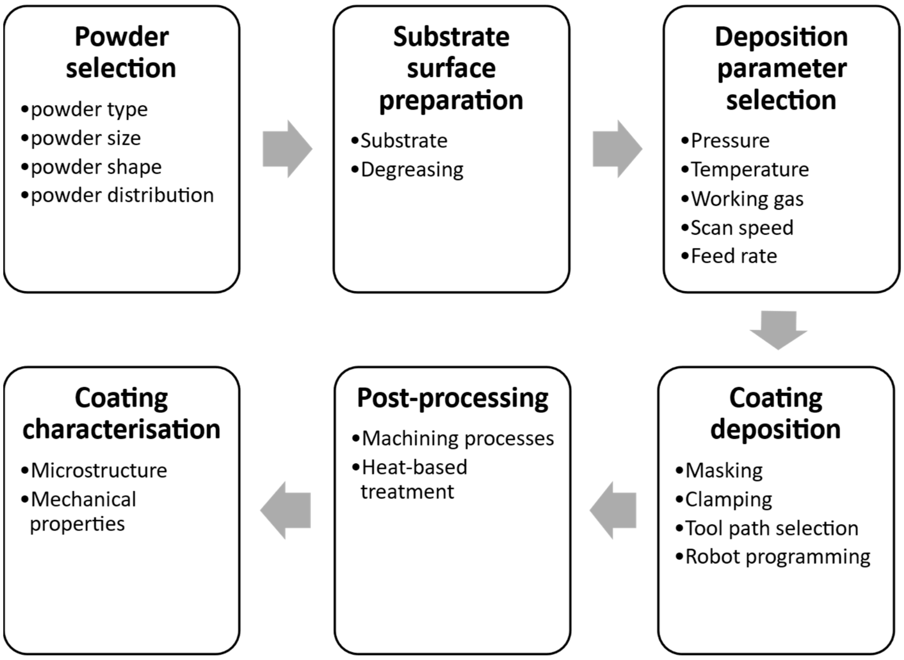

Figure 11. General procedure for cold spray deposition onto a targeted component surface.

Table 3. Cold spray implementation in repair applications.

No.	Applications	Country	Type of CS (HPCS or LPCS)	Materials/Parts	CS Process Parameters	Defect	Main Findings	Limitations	Year	Ref.
1	Aerospace	Ukraine	HPCS	Propeller Rotorcraft helicopter Cu, Ti, Al, Ni Mg, and stainless steel are widely used as raw materials.	-	Eroded blade Corrosion of rotor gearbox	Copper has good ductility, while titanium offers great corrosion resistance and a high strength-to-weight ratio. Ultra-high nickel-based alloy has good mechanical properties and corrosion resistance. Compared to other metals, magnesium and magnesium alloys have excellent machinability, high stiffness, low density, and good thermal conductivity.	-	2020	[109]
2	Aerospace	Singapore	HPCS	IN718 components	Gas: N_2 Pressure: 40 bar Temperature: 800 °C Standoff distance (SOD): 30 mm Feed rate: 23 g/min	Corrosion	For repairing IN718 components, CS provides a possible alternative to APS or HVOF.	Adhesion strength from APS is slightly better than that from CS.	2021	[105]
3	Aerospace	USA	LPCS	Aluminium alloy 7159 mass support	-	Corrosion Mechanical damage	Cold spray with aluminium powder is used to repair damaged areas and rebuild lost material.	-	2014	[110]
4	Aerospace	USA	LPCS	ZE41 magnesium accessory cover Gearbox	-	Corrosion	Certain aerospace materials, particularly magnesium alloys used to create lightweight aircraft components, have faced major corrosion and wear issues.	Due to a lack of technology in dimensional restoration, many of the parts cannot be recovered.	2014	[110]
5	Aerospace	USA	-	Cam-bearing mounting pad	-	-	The repairs could be completed easily without removing the engine block from the truck due to the portability of the LPCS equipment.	-	2014	[110]
6	Aerospace	-	HPCS (CSAM)	Helicopter gearbox sump Oil tube bores Rotor transmission housing	-	Severe corrosion and wear Electrochemical corrosion	The component lifetime is greatly decreased by electrochemical corrosion, which raises maintenance costs and increases the possibility of failure.	-	2018	[73]

Table 3. *Cont.*

No.	Applications	Country	Type of CS (HPCS or LPCS)	Materials/Parts	CS Process Parameters	Defect	Main Findings	Limitations	Year	Ref.
7	Marine	-	LPCS (CSAM)	Internal bore surface of a valve actuator	-	Corrosion	CSAM has been effectively used to restore the corroded internal bore surface of a naval aluminium alloy valve actuator without thermally damaging the base material.	Application of low-pressure cold spray is significantly limited	2018	[73]
8	Marine	Singapore	HPCS	IN718 parts	Powder: IN718 Gas: N_2 Pressure: 45 bar Temperature: 1000 °C Scan speed: 500 mm/s Feed rate: 48 g/min	Oxidation Corrosion	Inconel coating has great oxidation resistance. Compared to the bulk IN718, the cold-sprayed IN718 deposit was shown to have better oxy-chlorination resistance.	-	2022	[111]
9	Automotive	USA	HPCS	Aluminium plate	Gas: N_2 gas Pressure: 30 bar Temperature: 500 °C Feed rate: 0.2 kg/min	Damage	Cold spray provides protection against anticipated chemical, biological, radiology, and nuclear exposure.	This process can be improved by grinding off the damaged area first.	2019	[112]
10	Automotive	Italy	LPCS	Magnesium part	Gas: N_2 Pressure: 17.2 bar Temperature: 360–382 °C Scan speed: 50.8 mm/s SOD: 12 mm	Stress Corrosion	The coating displayed a bond strength of 22 MPa, hardness of 34–37 HB, and density greater than 99.5%.	-	2014	[113]
11	Automotive	Germany	HPCS	316L stainless steel coating on the aluminium surface	Gas: N_2 Pressure: 40 bar Temperatures: 500, 600, 720 °C	Residual stress	If nitrogen is utilised as a propellant gas, the cold spray deposited stainless steel coatings shows high porosity in contrast to soft materials like copper or aluminium.	Laser post-treatment is needed to decrease cold spray coating porosity.	2013	[114]

Table 3. *Cont.*

No.	Applications	Country	Type of CS (HPCS or LPCS)	Materials/Parts	CS Process Parameters	Defect	Main Findings	Limitations	Year	Ref.
12	Hydropower power plant	USA	HPCS	SS316; IN625; CrC-NiCr	*SS 316 deposition* Gas: He Pressure: 30 bar Temperature: 800 °C Feed rate: 1.2 kg/h *IN625 deposition* Gas: He gas Pressure: 30 bar Temperature: 850 °C Feed rate: 1.2 kg/h *CrC-NiCr* Gas: N_2 Pressure: 40 bar Temperature: 800 °C Feed rate: 0.7 kg/h	Corrosion	The porosity of IN625 was 6.4 times higher than SS316, but erosion resistance was much better for IN625 than for SS316. CrC-NiCr has a greater hardness than SS316, but erosion resistance was much poorer. Cold-sprayed SS316 and IN625 offer 2–3× improvement in cavitation erosion resistance compared to the base metal SS316.	The porosity and hardness levels cannot be used as an indicator of erosion resistance performance	2020	[102]
13	Nuclear power plant	China	LPCS	Titanium alloy powder (TI6Al4V) Steel button	Pressure: 20–25 bar Temperature: 450–500 °C SOD: 25 mm Feed rate: 59.5 g/min Scan speed: 300 mm/s	Corrosion	Without the use of pore-forming agents or post-treatment, CS may produce titanium-based alloy coatings with porosity ranging from 15.4% to 27.5%.	The bond strength of the coating decreases with the thickness and porosity of the coatings.	2021	[115]
14	Nuclear power plant	USA	HPCS	Stainless steel part 304L stainless steel powder	Gas: N_2 Pressure: 40 bar SOD: 25 mm Scan speed: 200 mm/s	Stress corrosion	The 304L stainless steel is successfully deposited with no cracks or spallation defects. The cold spray deposits showed great adhesion Strength with greater than 83 MPa.	-	2020	[116]

Table 3. *Cont.*

No.	Applications	Country	Type of CS (HPCS or LPCS)	Materials/Parts	CS Process Parameters	Defect	Main Findings	Limitations	Year	Ref.
15	Nuclear power plant	China	HPCS	Bellow expansion joint (IN600) Nickel + alumina powder	Gas: Compressed air; Presssure: 18–20 bar Temperature: 650 °C; SOD: 30 mm	Cavitation erosion Jet impingement erosion	The composite coating has a compact microstructure, relatively high hardness, and low porosity.	Due to the low cohesiveness between the Ni and Al_2O_3 components, the coating resistance to cavitation erosion was lower than uncoated IN600	2011	[117]
16	Thermal power plant		HPCS	Gas turbine IN738LC powder	Gas: Helium Pressure: 25, 35 bar Temperature: 600, 750, 800 °C	Corrosion	Higher gas pressure and temperature cause higher particle velocity on cold spraying. However, cold spraying at 600 °C has better quality than that at 750 °C due to the selection of particle size and size distribution.	-	2011	[118]
17	Thermal power plant	India	HPCS	Turbine blade Boiler tube	Gas: N_2 Pressure: 30 bar Temperature: 1000 °C SOD: 30 mm Particle speed: 990 m/s Feed rate: 48 g/min Scan speed: 500 mm/s	High-temperature erosion–corrosion	IN738 coating has a two- or three-times greater high-temperature solid particle erosion resistance than T11 steel.	-	2021	[119]
18	Thermal power plant	India	HPCS	Turbine blade CoNiCrAlY powder	*Helium gas route* Gas: Helium Pressure: 20 bar Temperature: 400 °C Feed rate: 18 g/min *N_2 gas route* Gas: N_2 Pressure: 38 bar Temperature: 450 °C Feed rate: 15 g/min	Wear and corrosion (form oxidation-resistant hard coating)	The wear rate falls drastically after 316L SS is coated with CoNiCrAlY coating.	-	2015	[120]

Table 3. *Cont.*

No.	Applications	Country	Type of CS (HPCS or LPCS)	Materials/Parts	CS Process Parameters	Defect	Main Findings	Limitations	Year	Ref.
19	Thermal power plant	Italy	HPCS	Turbine blade and vanes MCrAlY + Re overlay coating	Pressure: 40 bar Temperature: 800 °C Feed rate: 34 g/min	Corrosion	The fine nickel-based super-alloy powder has an efficiency of 33%, whereas the coarse powder has an efficiency of 31%.	-	2014	[121]
20	Power Plant	Canada	HPCS	Mild steel part Ni-WC composite powder	Gas: N_2 Pressure: 40 bar Temperature: 700 °C Scan speed: 30 mm/s	Sliding wear	The inclusion of WC resulted in a reduction in coating porosity The presence of WC particles in the coating stabilised CoF and decreased wear rate by a factor of seven.	The presence of WC (tungsten carbide) particles decreased deposition efficiency and reduced bonding between Ni particles.	2016	[122]

In Singapore, a study used cold spray to repair corroded IN718 components [105]. Figure 12 shows the difference between cold spray and APS methods. Cold spray can produce adherent and dense IN718 coatings, but the adhesion strength is slightly lower than the APS technique of around 2 MPa differences. However, cold spray is still a promising technique or alternative for repair technology.

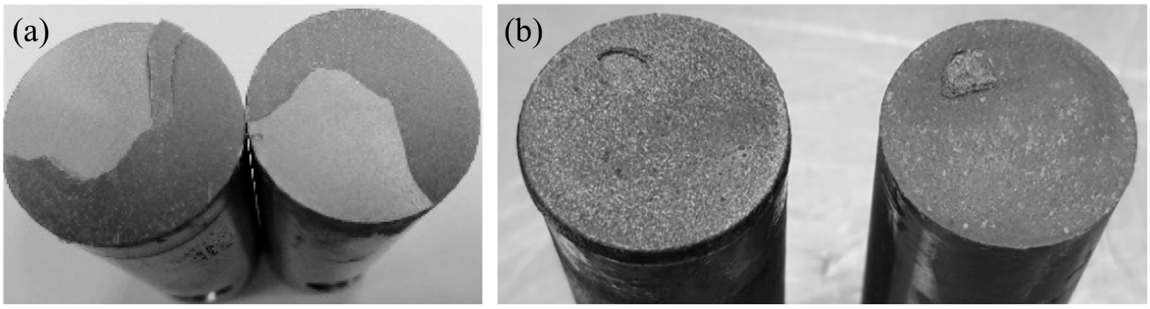

Figure 12. Fracture surfaces of IN718 coating deposited by (**a**) cold Spray (**b**) APS after adhesion strength stress (adapted from [105], with permission from © Elsevier).

In 2014, Champagne et al. conducted a study on cold spray to repair a few components [110]. LPCS was used to repair aluminium alloy 7159 mass support with corrosion and mechanical damage. The repair was performed by blending and machining the damaged area and rebuilding the lost material using an aluminium powder cold spray. Additionally, LPCS has also been used to repair corroded magnesium accessory covers and gearboxes. Magnesium is a material that is commonly used to fabricate lightweight aircraft components. Lastly, the cam-bearing mounting pad has also been repaired using cold spray. Cold spray is an excellent alternative because cold spray equipment that is portable allows the repair to be performed without unloading the engine block. S. Yin and his research group have also used HPCS to repair severe corrosion and worn helicopter gearbox sump and electrochemical-corroded oil tube bores [73]. Usually, electrochemical corrosion will reduce the components' lifetime and lead to rising maintenance costs and higher potential failure risks. This coating repair also showed a positive result where excellent adhesive strength, corrosion resistance, and wear resistance had been achieved.

Apart from aerospace applications, cold spray has been used for the marine industry. A study in Singapore has used HPCS to repair oxidised and corroded IN718 parts [111]. The IN718 material has shown an outstanding performance in cold spray. Cold-sprayed IN718 deposits have greater oxidation resistance than IN718 bulk due to the formation of a protective Cr_2O_3 layer on the surface. It also possesses excellent oxy-chlorination resistance. Furthermore, LPCS can also be used in the marine industry. LPCS has been explicitly used in cold spray additive manufacturing (CSAM) to repair the internal bore surface of valve actuators that had undergone corrosion in a study by Yin et al. [73]. CSAM had successfully and significantly repaired the aluminium alloy valve actuator, without affecting it thermally. Previously, tungsten inert gas welding was used to repair this defect. Besides the marine industry, the automotive industry has also used cold spray technology for repair work. A study has been conducted in the USA to repair damaged aluminum plates using HPCS [112]. In Italy, cold spray was used to protect against chemical exposure, while LPCS repaired magnesium parts with stress and corrosion. As a result, the repaired coating shows a great bonding strength of 22 MPa, a hardness of 34–37 HB, and a density higher than 99.5% [113]. In Germany, HPCS was used in a study to repair residual stresses in a 316L stainless steel coating on the aluminium surface [114]. Cold-sprayed stainless steel displayed significant porosities if nitrogen was used as a supply gas.

The cold spray process has also been a huge contributor in the power plant industry for repair works. Cold spray has been used in hydropower, nuclear power, thermal plants, etc. [16,108,109]. A hydropower plant study was performed using HPCS in 2020 [102]. This study used SS316 and IN625 to repair corroded parts. This study found that IN625 has a higher porosity than SS316 but greater erosion resistance. As a result, both cold-sprayed materials offer greater improvement in cavitation erosion resistance than based on SS316 alone. A study in China looked into repairing corroded steel buttons with titanium alloy powders [115]. The cold spray process that was performed without using any pore-forming agent and post-treatment also produced a titanium-based alloy coating with a porosity ranging from 15.4% to 27.5%. However, the bond strength decreased with the porosity and the thickness of the coating. In a nuclear power plant, Hwasung et al. studied the repair of stainless steel parts that underwent stress corrosion with cold sprayed 304L stainless steel powder [116]. Since increasing the particle velocity decreases porosity, the composite coating has a relatively high hardness and excellent adhesion strength. Furthermore, HPCS has also been used in nuclear power plants to repair Inconel 600 (IN600) bellow expansion joints with cavitation and jet impingement erosion by using nickel mixed with alumina powder [117]. This composite coating has a high hardness and low porosity.

Other than in hydropower and nuclear power plants, cold spray has also been widely used in thermal power plants such as coal-fired plants. In 2011, HPCS contributed to repairing corroded gas turbines by using low-carbon Inconel 738 (IN738LC) powder [118]. This study found that high gas temperatures and pressures lead to high particle velocities in cold spray. This study also ran a test by using different helium gas temperatures. It was found that using cold spray at 600 °C has a better quality than 750 °C. A study by Padmini et al. in India used Inconel 738 (IN738) coating powder to repair turbine blades and boiler tubes with high-temperature erosion–corrosion [119]. Using IN738, the erosion resistance increased by two to three times. Another study in India by Khanna et al. used HPCS to repair turbine blades with wear and corrosion [120]. This study used CoNiCrAlY powder instead of IN738 and produced a great result with a drastic fall in wear rate. HPCS has also been used in another thermal power plant in Italy to repair turbine blades and vanes with corrosion [121]. This study has compared the usage of fine powder and coarse powder. The result showed that fine powder has a deposit efficiency of 33% and coarse powder has a 31% deposit efficiency. Lastly, cold spray was used to repair sliding wear damage on mild steel parts using Ni-WC (tungsten carbide) powder [122]. It was revealed that Ni-WC costing has less plastic flow and cracking and higher hardness. However, the presence of WC leads to a decrease in deposition efficiency and lesser bonding between Ni particles.

6. Potential Cold Spray Implementation in Power Plants for Overlay Restoration

Overlay restoration has been used in many industries, such as aerospace, nuclear and thermal power plants, and food processing [8,73,123]. There are different types of repairs for damages and defects. Still, this review focuses on overlay restoration, where this process is used to restore parts to their original shape and dimension. Previously, welding and additive manufacturing have been widely used in overlay restoration [4,5]. The review observes the feasibility of hard material and whether it is suitable to be used in cold spray overlay restoration. Table 4 lists the implementation of cold spray power plants for overlay restoration. These studies have shown what type of material can be used in cold spray as an alternative to the welding process for overlay restoration.

Previous work has been performed in overlay restoration using welding techniques [123]. Weld overlay by cold metal transfer process has been used to deposit Inconel 617M (IN617M). This material has been chosen due to its properties, including high-temperature strength, high oxidation resistance, and great resistance to a wide range of corrosive environments. However, this technique could produce crack- and defect-free cladding of IN617M on SS316. Nevertheless, this coating has also contributed to saving costs and improving design flexibility. Furthermore, Guo et al. used a welding overlay by Pulse Tungsten inert gas welding (PTIG) in a nuclear power plant using IN625 [8]. IN625 shows a good metallurgical bond between cladding and substrate that is free of cracks or pores. However, the cooling process of the coating method can cause cold cracking [8]. Inconel material also has a high hardness, but a fatigue crack may be produced on the head penetration weld [124]. Besides Inconel, Liu et al. used carbon steel when depositing for the nuclear power plant in overlay restoration [125]. Compressive residual axial and hoop stress fields inside the original weld surface were improved using carbon steel. In a study by Mazur et al., another type of welding process named submerge arc welding process has been successfully used to repair steam turbine rotors in a power plant by using nickel alloy [126]. Figure 13a,b shows the failed rotor disc that needs to be restored. The highlight of this study is that nickel can overcome static stress, and it is also a material with high corrosion resistance. Therefore, using the welding process helps to increase the useful life of the steam turbine rotor.

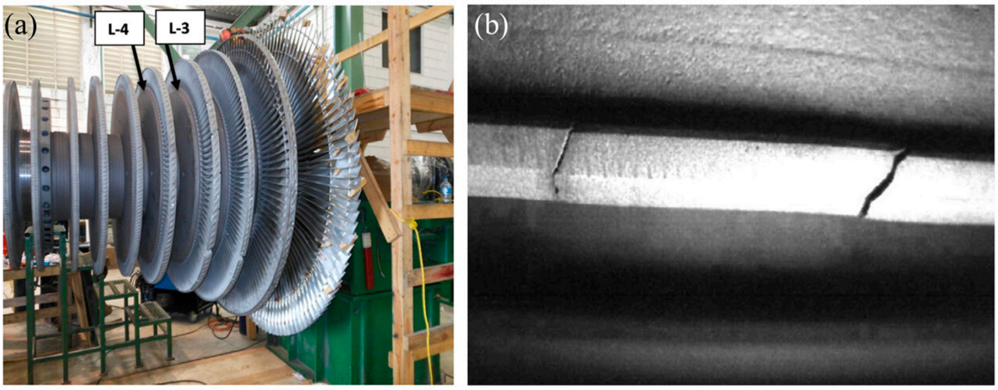

Figure 13. (**a**) Rotor of 84 MW steam turbine with arrows that indicate failed disc and (**b**) axial cracks in the blade grooves (adapted from [126], with permission from © Elsevier).

Besides that, welding has also been used in coal-fired power plants. Welding seems to be a cost-effective technique to repair the boiler with nickel-based alloys [127]. The nickel-based coating was chosen because it has high corrosion resistance, and Inconel 740 (IN740) can produce an optimum heat treatment for creep rupture strength. Another type of overlay restoration is the additive manufacturing process, which has been mainly performed on nickel-based alloys. Bi et al. showed that laser-aided additive manufacturing could deposit an Inconel coating to repair the knife edges of the gas turbine blade with a very accurate dimension [128]. However, the hardness of the substrate had slightly decreased. Next, laser metal deposition additive manufacturing was used to repair high-pressure turbine blades and engines in the aerospace industry. Inconel is a type of material that can be used at high temperatures and has excellent mechanical properties. These properties are vital for it to work under harsh or extreme conditions [129,130].

In addition, many studies on cold spray restoration, especially in overlay, have also been analysed to achieve a more accurate decision on the type of material that can be used in cold spray overlay restoration in Malaysia's power plant. One of the studies by Yeom et al. that has been conducted used 304L stainless steel powder to restore nuclear fuel storage by using HPCS [116]. This material provides a dense and continuous coating with excellent adhesion strength and a high degree of compressive stress and hardness. However, more optimisation needs to be achieved to realise a better balance between repair cost and expected performance. A study by Jafarlou et al. [131] has also demonstrated that Cr_3C_2-Ni powder can be used, and its deposition was found to improve the mechanical properties, including nano-hardness and elastic modulus, through local grain refinement [132]. In addition, mild steel material has been used to restore food processing machines [109]. Mild steel is a hard material with a high-density ratio, but using mild steel affects the deposit properties due to micro-pores that are usually found on the deposition. Thus, mild steel is not suitable for use as a cold spray for hard materials.

Yin et al. also used the HPCS of Inconel for overlay restoration in the aerospace industry [73]. As a result, the material showed mechanical stability in a high-temperature environment and had high corrosion resistance. Inconel material, specifically IN718, has been used widely in the aerospace industry and has shown impressive performances [106].

This material is suitable for the cold spray of hard materials due to its high hardness, high wear resistance, high tensile strength, and, most importantly, low porosity [96]. Furthermore, cold spray overlay restoration has also been used in a study in the automotive industry. Ma et al. have used IN718, which proves a balance between strength and ductility by using heat treatment [52]. IN718 has a high ultimate tensile strength, but the cons of using IN718 are that it has a typical brittle behaviour [52]. Raoelison et al. studied cold gas dynamic spray additive manufacturing to restore parts [133]. For example, Figure 14 shows that cold spray can fully restore a panel structure in the aerospace industry. Other than fastener holes, the helicopter gearbox and aeroplane engine can also be restored, and all these examples used Inconel-based alloys. However, there are consequences to performing repair work in the aerospace industry. This includes a detrimental disturbance of the airflow over the head of the fastener and a weak vibration resistance.

Figure 14. Cold spray repair of fastener holes enables a full restoration of a panel structure (adapted from [133], with permission from © Elsevier).

Additionally, another study used Nickel–Yttria material as cold spray powder to deposit on a stainless-steel part. The results showed that the coating has a high hardness and wear resistance [134]. Unfortunately, the coating has low strength and ductility under uniaxial tensile deformation. Furthermore, nickel with tungsten carbide has also been used to restore mild steel plates. This study proved that this material has high wear resistance and decreases the porosity of the coating. However, the presence of tungsten carbide decreased the deposition efficiency [122]. Lastly, Inconel-based material has been used in hydropower plants and aerospace industries. Studies in both industries have used IN625, which has been shown to provide better resistance to cavitation erosion [102]. The mechanical properties also improved due to the post-heat treatment, where an inter-splat bonding occurs during the material deposition [135]. Again, these studies proved that Inconel material is brittle in nature, but minimal cracks would occur even with high residual stresses.

Table 4. Cold spray implementation in power plant for overlay restoration.

No.	Materials	Applications	Techniques	Advantages	Savings in Terms of Material or Manhours	Impact/Challenges	Ref.
1	Inconel	Aerospace (helicopter gearbox, airplane engine)	Cold Spray (HPCS)	Great strength and ductility.	Avoiding manufacturing of new parts can save raw materials and energy consumption. Gives an important life extension for high-speed aeroplanes.	Disturbance of the airflow over the fastener head causes a weak vibration resistance.	[133]
2	Inconel	Aerospace	Cold Spray (HPCS)	Great mechanical properties at extreme temperatures and resistance to corrosion.	By using CSAM, the corroded parts can be restored, becoming smooth without any pits and cracks. Restoration can avoid new replacements.	-	[73]
3	IN718	Aerospace	Cold Spray (HPCS)	High hardness, good wear resistance, high tensile strength, and less porosity.	Restoring the structural integrity of the components through restoration is a saving cost.	The presence of compressive residual stress and grain fragmentation are the results of a forceful and excessive impact. IN718 coating is very brittle in nature.	[106]
4	IN718	Automotive	Cold Spray (HPCS)	Heat treatment is used to achieve a balance between strength and ductility. High ultimate tensile strength.	Cold spray additive manufacturing technique is able to restore equipment.	IN718 exhibits typical brittle behaviour.	[52]
5	Nickel–Yttria	Stainless-steel product	Cold Spray	High hardness and high wear resistance.	-	Lower strength and ductility under uniaxial tensile deformation.	[134]
6	Ni-WC composite	Mild steel plate	Cold spray	High wear resistance and reduction in coating porosity.	-	The presence of WC (tungsten carbide) decreases deposition efficiency.	[122]

Table 4. *Cont.*

No.	Materials	Applications	Techniques	Advantages	Savings in Terms of Material or Manhours	Impact/Challenges	Ref.
7	IN625	Hydropower plant	Cold spray	Better cavitation erosion.	Cost-saving and reliable as cold spray IN625 has close to a four-times improvement.	Minimal crack was observed due to high residual stress.	[102]
8	IN625	Aerospace	Cold Spray	The inter-splat bonding state upon deposition and post-heat treatment greatly influences the mechanical property evolution.	Using air as a process gas reduces deposition costs.	Inconel is brittle in nature.	[135]
9	304L Stainless steel	Nuclear Fuel Storage	Cold Spray (HPCS)	Continuous and dense coatings with strong adherence and high levels of compressive stress and hardness. Higher powder particle velocity results in lower porosity and lower porosity levels.	Able to save cracks in canisters that have been used in nuclear fuel storage.	With regard to a balance between the repair cost and projected performance, further specialised optimisation would need to be carried out for the on-site deployment of the cold spray procedure for DCSS mitigation and repair.	[116]
10	Mild Steel	Food-processing machine	Cold Spray (HPCS)	High hardness and high strength-to-density ratio.	Cold spray additive manufacturing can be used to restore damaged or affected parts.	Micro-pores are frequently found in the deposit, and micro-pores and inter-particle boundaries affect the deposit properties.	[73]
11	Cr_3C_2-Ni	Aerospace	Cold Spray (HPCS)	CS deposition was found to locally enhance the mechanical properties of the near-surface layers of the substrate.	The crack growth rate is low with CS coating.	-	[132]

7. Impact, Outlook, and Future Prospects

Cold spray coating technology has been utilised for decades as a coating process and has recently started to develop in the repair field, especially in overlay restoration in many industries. Grand View Research has reported that the market size for cold gas spray coatings was predicted to rise at a compound annual growth rate (CAGR) of 3.7% from 2020 to 2027 from an estimated USD 963.2 million in 2019 [136]. Over the course of the forecast period, the market is expected to increase due to the increasing acceptance of cold gas spray coating in aerospace, automotive, and power generation aftermarket repair and maintenance activities. The estimated revenue forecast for 2027 is around USD 1.23 billion. In 2019, North America dominated the market and generated more than 38.0% of the global revenue. This was attributed to strong demand from end-use industries, including transportation, utilities, electrical, and electronics. At the same time, Europe became the second-largest regional market and is expected to maintain its position over the forecast period. The development of cold spray technology in the power plant industry will certainly increase the expanse of the cold spray industry, especially for high-value components. The increase in the application of cold spray techniques to a wide range of materials in coating and repairing is expected to drive product demand in the future. Plasma Giken Co., Ltd., a pioneering company from Japan, and VRC Metal Systems, LLC from the United States are examples of companies that actively develop novel material systems with enhanced properties in cold spray technology [137,138]. These companies are some leading entities in the global commercial cold gas spray market.

Cold spray is a holistic deposition technology suitable for coating and repair, especially in overlay restoration. So far, the cold spray process has been an attractive and prominent method for coating deposition. There is a promising future for cold spray to be developed in overlay restoration and for the technology to expand in the power generation industry. Cold spray is a promising alternative to welding in overlay restoration because cold spray coating could produce an outstanding balance of strength, density, and thermal conductivity compared to welding. The cold spray process can also be an alternative to thermal spray due to the expensive equipment needed in the thermal spray technique for this process, which means an increase in the initial setup costs [16]. From previous studies, it can be observed that cold spray has a wide range of materials that can be used, including hard materials suitable for power plants [15]. Overlay restoration for equipment that works in extreme environments such as high temperature, high pressure, and highly corrosive environments requires the powder deposition of hard materials. Based on previous studies, an Inconel-based alloy is a common hard material used due to its excellent properties as a cold spray powder. Inconel is usually chosen because it has a high melting point, high creep and wear resistance, high hardness, high erosion and corrosion resistance, and excellent mechanical properties to work under extreme conditions [123]. In the cold spray process, operating conditions such as type of gas supply, temperature, pressure of the gas supply, standoff distance, and powder feed rate are essential to achieve a high deposition efficiency. Surface roughness also plays an important role in the cold spray overlaying process. Most of the past studies investigating the effect of surface roughness on cold spray deposition efficiency showed that a mirror finish or a finely polished substrate surface was proven to have better deposition efficiencies than a hot rolled surface and a semi-polished substrate surface because it has better properties in the cold spray process [116]. From all these studies and investigations, the cold spray process has proven its reliability in overlay restoration.

Despite the merits highlighted so far in the cold spray process in overlay restoration, many challenges still exist. Here are some suggestions and recommendations for future studies:

1. The current cold spray application in overlay restoration is mainly in the aerospace industry, and primarily soft materials have been used that are easy to deposit. In future work, more hard materials should be implemented in overlay restoration, especially

in the power generation industry. More tests and research on these materials will help determine whether they are appropriate for cold spray in overlay restorations.
2. Another future research that can be focused on is the spraying parameter, as their impacts on the deposition efficiency and quality are prime factors to consider. In addition, standoff distance, temperature, and pressure of the working gas particularly need further investigation.
3. From this review, it can be concluded that an Inconel-based alloy is one of the suitable hard materials for cold spray in overlay restoration. Nevertheless, more studies need to be performed to discover a method to overcome the problems that arise from its brittle nature.
4. Nickel-based material comes in various types, such as IN718, IN738, and IN625. Numerous studies need to be conducted to compare all these types of nickel-based alloys and understand their properties so that the best nickel-based alloy material can be distinguished for cold spray overlay restoration.
5. Further research to improve fatigue performance and extended anticipated life may open up new potential to lessen the environmental effect of manufacturing and maintenance processes. The environmental concerns and the high cost of manufacturing highlight the need to establish cold spray as a broad, sustainable solution for coatings, reliable maintenance, and repair strategies, specifically in overlay restoration.

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