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Review Article

Mohankumar Ashokkumar*, Duraisamy Thirumalaikumarasamy, Tushar Sonar, Sampathkumar Deepak, Packkirisamy Vignesh, and Mani Anbarasu

An overview of cold spray coating in additive manufacturing, component repairing and other engineering applications

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Abstract: Cold spray process (CSP) is a thermal spray technology in which coating (10–40 μm) is formed in the solid state by the impingement of power particles with supersonic velocity (200–1,200 m/s^2) on coupon employing compressed gas jet, below the melting point of coating powder. It is commonly referred as cold gas dynamic spray, high velocity powder deposition, kinetic spray and kinetic energy metallisation process. Using CSP, various engineering materials (metals, polymers and ceramics) and its composites can be deposited. It is unique and promising approach for obtaining surface coating and offers various technological benefits over thermal spray as kinetic energy is employed for deposition rather than thermal energy. This offers great benefits in additive manufacturing (AM) to develop a component denser, low oxide coating free of tensile residual stresses, and undesired chemical reactions compared to conventional AM and coating techniques. Cold spray additive manufacturing (CSAM) is the powerful and emerging technique in the field of AM to develop engineering components with improved performance covering broad range of functionalities of surface, subsurface and interfaces. There are few flaws in this technique; however, extensive research work is going in CSAM and repairing of components to meet the real-time applications. The main objective of this review article is to summarise the history, effect of process parameters on surface coating, research and development in CSP along with its implementation in AM, component repairing and biomedical, antimicrobial and electrical applications. A discussion on future trends in CSAM is also provided at the end part of this article.

Keywords: cold spray processing, cold spray additive manufacturing, cold spray repairing

*** Corresponding author: Mohankumar Ashokkumar,** Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar 608002, Tamil Nadu, India, e-mail: ashokleadsaero12@gmail.com
Duraisamy Thirumalaikumarasamy: Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar 608002, Tamil Nadu, India, e-mail: tkumarasamy412@gmail.com
Tushar Sonar: Centre for Welding and Additive Manufacturing (C-WAM), Department of Manufacturing Engineering, G. S. Mandal's Maharashtra Institute of Technology, Aurangabad 431010, Maharashtra, India, e-mail: tushar.sonar77@gmail.com
Sampathkumar Deepak: Department of Mechanical Engineering, Government College of Engineering, Bargur, India, e-mail: naamphd@gmail.com
Packkirisamy Vignesh: Department of Mechanical Engineering, Arasu Engineering College, Kumbakonam 612501, Tamil Nadu, India, e-mail: vigneshpackkirisamy@gmail.com
Mani Anbarasu: Department of Mechanical Engineering, Government College of Engineering, Bargur, India, e-mail: kmanbarasumani@gmail.com

Abbreviations

AM	additive manufacturing
CSAM	cold spray additive manufacturing
CSP	cold spray process
DE	deposition efficiency
DR	depistion rate
HPCSP	high-pressure cold spray process
LPCSP	cold-pressure cold spray process
RIGDS	radial injection gas dynamic spraying
V_{cr}	critical velocity

1 Introduction

Cold gas dynamic technique is the solid form deposition technique of nearly all types of metal, alloy and cermet powder that can be deposited through high velocity impact of the process gas (helium, nitrogen and air) with fewer temperatures [1]. They are various types of cold spray process (CSP), and they are low-pressure, high-pressure, vacuum, laser-assisted, electrostatic force-assisted and coincident grit blasting CSP [2]. Among all the above technique, the most widely used is low- and high-pressure cold spray (CS) technique for various applications. The coating development in cold spray technique is based on the high velocity impact of the feedstock powder unlike the heat energy used in traditional high temperature coating techniques [3]. The powder particle used for this technique stayed solid form throughout the whole coating techniques. Coatings are formed by metallurgical bonding and mechanical interlocking. It is due to localised plastic distortion between particles and base material [4]. This process helps the elimination of flaws primarily produced by conventional thermal spray process of high oxidation, residual stress and phase transition [5].

To develop the excellent coating properties, the coating powder must reach a critical velocity (V_{cr}) [6–8]. In this process, the development of a coating is divided into two phases. The first phase includes the development of a first layer of particles; thus, interlocking (adhesion) takes place between the coating powder and the substrate. The second phase involves the coating of upper surface where mechanical interlocking take place between particles of coating powder [9]. Each phase needs certain V_{cr}. Coating powder velocity must meet all criteria for efficient coating [10]. Commonly, greater coating powder velocity will enchane the coating properties [11]. The V_{cr} is dependent on a number of variables, based on the classification of substrate, coating powder size, and feed stoke powder temperature [12]. Coating material is usually spherical or irregular in shape. The particle size of the CS is generally in range from 10 to 100 μm to develop good quality of coating. The coating material having particle size greater than 100 μm provides improper development of coating as the particles are difficult to propel using the carrier gas [13]. However, CSP is the emerging and advantageous method for various applications due to its unique coating properties [14]. This review article focus on the advanced versatile application of CS deposit in additive manufacturing (AM), the repair and restore of aerospace components and biomedical, antimicrobial and electrical application.

2 History of CSP

CS is a new spray coating technology that was initially developed in the mid-1980s at the former Soviet Union's Theoretical and Applied Mechanics Institute. Professor Anatolii Papyrin and his colleagues developed the CSP while studying models in a wind tunnel subjected to gas and copper particles' flow at supersonic velocity [15]. As the particles were moving so rapidly (above the CS V_{cr}), they began to deposit on the part's surface rather than travelling around it. The researchers recognised that they could utilise this technology to prepare coatings because of this fortuitous event [16]. They established the practicality of the CS technique for numerous applications by effectively depositing a wide range of pure metals, metal alloys and composites onto a variety of substrate materials. A variety of technological solutions connected to the development of CS equipment and technologies were recommended based on the findings of the investigation. At this moment, numerous research centres and firms throughout the world are doing a wide range of study [17].

3 Working of CSP

Figure 1 shows the schematic representation of CS set up. It commonly divided into two catageries – high-pressure cold spray process (HPCSP) (greater than 10 bar) and low-pressure cold spray process (LPCSP) (less than 10 bar) as shown in Figure 2; both have unique benefits and limitation. Figure 3 shows the deposition development in HPCSP and LPCSP. In HPCSP, the processing gas is helium or nitrogen which is heated with help of the electrical heater. The coating material mixes with the processing gas in the mixing chamber region and passes to the convergent divergent nozzle (CD nozzle). This results in supersonic ($M > 1$) flow of the coating mixture. Thus, the powder particles impact over the substrate with greater velocity and develop coatings with excellent cohesive and adhesive properties. In LPCSP, the processing gas is air. The premixing of feedstock powder and carrier gas does not take place because the powder feeder is placed at the convergence region of the CD nozzle. It develops coating with better adhesion. However, the cohesive properties are poor compared to HPCSP coating. [18].

The CS bonding behaviour is differed from the other conventional coating processed, in which coating material in the feed stoke gets deformed plastically and forms coating. But different authors have suggested various concepts of bonding to CS coating. The above model is commonly agreed concept that feed stoke powder experiences plastically deformed condition. This is owing to remove the oxide film layer of the base material by kinetic energy and develop coating [3]. Champagne *et al.* [19] developed the copper coating on the aluminium substrate and observed that the interfacial bonding depends on the physical properties of base material and velocity of the coating material. Assadi *et al.* [6] examined that the

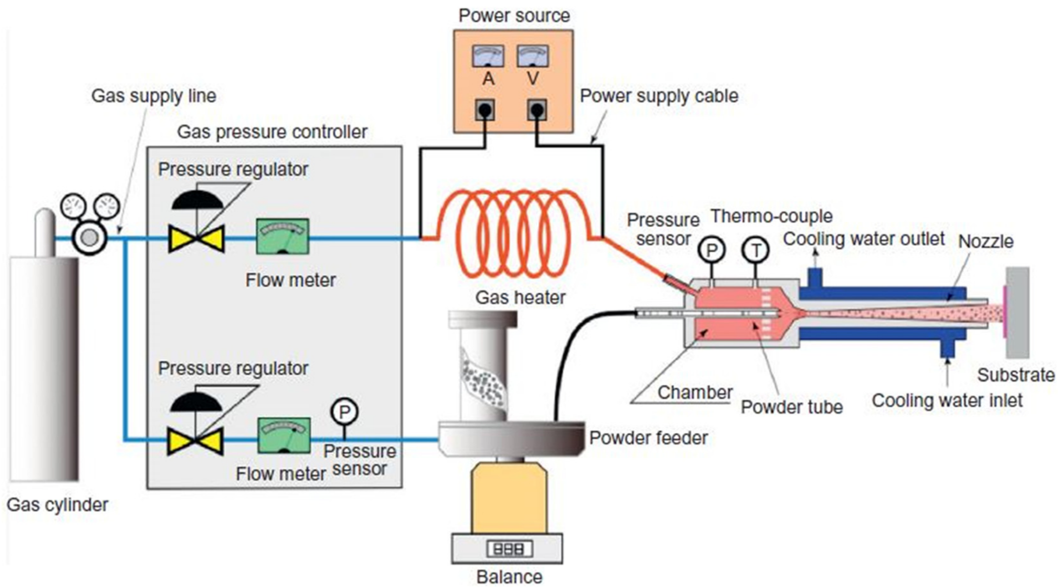

Figure 1: Set up of CS coating system [1].

excellent properties of bonding are achieved beyond the V_{cr}. The V_{cr} depends on the melting temperature of the feed stoke particle. The bonding phenomenon is attributed to the adiabatic shear instability which occurs beyond the V_{cr}. In addition, the most agreed bonding criteria is well explained by four major phases. [20]. The stages of deposition in cold spraying are displayed in Figure 4. In the first phase, a very thin flim of deposition material is coated above the base material. This stage delivers the impact and formation of coating with the base material. it is highly based on the surface treatment and properties of base materials. In the second phase, the coating material gets deformed plastically and realignment takes place and develops a certain thickness of deposit. In the third phase, metallurgical bonding develops between the coating materials, and the voids are get reduced in the coating layer and produce the dense coating. Finally, in the fourth phase, work hardening occurs to get the excellent physical properties. However, this phase needs more kinetic energy [21].

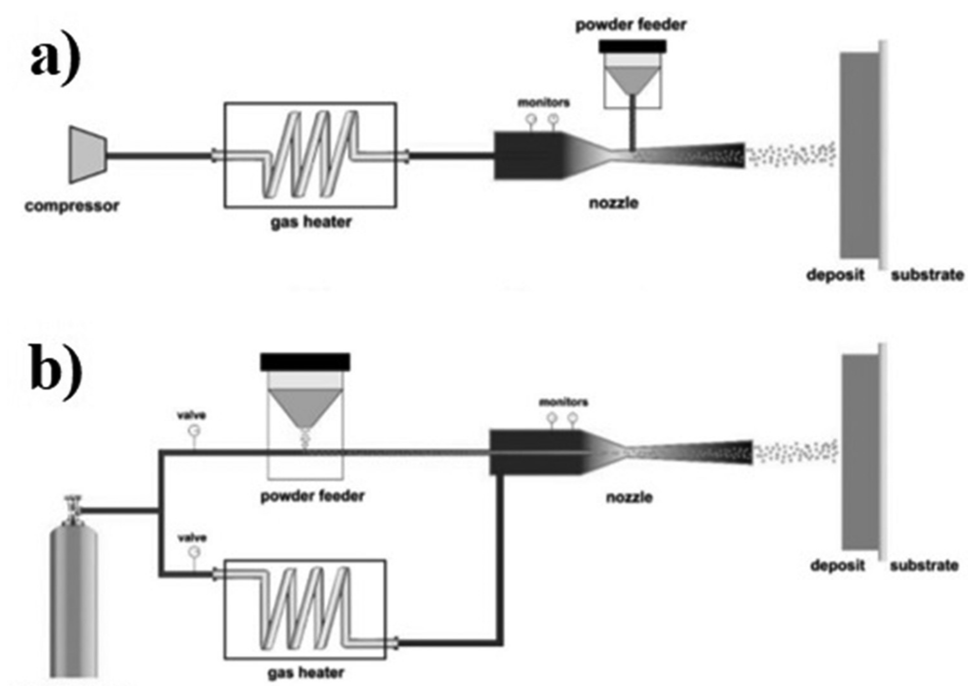

Figure 2: Schematic CS coating system: (a) LPCPS and (b) HPCPS [1].

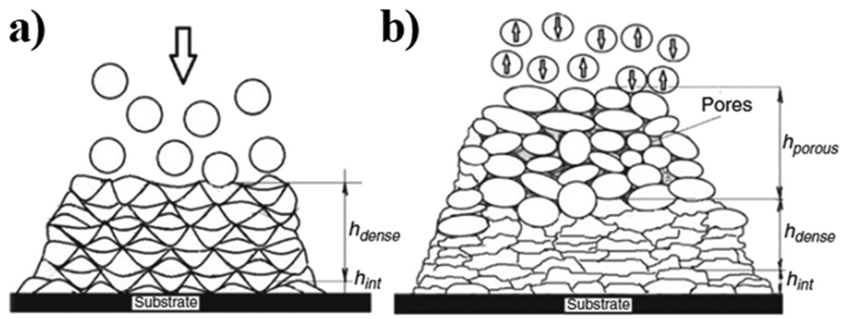

Figure 3: Deposition development in (a) HPCP and (b) LPCPS [1].

4 Significance of temperature and velocity of particles in CS coating evolution

The CS technique is a method for creating a coating by employing particles associated with high velocity that convert their kinetic energy into plastic deformation, strain and eventually heat when they collide with a substrate or previously deposited particles. Because there is no melting of particles, the coatings have lower oxidation and residual stresses [22]. To make coatings, the radial injection gas dynamic spraying technique combines coarser hard particles that do not bend plastically, such as ceramics and tungsten with smaller ductile particles. To develop the bonding of particles with other and substrate, all procedures depend on the transformation of the kinetic energy of particles. The kinetic energy of particles and momentum in the development of coating must be turned into other energy forms through plastic deformation, consolidation of voids, particle rotation, plastic strain and eventually heat. If all of the incident kinetic energy is converted into heat and plastic strain energy, the particles bounce off, resulting in an elastic collision. The development of CS coatings is influenced by the number of variables [23].

The most important factors to consider in the development of CS coatings are particulate velocity and temperature. Coatings are created by the interaction of these

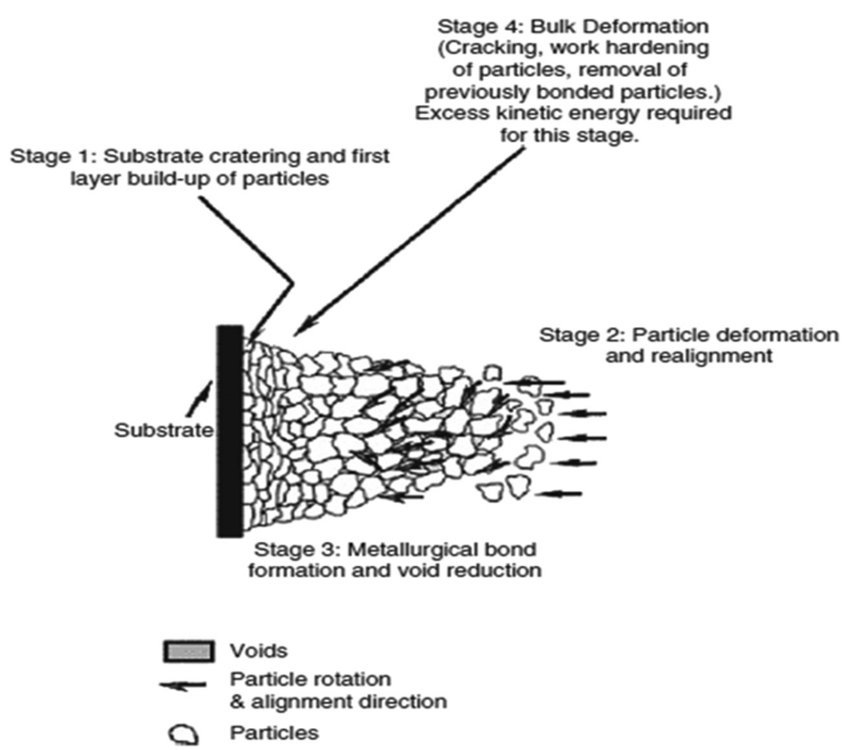

Figure 4: Stages of deposition in cold spraying [6].

two factors. The quantity of available kinetic energy for plastic deformation and bonding is determined by the particulate velocity [24,25]. The physical characteristics of the particle at the time of collision are determined by its temperature. When the particle temperature is increased, the V_{cr} is normally reduced, but when the particle temperature is decreased, the V_{cr} is generally increased [26]. CS coating of high-performance materials necessitates the procedures with higher temperatures of main gas heater (to obtain greater critical velocities) and techniques for achieving higher particle temperature. To produce coatings utilising the CS technique, the equilibrium between the kinetic energy and momentum of each individual particle must be converted 100% by plastic deformation and strain, consolidation of voids, heat, and other factors [27]. Ceramic particles have been compressed effectively using explosive compaction tests. Theoretically, if particle velocities and temperatures were increased further, there should be a spray parameters processing window that results in ceramic coatings. The advantages of the CSP – minimal residual stresses, no oxidation and thickness constraints – have proved that the CSP is a viable alternative to some classic coating techniques, such as thermal spray [28].

5 Merits of CSP

5.1 High spray deposition efficiency (DE)

For most metals, alloys and composites, very high DE values have been attained using the CS technique. DE values of over 95% have been attained for aluminium, copper and their alloys, for example. Investigations showed that by (a) reducing O_2 content of feedstock; (b) stress relieving powder; (c) optimising the size of particle distribution; and (d) optimising the spray parameters, very high DE values can be obtained for most materials, including refractory metals (such as tantalum, niobium and others) and high strength materials (superalloys and Ti–6Al–4V alloys) [29].

5.2 High deposition rate

The CS beam's spray footprint is small and clearly defined. A typical spray beam has a diameter of around 10 mm with sharp edges. A narrow spray beam combined with a high powder input rate results in extremely high deposition rates. In most cases, a 1–2-mm-thick coating may be applied in a single pass to most materials. CS, unlike other coating methods, creates ultra-thick layers with exceptional binding strength. This property has been taken advantage of in the development of CS as a technique for fabricating near-net-shape objects as well as additive manufacture of features [30].

5.3 No grit blasts

A triplex method (grit blast–spray coat–shot peen) may be seen as the CSP. The velocity distribution over the spray beam follows a Gaussian pattern, as one would anticipate. When the system's parameters are optimised, particles in the core have a velocity greater than the V_{cr}, while particles in the rim have a velocity less than the V_{cr}. When such a spraying beam is scanned, the particle at the leading-edge strike on the substrate surface at a velocity less than the critical deposition velocity (V_c) which causes solid particle erosion of the surface and *in situ* micro-grit blasting. Particles in the core collide with a velocity greater than V_c on the substrate surface, deform plastically across the recently cleaned rough surface, and produce a coating. Particles in trailing edge, which collide with a lower V_c, not only sputter loosely attached particles but also shot peen newly created coatings. Experiments have demonstrated that several substrate materials, such as aluminium, copper, and titanium, do not require traditional grit blasting [6].

5.4 High density

Only particles having impact velocity greater than V_c plastically deform and deposit in CS procedure. High strain rate deformation adds extra thermal energy to the conversion of kinetic energy to thermal energy on impact throughout deformation. These tiny processes cause hydrodynamic instabilities, which result in the creation of a metal vapour jet. This jet creates vapour deposition of material at the inter-particulate contacts, filling any gaps or fissures that may present. As a result, CS may be thought of as a hybrid of particle and tiny vapour deposition techniques. Furthermore, any weakly bonded particles are flicked away, and spray beam's trailing edge particles micro-peen the deposited splats. Finally, the underlying layer is peened with each succeeding pass of spray beam shot, increasing its density. CS creates near-theoretical density coating due to the combination of these events [31].

5.5 No or little masking

The particle beam in the CS method is narrow and highly defined. Despite the fact that a normal spray beam has a width of roughly 10 mm, customised rectangular nozzles may be designed to produce spray beams as tiny as 1–2-mm wide with sharp edges. As a result, in many applications, masking of areas where overspray is prohibited is unnecessary [32].

5.6 Flexibility in substrate-coating selection

Many applications need substrate-coating pairs with different materials, which are challenging to achieve using traditional methods. Even common materials like aluminium over copper or copper over aluminium can result in undesirable interfaces. When a molten copper droplet strikes an aluminium substrate, a brittle Cu–Al intermetallic phase forms, which can cause the coated structure to break during service. As a result, it is critical to carefully examine phase diagrams and pick substrate-coating couples to guarantee that no intermetallic phases emerge during high-temperature processing, which might cause the coated system to fail prematurely. The creation of weak interfaces is prevented since CS does not heat and melt the coating material. As a result, the engineer has freedom to choose materials based on design needs [33].

5.7 High bond strength

Cold-sprayed coatings have a high binding strength to a variety of substrate materials, including metals (aluminium, copper, titanium, nickel and so on), alloys (Inconel, steels, *etc.*) and composites (aluminium, copper, titanium, nickel, *etc.*) (metal matrix composites, carbon composites, *etc.*). Some materials, such as aluminium, can be used to coat glass. Even ultra-thick coatings have appropriate binding strength values, as can be observed [34].

5.8 Minimum thermal input to the substrate

The substrate is heated to different degrees by the flame in traditional thermal spray processing. As a result, temperature-sensitive materials, such as magnesium and polymers, are difficult to treat. Furthermore, temperature-induced substrate warping is an issue, especially when the specimen thickness is tiny. There is no high-temperature jet to heat the substrate in CSP; therefore, substrate only gets striking particles' stagnation enthalpy. As a result, CS can be utilised to repair temperature-sensitive parts and components [35].

5.9 Compressive residual stresses

The majority of coating processes result in tensile residual stresses in the deposits. These strains cause microcracking on the coating's top surface in addition to bond failure. As a result, the coating's fatigue qualities deteriorate, and the coating's performance attributes in the real application environment deteriorate. Because the coating is created by plastic deformation in the solid state in the CSP, the residual tension over the whole coating thickness is compressive. Coatings with compressive residual stresses are required in many high-tech sectors, such as gas turbines, since such a stress condition results in higher fatigue performance. Post-spray shot peening is used in some key applications to improve fatigue performance. Because the CS procedure generates compressively stressed coatings, they have higher fatigue qualities and do not require the extra shot peening phase [36].

5.10 Ultra-thick coatings

Most methods generate tensile stresses during coating process. These stresses build up at substrate-coating contact when coating thickness is raised, resulting in a loss in bond strength. The coating spontaneously spalls off the substrate when the coating thickness reaches a threshold amount. Because a cold-sprayed coating is compressively strained, ultra-thick layers may be created without bond failure over a wide range of substrates. In some applications, such as replacement of thick electroplated layers, this has proved advantageous [37].

5.11 No oxidation

Thermal spray treatment of oxygen-sensitive metals including aluminium, copper, magnesium, titanium and their alloys is challenging since raising the temperature dramatically promotes oxidation. The material is not heated to a high degree by CS. Furthermore, the particles are propelled by an inert gas, which effectively protects the splats that develop on the substrate. As a result, in the CS procedure, oxidation of the particle is virtually totally avoided. In fact, cold-sprayed coatings have been shown to have a somewhat lower oxygen concentration than the starting material. This deoxygenation takes place in the following way. A thin oxide layer coats each tiny particle in the feedstock material. The brittle oxide skin shatters and is carried away by the gas jet as the particle collides with the substrate surface, while the nascent metal surface attaches to the underlying surface [38].

5.12 No grain growth

CS is a solid-state consolidation method that works with temperature-sensitive materials including nanomaterials and amorphous materials at low temperatures. CS generates nanostructured coatings with no discernible grain formation, unlike other powder consolidation processes like as pressing and sintering, thermal spray and so on. Experiments have demonstrated that CS consolidation of micro-WC powders can attain unique features, such as extremely high toughness. Amorphicity retention has also been shown when amorphous alloys are CS treated [37,39].

5.13 No phase changes

During any high-temperature operation, oxidation, breakdown, development of metastable phases, preferential loss of some ingredient and so on are to be expected. Because the particles in the CS technique remain close to ambient, no phase shifts occur [38].

5.14 High strength and hardness

According to the mechanical property evaluation, the tensile strength of cold-sprayed coatings will always be greater than the bulk values. Furthermore, coatings have a higher hardness than bulk values due to its high degree of plastic deformation of the particles. Finally, there are various advantages to using the CS method. Oxidation, breakdown, phase change, grain growth and other detrimental high-temperature processes are all avoided. Phase-pure coatings with a wrought-like microstructure and relatively close density, as well as high electrical and thermal conductivities and improved corrosion resistance, are created using compressive rather than tensile stresses. Spray coatings can be used to create protective layer or to repair/refurbish oxygen- and temperature-sensitive surfaces. Ultra-thick (several cm thick) coats with high binding strength to a variety of substrates are feasible. Cold spraying eradicates necessity grit blasting on many substrate materials. The CS beam's imprint is much narrow and well defined, allowing for a faster rate of coating layer growth and greater control of the coating's shape without the use of masking. That can be used to create free-form and feature pieces. Because CS generates almost minimal grain growth, it may be utilised to combine nanomaterials into coating and structures [34].

5.15 High conductivity

Cold spraying produces thick coatings with excellent inter-particle bonding. In addition, coatings have a high degree of phase purity, with holes, oxides and other contaminants being negligible or non-existent. As a result, cold-sprayed coatings have a high thermal and electrical conductivity. Cold-sprayed coatings exhibit bulk conductivity values from over 92%, opposed to 40–63% for thermal-sprayed coatings, according to tests [39].

5.16 High corrosion resistance

Because of its high density, phase purity and homogeneous microstructure, cold-sprayed coatings offer outstanding corrosion characteristics. In fact, cold-sprayed aluminium and other coatings have shown to outperform bulk materials in terms of corrosion resistance [30].

6 Demerits of the CSP

- Although post-spray heat treatment can provide mechanical property values similar to bulk values, the cold-sprayed coating has near-zero ductility in its as-sprayed state.
- Pure ceramics and certain work-hardening alloys cannot be sprayed and necessitate the substrate to have at least some ductility to generate well-bonded coatings. As a result, cold-sprayed coatings on ceramic substrates have a low bond strength.

- To attain the velocities required for deposition, high-quality coating, such as MCrAlYs, Inconel, and others, is manufactured with pricey helium as the processing gas.
- Spraying complicated and interior surfaces is problematic [34].

7 Current trends in CS technique

In the last 30 years, CST has advanced at a breakneck pace. In various industrial domains, mass production applications have arisen. The process has been used to spray ductile materials, such as copper [40,41], aluminium [42], nickel [43], nickel-based alloys [44], and zinc [45], as well as metal matrix composites [46,47]. The next sections will go through the properties and applications of this new technology.

7.1 CS additive manufacturing (CSAM) process

A wide variety of industrial parts have cylindrical structures, CSAM has the ability to manufacture those parts. The cylindrical structures are developed *via* CS technique using an exterior spindle to support the mandrel substrate. The CSAM Al pipe and flange after machining are shown in Figure 5. Al flange was developed for an Irish corporation. Initially, the Al powder coated on the Al pipe was controlled and turned through the spindle; after the development of the components, it is passed to the machining process to get the successful flange.

Figure 6 displays the photograph of CSAM Cu flange with the thickness of 50–60 mm thickness [48]. It is important to remember that CSAM can only generate an irregular structure, not a net-shape structure. As a result, to achieve the desired form, CSAM coatings usually need a post-machining (deductive manufacturing) operation. Any type of internal and external walls of the rotational structure (cylindrical shape) can also be fabricated through the CSAM [49–51]. The production technique is same to flange manufacturing, especially for external wall. Figure 7a shows 1–10 scale of canister manufactured with CSAM for the removal of CANDU spent fuels. A copper coating of 10 mm is deposited on the cast iron cylinder with pours 0.3% and density about 8,900 kg/m^3, the deposit fabricated with high tensile, thermal and mechanical characteristics. For a few parts, the mandrel substrate is not required and has to be extracted at the time of deductive manufacturing. Figure 7b depicts a CSAM 10Ta-W alloy tube ultilised for the manufacturing of gun barrel liners; then 10Ta-W alloy powder was coated on the cylinder shaped Al mandrel substrate, and then internal mandrel was extracted. The extracted component is freely dipped into NaOH solution.

The fabrication strategy for internal wall manufacture varies depending on the internal diameter. If the internal diameter is huge enough to accommodate a typical CS nozzle and its mounting attachments, then the manufacturing procudure was similar as developing the external wall. However, if the component is too small to fit a CS nozzle, the nozzle must be mildly tilted to accommodate the tiny area; therefore, due to the deposition angle, the deposit content is fewer. Figure 8aa illustrates the dense copper coating in the cylindrical structural component of the food-processing equipment through CSAM [52]. For some instant, the gun (nozzle) must be angled to the aimed substratum at the time of manufacturing owing to the restriction of the inner diameter of the

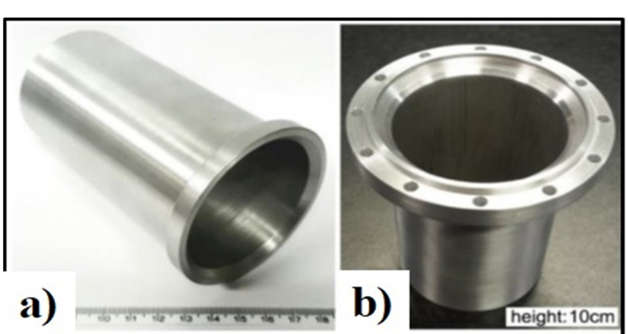

Figure 5: CSAM pipe after machining: (a) Al alloy cylindrical pipe and (b) Al alloy flange.

Figure 6: Photographic view of CSAM copper flange [48].

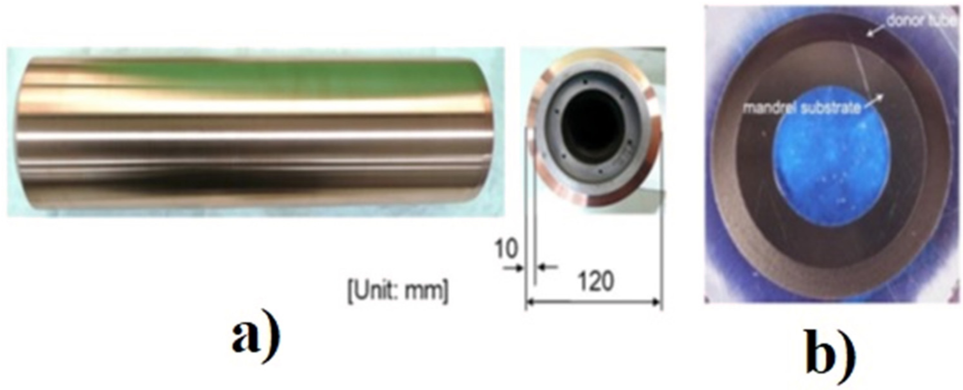

Figure 7: Photograph of CSAM cylindrical structure: (a) scaled canister for the disposal of CANDU spent fuels [49] and (b) 10Ta-W alloy donor tube utilised for the gun barrel liners [50].

product. In this specially engineered nozzle need to be used having very small internal diameter. [53]. Figure 8b shows a specially designed small CS nozzle to the minimum diameter interior walls and Figure 8c reveals the interior Cu coating wall with the thickness of 80 mm on the metal tube with specially designed small nozzle. CSAM is also able to generate other unique cylindrical structures as shown in Figure 8. The CSAM parts of intricate structures, such as cone and gear, are presented in Figure 9. The cone and gear component is produced with higher hardness with low porosity. To develop such components, a detailed design and scan pathway should be created prior fabrication. Nozzle moving speed and scan phase with pathway must be connected with the spindle axis [54].

Pattison *et al.* [55] fabricated the three sheathed thermocouples and solid hemisphere mould tool through titanium particle, coating produced with high mechanical strength as shown in Figure 10. They also investigated the CSAM of Ti–6Al–4V/Al and Ti/Cu substratum; it produces the deposition with excellent adhesive and cohesive properties to the component as shown in Figure 11. Recently, a synthesis of CSAM and traditional deductive manufacturing has shown promising results in manufacturing intricate structural components. The researchers fabricated the intricate – structured cooling channel made of copper elements which meets the real time application as shown in Figure 12. Similarly, Figure 13 depicts a CSAM-fabricated part

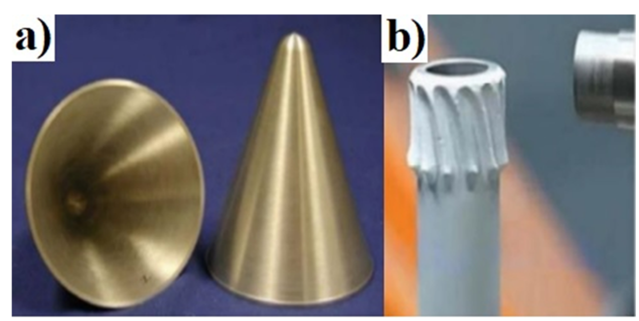

Figure 9: CSAM parts of intricate structures: (a) cone and (b) gear [51].

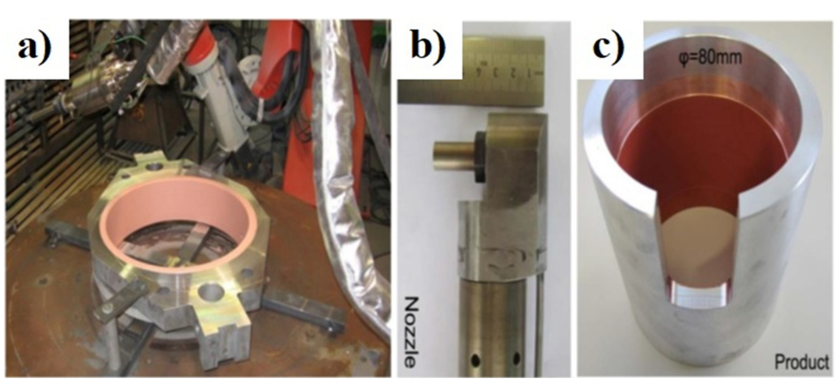

Figure 8: CSAM cylinder: (a) internal wall of pressure ring for food processing machine; (b) small-size CS nozzle; and (c) internal wall of small-space cylindrical pipe [51,52].

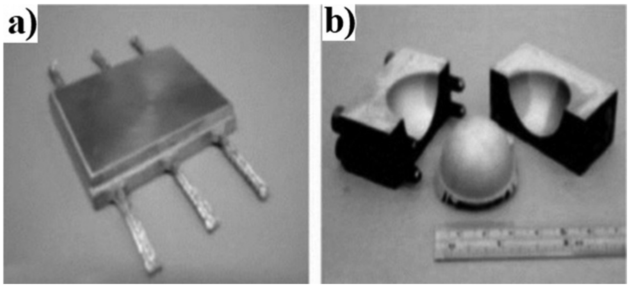

Figure 10: (a) Three sheathed thermocouples embedded within a titanium part and (b) titanium hemisphere formed by mould tool [55].

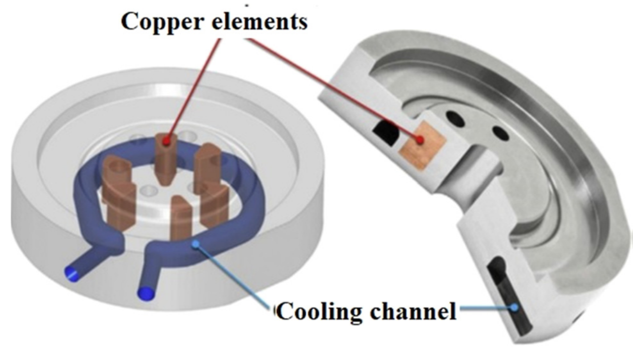

Figure 12: AM with copper and tool steel with cooling channel-drawing [1].

with a structure of intricately. To develop these parts, the additive components were first coated onto a uniquely engineered substratum. After deposition, the substratum was extracted and, then, the CSAM components get retained. From this, an intricate part was developed using a hybrid of CSAM and deductive manufacturing. In this technique, substrate must be constructed in such a way that it is simple to remove and post-process machining is minimal. Thus, CSAM can also be used to change the current part. Figure 14 depicts the modification technique of attaching a new component onto a bearing lid through CSAM. After CSAM, an entirely new part was acquired with no clear distinction between the boundary of new element and original section [56]. Manufacturing of such complicated mechanisms is essential for CSAM technique, as it greatly extends the range of applications.

CSAM can build array structural components, as illustrated in Figure 15, the production method requries a uniquely engineered mask to avoid the deposit of superfluous materials and enable to deposition on the specified template to fabricate the high densities pyramidal fin arrays [57–60]. By changing the SOD and model structure of the wire mask, the fin array structure and density may be precisely managed [61]. The thermal and mechanical characteristis are better comparision with the conventional rectangle shaped fins; this is owing to the greater convection heat dissipation coefficients [62]. Cormier *et al.* [63] observed that the heat transfer efficiency can be enhanced by raising fin altitude and fin density at the expense of a greater pressure drop. Mask-attached CSAM may also be utilised to develop chip heat sinks, metal markings and various components (unique structure).

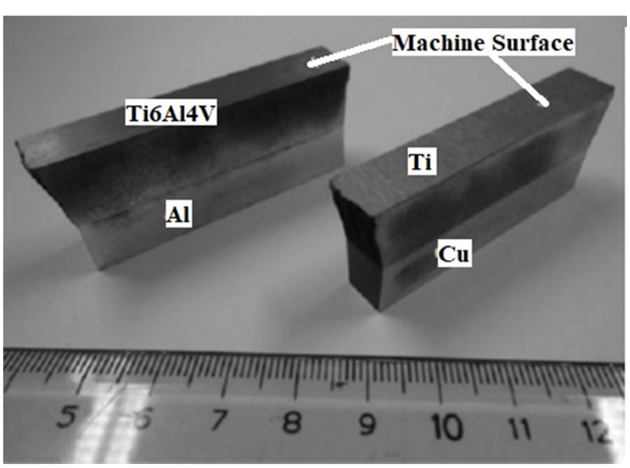

Figure 11: Fragments of bimetal Ti–6Al–4V/Al and Ti/Cu plates manufactured through CS process and machining is made by milling after deposition [55].

7.2 CS repair and restoration of components

The mechanical component gets degraded after certain periods of time owing to electrochemical or tribological actions or other factors. The defected parts are often

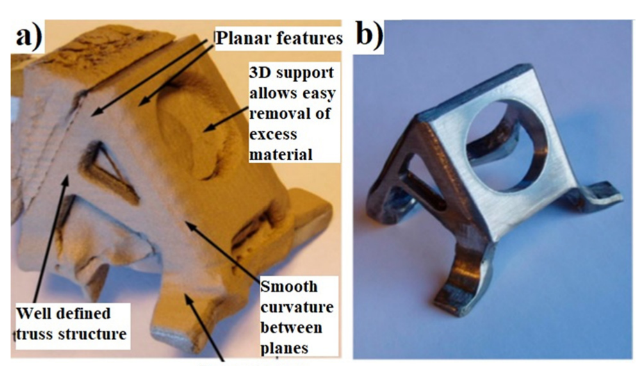

Figure 13: CS interpreted concept: (a) mandrel after deposition and (b) mandrel removed and post-machined [55].

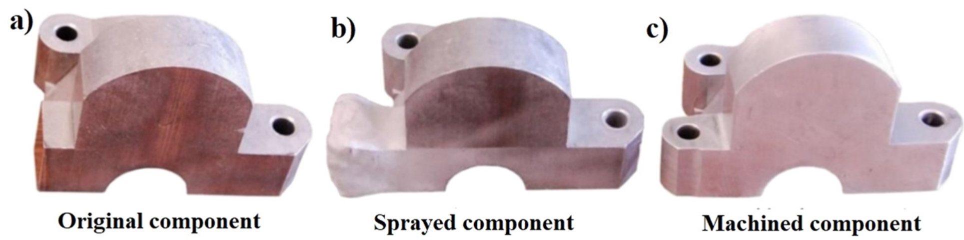

Figure 14: Modification technique of adding a new component to a bearing cap through CSAM [56].

unable to be restored and must be changed owing to a shortage of appropriate restoration techniques [64]. CSAM is a economical method that has the tremendous ability to restore the defected parts; this is owing to the ability to neglect the thermal defect of the fundamental substratum and able to sustain the same characteristic of the coating material. CSAM had effectively used to recover a numerous of detorated and defected parts in different disciplines [65]. From this process the feed stock material does not directly deposited on the defected area due to its intricate surface geometry, and the ability for the degraded surface of the defected region will affect bonding behaviour. So, prior machining is needed above the affected area to rebuild the degraded region. Surface healing needs to be carried out on the restored area with various machining operations to get the better surface finish that is acceptable to the CSAM [66]. Even for the CSAM, the deposited products must be carried out for the machining process to attain the stanadard geometries. The typical restore procedure of a component is shown in Figure 16.

In the aviation sector, the restoration and maintenance of aerospace components is the more challenge owing to the poor behaviour of electrochemical and tribological properties. This happens on the component owing to high speed impact and rotation [67]. The Mg and Mg alloy posses the excellent properties (greater strength-to-weight ratio) compared with other alloys. So, it is widely used in the manufacturing of aircraft transmission gearboxes. The application of Mg alloy in the gear boxes is challenging because the Mg alloy gets oxidized due to the anodic reaction with other metal. So, the periodic service is required to improve the life span of the gear boxes to avoid the failure risk of the aircraft [68]. To overcome this corrosion and wear problem, CSAM is used to repair or restore the components by depositing Al or Al alloy materials on the defected area as shown in Figure 17. Schell [69] reveals enhanced adhesion, cohesion properties of the component with improved wear and corrosion behaviour in restored components. The repaired components meet real-time application in aircraft.

Al alloys are widely used in aviation sector owing to its good mechanical, electrochemical and tribological properties. Several components of the helicopter are fabricated by using the Al alloy. Electrochemical properties are poor in snap ring groove region. It is a common type of defect which affects the life span of chopper mast support. When the pitting corrosion occurs on the mast supports, it needs not to be replaced with a new one [70]. It can be restored to real time application using CSAM as

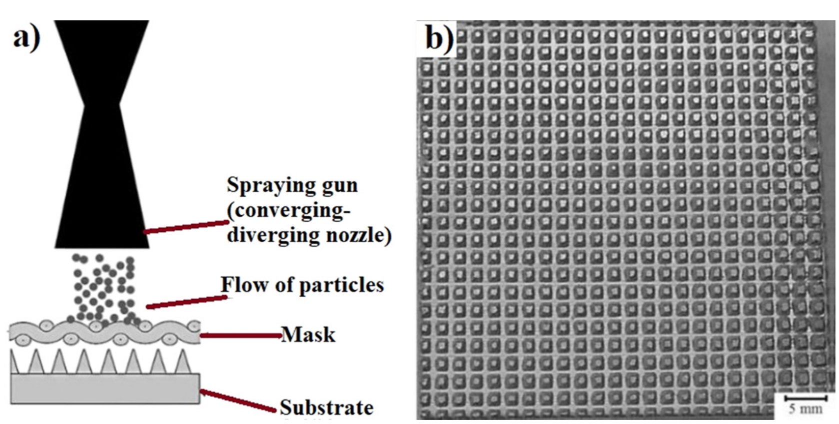

Figure 15: CSAM pyramidal fin arrays heat sink: (a) schematic view of the manufacturing technique and (b) photograph of a CSAM fin array heat sink [57].

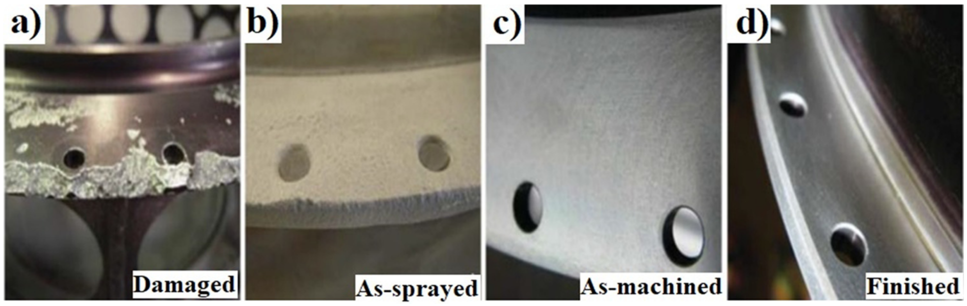

Figure 16: Repairing steps for CSAM [66].

shown in Figure 18a. The thorough restoration process includes removing of pitting corrosion from the defected area and refilling the removed element with CSAM deposition of Al alloy, and to get the required geometry post-machining is carried out. Kilchenstein [68] restored the pitting corroded F18-AMAD gearbox made of Al alloy using CSAM. This increased the life of the gear box and reduced the cost of component replacement owing to the excellent coating properties which helped to meet the real time application as shown in Figure 18b. The same result was obtained by Howe [71] who restored the Al alloy T-700 engine frontal frame by CSAM with excellent corrosion and wear resistance as shown in Figure 18c.

CSAM is effectively implemented to restore the corroded surface of inner bore of Al alloy valve actuator. It does not cause thermal damage to the underlying substrate and offers enhanced capabilities compared to conventional repair techniques as shown in Figure 19a. The CSAM actuator is assembled in the engine section to service in the actual time application after passing through all property tests [72]. Furthermore, in the automobile sector, CSAM restored the Al alloy Caterpillar-3116 and 3126 engines' oil pump housings affected by corrosion as shown in Figure 19b. Lyalyakin *et al.* [73] reported that nearly 30 number of oil pump housings are restored, and these repaired products are passed to real-time service; still no failure reports are reported.

In the aeroplane, the front landing gear steering actuator barrels are fabricated by nickel super alloy because of its better corrosion and wear resistance, but at the time of flight, the steering actuator barrels are affected by corrosion and wear due to humid air and impact of foreign particles while landing. To overcome this problem, the CSAM is introduced to repair the pitting

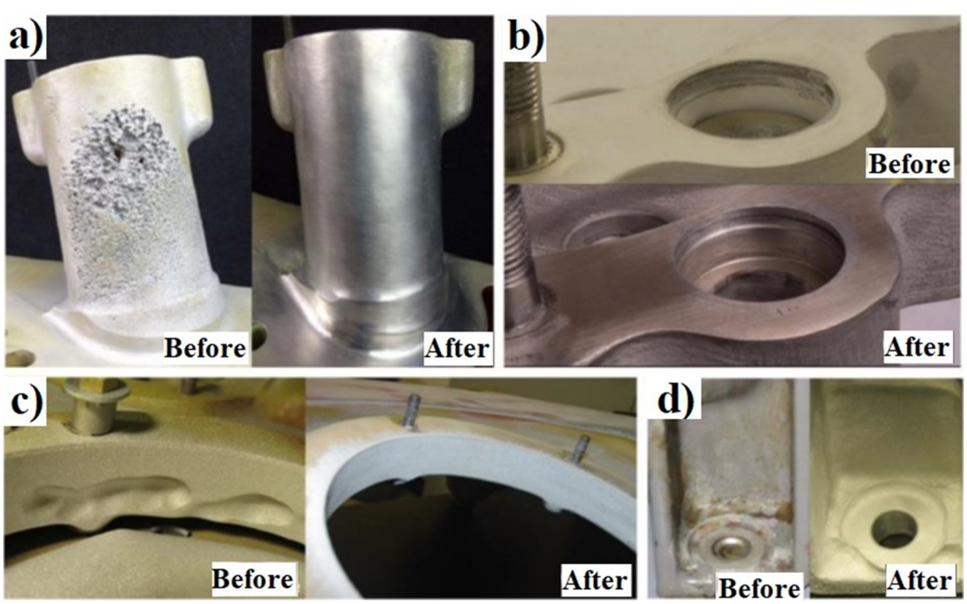

Figure 17: Comparing the deteriorated and restored parts by CSAM: (a) S-92 helicopter gearbox sump; (b) oil tube bores in CH47 helicopter accessory cover; (c) UH-60 helicopter gearbox sump; and (d) UH-60 rotor transmission housing [68].

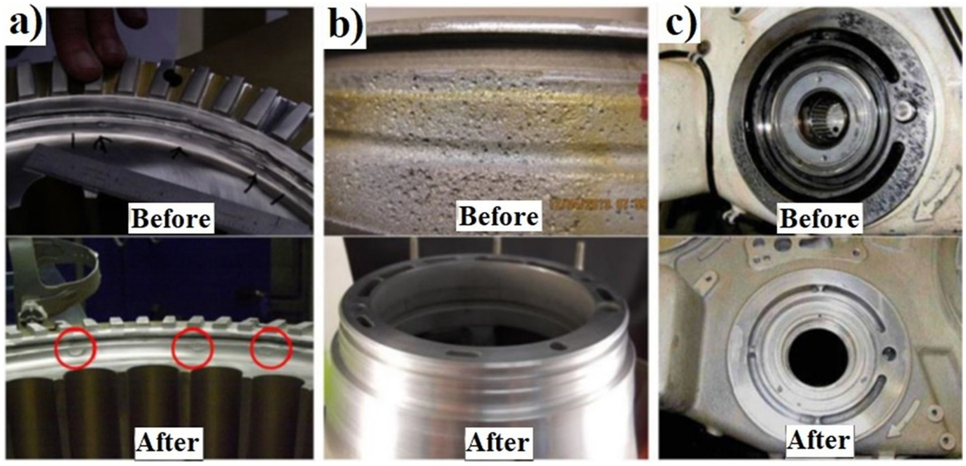

Figure 18: Comparing the deteriorated and restored parts by CSAM: (a) AH-64 helicopter mast support, (b) F18-AMAD gearbox, and (c) front frame of T-700 engine [70].

corrosion and cracks in the B737 front landing gear steering actuator barrels [69]. Figure 20 shows the photograph of repaired B737 nose wheel steering actuator barrel by CSAM. It helps to increase the life span of the component by periodic servicing. In the aviation sector, another type of damage that components can suffer is mechanical defects due to fatigue, unexpected impact, repair or improper service. These kinds of mechanical defects are restored by CSAM. Figure 21 illustrates the CSAM repair technique of a mechanical process *via* damaging the flap transmission tee box assembly of an aeroplane component. The defected parts were restored to the original state after post-machining process. CSAM is even utilised to restore the mechanically defected huge cast automobile components as shown in Figure 22a [74]. It also used to restore the defected mould *via* CSAM as shown in Figure 22b. Then, in a cutting force experiment using bulk material, the restored mould showed the same output and reveals good tribological behaviour than the original parts [75].

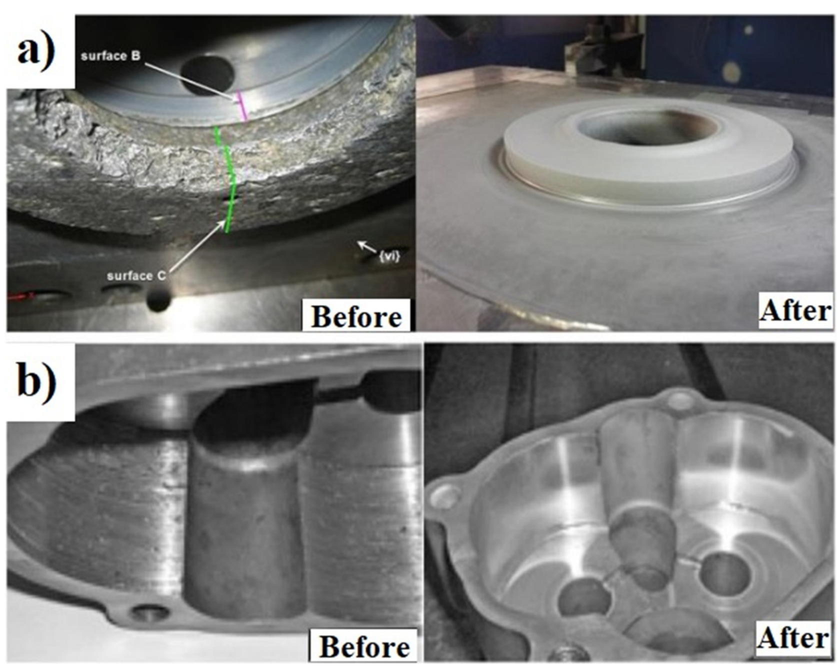

Figure 19: Comparing the deteriorated and restored parts by CSAM: (a) inner bore surface of a navy valve actuator and (b) oil pump housing of Caterpillar engine [72].

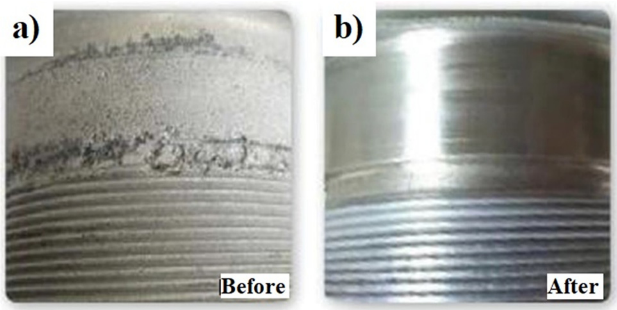

Figure 20: Repaired B737 nose wheel steering actuator barrel by CSAM [69].

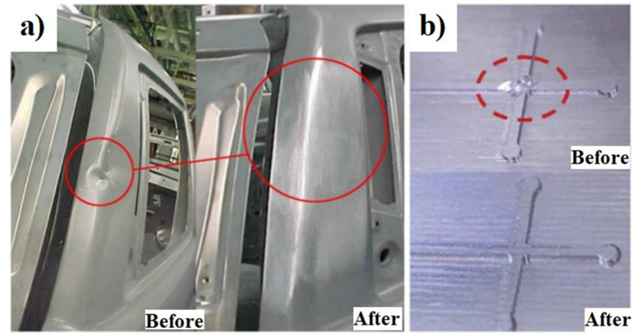

Figure 22: Comparing the deteriorated and restored parts by CSAM: (a) larger cast automotive components [74] and (b) mould [75].

The skin surfaces of boeing and defence aircraft are mainly made of Al alloy material, with Al cladding to avoid electrochemical behaviour. When the aircraft flies continuously, the aeroplanne surface has a greater possibility of affecting erosion as well as wear defect because of high-velocity impact of foreign particles in the atmosphere. The destruction region behaves as a weak spot, promoting to corrosion, and passes into the defensive Al clad film, bottom to the base Al alloy. When the Al alloy is heavily affected by corrosion, the refurbishment and failure expense were huge. As a result, the weakened aluminium cladding must be repaired prior to corrosion spreads to the base substrate [76]. To overcome this problem, various types of thermal spray process are often used to restore the defected aircraft skin when comparing the CSAM with other convectional thermal spray process [77]. The conventional thermal spray process produce coatings with high temperature it affect the thin Al alloy skin surface of the aircraft. CSAM has the ability to restore this destruction without risking damage to the corresponding base material because it works at very low temperature [78]. Figure 23 illustrates the restoration of an Al cladding on an Al alloy plate through CSAM. The affected area tends to be absolutely covered by the Al coating, with no discernible difference from the Al cladding. The result reveals that the restored component with higher hardness and fatigue strength, as well as the corrosion resistance of the component, is enhanced [79].

Fatigue analyses of CSAM-restored Al alloy 2099 plates were performed. Figure 24a reveals that the photograph view of the notch was developed during the machining process on the Al alloy 2099 plate area. Then, the notch was restored through CSAM using the Al alloys 2198 and 7075. On the coated frames, crack growth studies were conducted [80]. Figure 24b indicates the crack behaviour based on the number of cycles for the defected and restored Al alloy frame. The crack size of the restored frame was reduced owing to the higher adhesive behavior of CSAM coating with the base material. This investigation reveals that the CSAM has the potential for enhancing the fatigue behaviour of defected plate. In the aviation sector, the aeroplane fuselages were affected by the multi-site damage (MSD) problem. Almost every type of aeroplane fuselage is manufactured by Al alloy lap joint skin frame. As a result, flaws and damages related to lap joints can develop after long periods of time. The corrosion arises between the interface of the fastener bore and skin. Furthermore, various fastened strip repairs serve as a weak point, allowing cracks to form more frequently. These affect the MSD on the surface of the aeroplane.

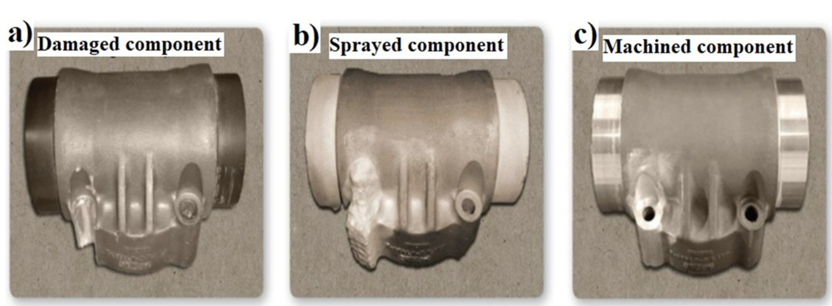

Figure 21: Repairing steps of a mechanical means deteriorated flap transmission tee box housing of an aero-plane by CSAM [69].

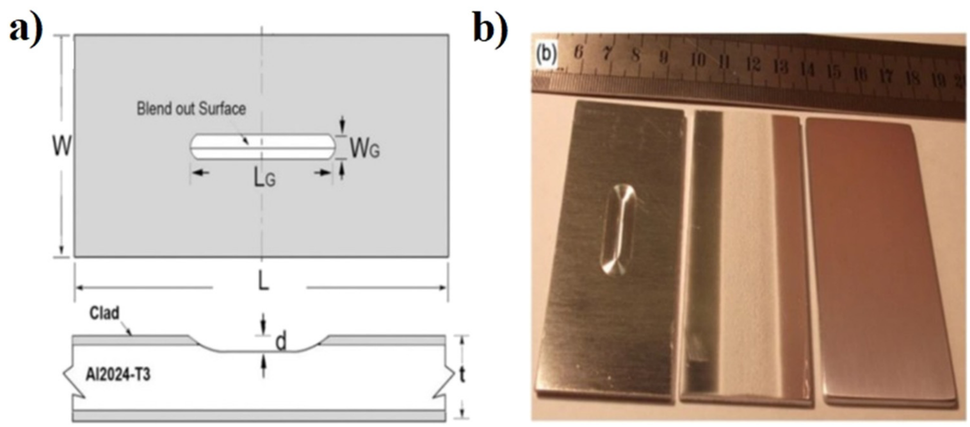

Figure 23: Restoration of Al cladding layer on Al alloy panel with self-machining damages by CSAM: (a) schematic representation of self-machined damage and (b) restoration technique [79].

Using CSAM with quality sealant, the sealant humidity inside the joint produces the interface among the mating frames and fasteners and aeroplane upper surface can be avoided [73]. Figure 25 illustrates the photograph of CSAM coatings on the fuselage fasteners. As a result, the layers of the fasteners are totally closed through the CSAM coatings. As a result, the fatigue strength of the deposit is improved; it leads to improve the fuselage structural integrity of the aircraft. The aeroplane propellers are affected by severe erosion owing to high-velocity stick by foreign object and moisture air in the environment. However, a high amount of blade damage is developed at the time of aeroplane taking off and landing. The current technique used to restore this defect involves removing of the eroded blade up to the point of defect by machining process. To overcome this failure, CSAM is used to deposit the material in the eroded region. Then, the restored blade is fitted to the aircraft which meets the real time application [81]. The restoration technique of Al alloy blades by CSAM is shown in Figure 26.

7.3 CS coatings on biomedical application

Cold gas dynamic sprayed hydroxyapatite (HAP) deposit is commonly used due to its excellent biological properties. Then, the osteoconduction element will produce skelet-developing cells with adjacent skelet tissue [82]. Choudhuri *et al.* [83] investigated the bio-ceramic deposit (HAP and Ti) for various purposes of medical implants and dental to improve bone amalgamation. Several investigations were carried out on HAP deposit $(Ca_{10}(PO_4)_6\ (OH)_2$

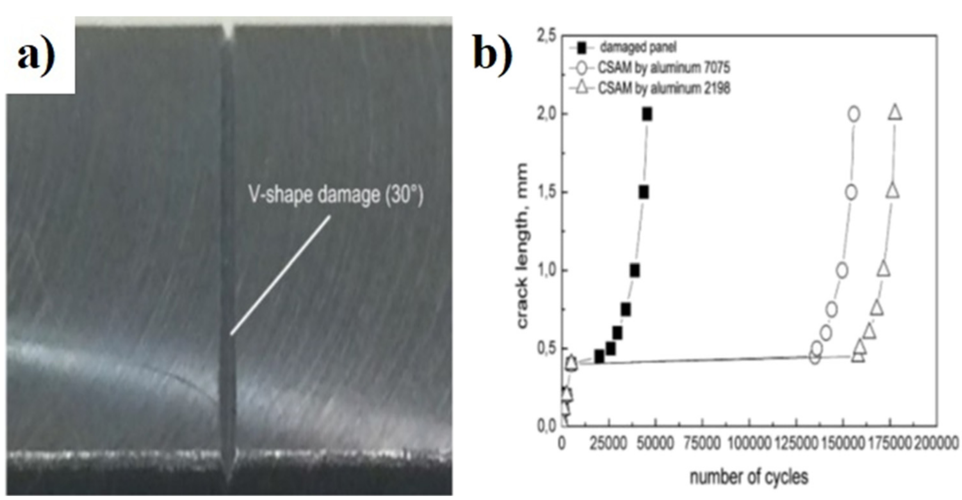

Figure 24: (a) Photograph of machining process made notch on Al alloy 2,099 panel surface and (b) crack length *vs* number of loading cycles [80].

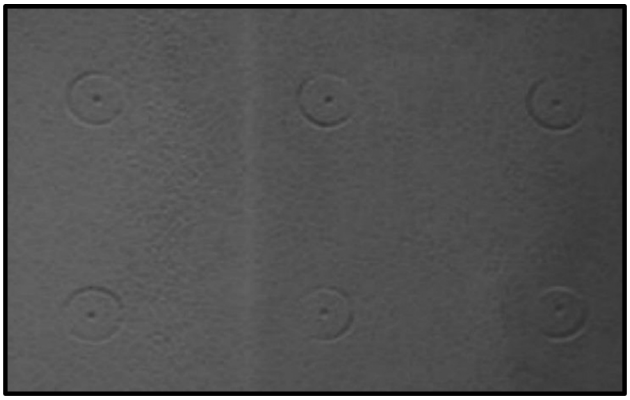

Figure 25: CS coating on simulated fuselage fasteners [76].

for various medical surgical applications since HAP deposit delivers same crystallised and chemicalised properties as that of skelet mineral [84–86]. Cinca *et al.* [87] investigated the coating properties of bioactive HAP, CS deposit on Ti–6Al–4V and Al7075T6 base material. As a result that coated specimen is less expensive for biomedical purpose, yet it is ductile in nature. Al-Mangour *et al.* [88] revealed the effect of heat treatment on hardness properties and microstructure of CS 316L-deposited stainless steel by helium and nitrogen as a process gas. They concluded that heat treatment leads to reduce porosity, enhanced interparticle bonding and ductility.

Dikici *et al.* [89] investigated the electrochemical properties of kinetic-sprayed 316L steel powder on the Al5052 alloy base substrate. Based on the investigation, coated specimen has excellent adhesive properties. To further enhance the hardness and electrochemical characteristics, heat treatment techniques are adopted. Gardon *et al.* examined the Ti coatings on polyetheretherketone base material. According to the results, no polymer deterioration was found at the time of coating. It even discovered that titanium with biocompatible polymer implants may be effectively coated. It results in homogenous, dense and high bonding deposit [90]. El-Eskandrany and Al-Azmi [91] investigated the Cu50Ti20Ni30 coatings on SUS 304 base material to assess its antibacterial characteristics for food and medical industries. The findings of this study revealed that bacterial prevention is efficient. Biofilm formation developed after coatings offers viable options for managing microbial growth.

7.4 CS coatings on antimicrobial application

In various food preservation sectors and hospitals, the growth of bacteria on the surface happens owing to the possibility of increased bacterial infection [92]. In the hospital floors, comprising nurse station, patient rooms and kitchens were contaminated by bacteria [93–95]. Champagne and Helfritch [96] examined the antimicrobial characteristis of Cu and its alloys' opposition to variety of microorganisms that cause health issue in health-care and food sectors. Even so, a preferred technique of copper surface coatings in these applications has not yet been found. Champagne and Helfritch examined the antimicrobial effectiveness of various Cu surfaces. The various methods of thermal spray technique were used to coat Cu on the substrate. Compared with other spray techniques, CS was found to be more efficient. It is resulted in 99% microbial degradation after a 2 h. Da Silva *et al.* [97] studied the antibacterial and electrochemical behaviours of cold gas dynamic-sprayed copper deposit on carbon steel alloy. The investigation reveals that no electrochemical behaviour was detected between the base material and deposit at the completion of 1,100 h of immersion in Cl solution.

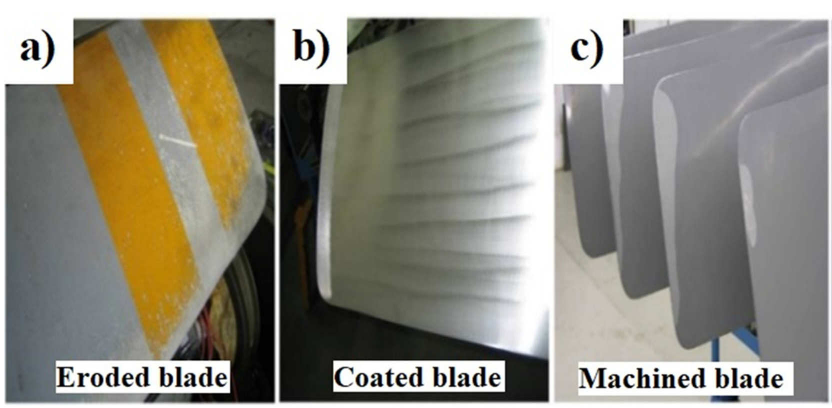

Figure 26: Restoration technique of Al alloy blades by CSA [81].

7.5 CS coatings on electrical application

The CS coatings have a superior electrical and thermal conductivities; they are widely used to improve the electrical properties of any alloy metal and are best equipped for electrical application. CS deposit is primarily used in electrical industries since ceramic coatings are commonly used as insulating element. Tazegul *et al.* [98] examined the copper and Al_2Cu coatings on copper substrate for electric tonics applications. The amount of Al_2Cu particle varies from 0 to 15% by volume. According to this study, the composite deposit with the presence of 5 and 10% volume of Al_2Cu particle reveals the better tribological behaviour and electrical conductivity to the coatings due to the high dense coating. Wang *et al.* [99] investigated the impact of heat-treated Ag-SnO_2 coatings on copper substrate for voltage switching devices. The experiment reveals that eroded region of Ag-SnO_2 deposit is steady and stable at 850°C. Furthermore, the contact resistance of the deposit is reduced and stabilised in 3.4 mΩ. They revealed that heat treatment is the most important factor that impacts on contact resistance. Li *et al.* [45] examined the copper coatings on copper substrate with the thickness of 7 mm to improve the electrical resistivity of the deposit. The experiment reveals that coating posses the excellent cohesive and adhesive behaviours, resulting in the enhancement in electrical resistivity contract to uncoated copper substrate.

8 Future trends in CSAM

Although the idea of cold spraying is for 40 years (it was found in Russia in the 1980s), it has only just started to gain acceptance in this country as a practical substitute for the more conventional thermal spray coating. In contrast, the coating method of thermal spraying has been in use for the past century. Some information on current advancements and potential uses for CS is provided in the sections given below.

8.1 New design techniques

New design and production options are opened up by combining CS with conventional subtractive manufacturing techniques:

- Finishing the inside surface of channels that have been machined. These coatings might be added to offer anticorrosion or other protective characteristics, as well as lower drag coefficients.
- Adding minute, intricate elements to substantial machined components.
- Making a component out of a lightweight material and applying desirable or conductive surface coatings.
- Manufacturing the same kind of lightweight component but adding materials to improve structural integrity while preserving weight-savings.

8.2 Post-processing of CS coatings

The completion of conventionally made components frequently involves heat treatment and other post-fabrication procedures. There is growing investigation into post-deposition heat treatments, even though CS coatings are normally left as-deposited. With the use of brief induction heating periods, which restrict the heat input and the depth of heating, for instance, there have been favourable test results lowering the porosity of the coatings [100].

8.3 Increased use for repairs

As manufacturers explore for methods to minimise costs, specialised repairs are an increasingly significant service. To swiftly restore damaged components to their original dimensional tolerances, CS coating can be used. These same coatings may also have improved performance qualities like anti-corrosion defence that will further increase the lifespan of the restored component. For enhanced wear resistance without sacrificing corrosion resistance, hard, galvanically inert phases like ceramic particles can be used [101]. The choices to repair massive components already *in situ* will also become more attractive as progress is made in the development of portable CS systems. By choosing this method, there will be more options for fixing major things rather than having to wait for them to be shipped off-site or spending more money to replace them entirely. A rising number of businesses will think about incorporating CS technology into their manufacturing and repair capabilities as awareness of its adaptability, rapid setup and improved economic costs rises [102].

9 Conclusions

1. CS process is a thermal spray technology in which coating (10–40 μm) is formed in the solid state by the

impingement of power particles with supersonic velocity (200–1,200 m/s^2) on coupon employing compressed gas jet, below the melting point of coating powder. It is commonly referred as cold gas dynamic spray, high velocity powder deposition, kinetic spray and kinetic energy metallisation process.
2. Using CSP, various engineering materials (metals, polymers and ceramics) and its composites can be deposited. It is unique and promising approach for obtaining surface coating and offers various technological benefits over thermal spray as kinetic energy is employed for deposition rather than thermal energy. This offers great benefits in AM to develop a component denser, low oxide coating free of tensile residual stresses and undesired chemical reactions compared to conventional AM and coating techniques.
3. CSAM is the powerful and emerging technique in the field of AM to develop engineering components with improved performance covering a broad range of functionalities of surface, subsurface and interfaces.
4. Cold spraying has demonstrated significant application in AM, repairing and refurbishing of industrial parts. It is attributed to its capability to restore the actual feedstock powder characteristic and minimise the impact on the base materials. There are few flaws in this technique; however, extensive research work is going on in CSAM and repairing of components to meet the real-time applications.
5. CSAM has successfully manufactured or restored a wide range of industrial parts in recent years. The experimental results reported that CSAM components have excellent mechanical characteristics to be utilised in a broad range of applications.
6. Furthermore, it is utilised in various sectors and showed the better result in various applications, such as biomedical, antimicrobial and electrical. As a result, the CS methord is a diverse and effective method for tackling a wide range of industrial issues.

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References

[1] Assadi H, Kreye H, Gärtner F, Klassen TJ. Cold spraying–A materials perspective. Acta Mater. 2016;116:382–407.
[2] Raoelison RN, Xie Y, Sapanathan T, Planche MP, Kromer R, Costil S, et al. Cold gas dynamic spray technology: A comprehensive review of processing conditions for various technological developments till to date. Addit Manuf. 2018;19:134–59.
[3] Rokni MR, Nutt SR, Widener CA, Champagne VK, Hrabe RH. Review of relationship between particle deformation, coating microstructure, and properties in high-pressure cold spray. J Therm Spray Technol. 2017;26(6):1308–55.
[4] Hassani-Gangaraj M, Veysset D, Nelson KA, Schuh CA. In-situ observations of single micro-particle impact bonding. Scr Mater. 2018;145:9–13.
[5] Meng F, Yue S, Song J. Quantitative prediction of critical velocity and deposition efficiency in cold-spray: A finite-element study. Scr Mater. 2017;107:83–7.
[6] Assadi H, Gärtner F, Stoltenhoff T, Kreye H. Bonding mechanism in cold gas spraying. Acta Mater. 2003;51(15):4379–94.
[7] Grujicic M, Saylor JR, Beasley DE, DeRosset WS, Helfritch D. Computational analysis of the interfacial bonding between feed-powder particles and the substrate in the cold-gas dynamic-spray process. Appl Surf Sci. 2003;219(3–4):211–27.
[8] Raletz F, Vardelle M, Ezo'o G. Critical particle velocity under cold spray conditions. Surf Coat Technol. 2006;201(5):1942–7.
[9] Assadi H, Schmidt T, Richter H, Kliemann JO, Binder K, Gärtner F, et al. On parameter selection in cold spraying. J Therm Spray Technol. 2011;20(6):1161–76.
[10] Schmidt T, Gärtner F, Assadi H, Kreye H. Development of a generalized parameter window for cold spray deposition. Acta Mater. 2006;54(3):729–42.
[11] Bae G, Kumar S, Yoon S, Kang K, Na H, Kim HJ, et al. Bonding features and associated mechanisms in kinetic sprayed titanium coatings. Acta Mater. 2009;57(19):5654–66.
[12] Yin S, Wang X, Suo X, Liao H, Guo Z, Li W, et al. Deposition behavior of thermally softened copper particles in cold spraying. Acta Mater. 2013;61(14):5105–18.
[13] Yin S, Meyer M, Li W, Liao H, Lupoi R. Gas flow, particle acceleration, and heat transfer in cold spray: a review. J Therm Spray Technol. 2016;25(5):874–96.
[14] Kashirin A, Klyuev O, Buzdygar T, Shkodkin A. Modern applications of the low pressure cold spray. Thermal Spray

2011: Proceedings of the International Thermal Spray Conference; 2011 Sep 27-29; Hamburg, Germany. ASM International; 2011. p. 1–7.
[15] Alkhimov AP, Boiko VM, Papyrin AN, Soloukhin RI. Diagnostics of supersonic two-phase streams from scattered laser radiation. J Appl Mech Tech Phys. 1978;19(2):173–80.
[16] Alkhimov AP, Klinkov SV, Kosarev VF, Papyrin AN. Gas-dynamic spraying study of a plane supersonic two-phase jet. J Appl Mech Techn Phys. 1997;38(2):324–30.
[17] Alkhimov AP, Kosarev VF, Klinkov SV. The features of cold spray nozzle design. J Therm Spray Technol. 2001;10(2):375–81.
[18] Papyrin A. The development of the cold spray process. In: Champane VK, editor. The cold spray materials deposition process. Cambridge: Woodhead Publishing; 2007. p. 11–42.
[19] Champagne VK, Helfritch D, Leyman P, Grendahl S, Klotz B. Interface material mixing formed by the deposition of copper on aluminum by means of the cold spray process. J Therm Spray Technol. 2005;14(3):330–4.
[20] Grujicic M, Zhao CL, DeRosset WS, Helfritch D. Adiabatic shear instability based mechanism for particles/substrate bonding in the cold-gas dynamic-spray process. Mater Des. 2004;25(8):681–8.
[21] Karthikeyan J. Evolution of cold spray technology. Adv Mater Process. 2006;164(5):66–8.
[22] Dykhuizen RC, Smith MF. Gas dynamic principles of cold spray. J Therm Spray Technol. 1998;7(2):205–12.
[23] Gilmore DL, Dykhuizen RC, Neiser RA, Smith MF, Roemer TJ. Particle velocity and deposition efficiency in the cold spray process. J Therm Spray Technol. 1999;8(4):576–82.
[24] VanSteenkiste TH, Elmoursi A, Gorkiewicz D, Gillispie B. Fracture study of aluminum composite coatings produced by the kinetic spray method. Surf Coat Technol. 2005;194(1):103–10.
[25] Zhao ZB, Gillispie BA, Smith JR. Coating deposition by the kinetic spray process. Surf Coat Technol. 2006;200(16–17):4746–54.
[26] Dykhuizen RC, Smith MF, Gilmore DL, Neiser RA, Jiang X, Sampath S. Impact of high velocity cold spray particles. J Therm Spray Technol. 1999;8(4):559–64.
[27] Van Steenkiste T, Smith JR. Evaluation of coatings produced *via* kinetic and cold spray processes. J Therm Spray Technol. 2004;13(2):274–82.
[28] Van Steenkiste T. The role of particle temperature and velocity in cold spray coating formation. In: Champane VK, editor. The cold spray materials deposition process. Cambridge: Woodhead Publishing; 2007. p. 127–47.
[29] Davis JR, editor. Handbook of thermal spray technology. Russel Township (OH), USA: ASM International; 2004.
[30] Karthikeyan J. Cold spray technology: the cold spray process has the potential to reduce costs and improve quality in both coatings and freeform fabrication of near-net-shape parts. Adv Mater Proc. 2005;163(3):33–6.
[31] Lima RS, Karthikeyan J, Kay CM, Lindemann J, Berndt CC. Microstructural characteristics of cold-sprayed nanostructured WC–Co coatings. Thin Solid Films. 2002;416(1–2):129–35.
[32] Haynes J, Karthikeyan J. Cold spray copper application for upper stage rocket engine design. Thermal Spray 2003: Advancing Science Applying Technology; 2003 May 5–8; Orlando (FL), USA. ASM International; 2003. p. 79–84.
[33] Borchers C, Gärtner F, Stoltenhoff T, Assadi H, Kreye H. Microstructural and macroscopic properties of cold sprayed copper coatings. J Appl Phys. 2003;93(12):10064–70.
[34] Karthikeyan J. The advantages and disadvantages of the cold spray coating process. In: Champane VK, editor. The cold spray materials deposition process. Cambridge: Woodhead Publishing; 2007. p. 62–71.
[35] Haynes J, Pandey A, Karthikeyan J, Kay A. Cold sprayed discontinuously reinforced aluminum (DRA). In: Marple BR, Hyland MM, Lau Y-C, Lima RS, Voyer J, editors. Thermal Spray 2006: Proceedings of the International Thermal Spray Conference; 2006 May 15–18; Seattle (WA), USA. ASM International; 2006.
[36] Ajdelsztajn L, Lavernia EJ, Jodoin B, Richer P, Sansoucy E. Cold gas dynamic spraying of iron-base amorphous alloy. J Therm Spray Technol. 2006;15(4):495–500.
[37] Kim HJ, Lee CH, Hwang SY. Superhard nano WC–12% Co coating by cold spray deposition. Mater Sci Eng A. 2005;391(1–2):243–8.
[38] McPherson R. Formation of metastable phases in flame-and plasma-prepared alumina. J Mater Sci. 1973;8(6):851–8.
[39] De Villiers Lovelock HL. Powder/processing/structure relationships in WC-Co thermal spray coatings: a review of the published literature. J Therm Spray Technol. 1998;7(3):357–73.
[40] Calla E, McCartney D, Shipway P. Deposition of copper by cold gas dynamic spraying: an investigation of dependence of microstructure and properties of the deposits on the spraying conditions. In: von Hofe D, editor. Thermal Spray 2004: Advances in Technology and Applications; 2004 May 10–12; Osaka, Japan. ASM International; 2004. p. 382–7.
[41] Xiong T, Bao Z, Li T, Li Z. Study on cold-sprayed copper coating's properties and optimizing parameters for the spraying process. Thermal spray 2005: Exploring its surface potential; 2005 May 2–4; Basel Switzerland. ASM International; 2005. p. 2–5.
[42] Morgan R, Fox P, Pattison J, Sutcliffe C, O'Neill W. Analysis of cold gas dynamically sprayed aluminium deposits. Mater Lett. 2004;58(7–8):1317–20.
[43] Decker MK, Neiser RA, Gilmore D, Tran HD. Microstructure and properties of cold spray nickel. Thermal Spray 2001: New Surfaces for a New Millennium; 2001 May 28–30; Singapore. ASM International; 2001. p. 28–30.
[44] Raletz F, Ezo'o G, Vardelle M, Ducos M. Characterization of Cold-Sprayed Nickel-Base Coatings. In: von Hofe D, editor. Thermal Spray 2004: Advances in Technology and Applications; 2004 May 10–12; Osaka, Japan. ASM International; 2004. p. 344–9.
[45] Li WY, Li CJ, Yang GJ. Effect of impact-induced melting on interface microstructure and bonding of cold-sprayed zinc coating. Appl Surf Sci. 2010;257(5):1516–23.
[46] Morelli DT, Elmoursi A, Vansteenksite T, Gorkiewicz D, Gillispie B. Kinetic spray of aluminum matrix composites for thermal management applications. In: Marple BR, Moreau C, editors. Thermal Spray 2003: Advancing the Science and Applying the Technology; 2003 May 3–5; Orlando (FL), USA. ASM International; 2003. p. 85–90.

[47] Yang GJ, Li CJ, Han F, Li WY, Ohmori A. Low temperature deposition and characterization of TiO_2 photocatalytic film through cold spray. Appl Surf Sci. 2008;254(13):3979–82.
[48] Abreeza M, Yuji I, Kazuhiro O. Computational simulation for cold sprayed deposition. Elyt Laboratory Workshop. Sendai, Japan: 2011.
[49] Barnett B, Trexler M, Champagne V. Cold sprayed refractory metals for chrome reduction in gun barrel liners. Int J Refract Met Hard Mater. 2015;53:139–43.
[50] Choi HJ, Lee M, Lee JY. Application of a cold spray technique to the fabrication of a copper canister for the geological disposal of CANDU spent fuels. Nucl Eng Des. 2010;240(10):2714–20.
[51] Richter P. New value chain for advanced coatings by using cold spray. Basel, Switzerland: Industrial Technol; 2014.
[52] May C, Marx S, Paul A. Selected R&D results and industrial applications. CSAT Workshop; Worcester, USA: 2013.
[53] Sova A, Okunkova A, Grigoriev S, Smurov I. Velocity of the particles accelerated by a cold spray micronozzle: experimental measurements and numerical simulation. J Therm Spray Technol. 2013;22(1):75–80.
[54] Kumar S, Chavan NM. Cold spray coating technology: activities at ARCI. Briefing, International advanced research centre for powder metallurgy and new materials (ARCI) Hyderabad; 2011.
[55] Pattison J, Celotto S, Morgan R, Bray M, O'neill W. Cold gas dynamic manufacturing: A non-thermal approach to freeform fabrication. Int J Mach Tools Manuf. 2007;47(3–4):627–34.
[56] Goldbaum D, Shockley JM, Chromik RR, Rezaeian A, Yue S, Legoux JG, et al. The effect of deposition conditions on adhesion strength of Ti and Ti6Al4V cold spray splats. J Therm Spray Technol. 2012;21(2):288–303.
[57] Cormier Y, Dupuis P, Farjam A, Corbeil A, Jodoin B. Additive manufacturing of pyramidal pin fins: Height and fin density effects under forced convection. Int J Heat Mass Transf. 2014;75:235–44.
[58] Cormier Y, Dupuis P, Jodoin B, Corbeil A. Mechanical properties of cold gas dynamic-sprayed near-net-shaped fin arrays. J Therm Spray Technol. 2015;24(3):476–88.
[59] Cormier Y, Dupuis P, Jodoin B, Corbeil A. Pyramidal fin arrays performance using streamwise anisotropic materials by cold spray additive manufacturing. J Therm Spray Technol. 2016;25(1):170–82.
[60] Dupuis P, Cormier Y, Fenech M, Jodoin B. Heat transfer and flow structure characterization for pin fins produced by cold spray additive manufacturing. Int J Heat Mass Transf. 2016;98:650–61.
[61] Farjam A, Cormier Y, Dupuis P, Jodoin B, Corbeil A. Influence of alumina addition to aluminum fins for compact heat exchangers produced by cold spray additive manufacturing. J Therm Spray Technol. 2015;24(7):1256–68.
[62] Kotoban D, Grigoriev S, Okunkova A, Sova A. Influence of a shape of single track on deposition efficiency of 316L stainless steel powder in cold spray. Surf Coat Technol. 2017;309:951–8.
[63] Cormier Y, Dupuis P, Jodoin B, Corbeil A. Net shape fins for compact heat exchanger produced by cold spray. J Therm Spray Technol. 2013;22(7):1210–21.
[64] Yin S, Xie Y, Suo X, Liao H, Wang X. Interfacial bonding features of Ni coating on Al substrate with different surface pretreatments in cold spray. Mater Lett. 2015;138:143–7.
[65] Nastic A, Vijay M, Tieu A, Rahmati S, Jodoin B. Experimental and numerical study of the influence of substrate surface preparation on adhesion mechanisms of aluminum cold spray coatings on 300M steel substrates. J Therm Spray Technol. 2017;26(7):1461–83.
[66] Sun W, Tan AW, Khun NW, Marinescu I, Liu E. Effect of substrate surface condition on fatigue behavior of cold sprayed Ti6Al4V coatings. Surf Coat Technol. 2017;320:452–7.
[67] Howe C. Cold spray repair of the CH-47 accessory cover. CSAT Workshop; Worcester, USA: 2014.
[68] Kilchenstein G. Cold spray technologies used for repair. JTEG Monthly Teleconference; 2016 Nov. p. 9. http://jteg.ncms.org/wp-content/gallery/ColdSpray/ColdSpray_SlideDeck.pdf.
[69] Schell J. Cold spray aerospace applications. CSAT Workshop; Worcester, USA: 2016.
[70] Leyman PF, Champagne VK. Cold spray process development for the reclamation of the apache helicopter mast support. Army research lab aberdeen proving ground MD weapons and materials research directorate; 2009 Aug 1.
[71] Howe C. Cold spray qualification of T700 engine front frame. CSAT Workshop; Worcester, USA: 2015.
[72] Widener CA, Carter MJ, Ozdemir OC, Hrabe RH, Hoiland B, Stamey TE, et al. Application of high-pressure cold spray for an internal bore repair of a navy valve actuator. J Therm Spray Technol. 2016;25(1):193–201.
[73] Lyalyakin VP, Kostukov AY, Denisov VA. Special features of reconditioning the housing of a Caterpillar diesel oil pump by gas-dynamic spraying. Weld Inter. 2016;30(1):68–70.
[74] Maev RG, Strumban E, Leshchinskiy V, Dzhurinskiy D. Repair applications of the LPCS process. CSAT Workshop; Worcester, USA: 2014.
[75] Lee JC, Kang HJ, Chu WS, Ahn SH. Repair of damaged mold surface by cold-spray method. CIRP Ann. 2007;56(1):577–80.
[76] Jones R, Molent L, Barter S, Matthews N, Tamboli D. Supersonic particle deposition as a means for enhancing the structural integrity of aircraft structures. Int J Fatigue. 2014;68:260–8.
[77] Matthews N, Jones R, Sih GC. Application of supersonic particle deposition to enhance the structural integrity of aircraft structures. Sci China: Phys Mech Astron. 2014;57(1):12–8.
[78] Jones R, Matthews N, Rodopoulos CA, Cairns K, Pitt S. On the use of supersonic particle deposition to restore the structural integrity of damaged aircraft structures. Int J Fatigue. 2011;33(9):1257–67.
[79] Yandouzi M, Gaydos S, Guo D, Ghelichi R, Jodoin B. Aircraft skin restoration and evaluation. J Therm Spray Technol. 2014;23(8):1281–90.
[80] Cavaliere P, Silvello A. Crack repair in aerospace aluminum alloy panels by cold spray. J Therm Spray Technol. 2017;26(4):661–70.
[81] Stoltenhoff T, Zimmermann F. LOXPlate® coatings for aluminum aerospace components exposed to high dynamic stresses. Ratingen: Praxair Surface Technologies GmbH; 2012.

[82] Gadow R, Killinger A, Stiegler N. Hydroxyapatite coatings for biomedical applications deposited by different thermal spray techniques. Surf Coat Technol. 2010;205(4):1157–64.
[83] Choudhuri A, Mohanty PS, Karthikeyan J. Bio-ceramic composite coatings by cold spray technology. In: Marple BR, Hyland MM, Lau Y-C, Li C-J, Lima RS, editors. Thermal Spray 2009: Expanding Thermal Spray Performance to New Markets and Applications; 2009 May 4–7; Las Vegas (NV), USA. ASM International; 2009. p. 391–6.
[84] Tsui YC, Doyle C, Clyne TW. Plasma sprayed hydroxyapatite coatings on titanium substrates Part 1: Mechanical properties and residual stress levels. Biomater. 1998;19(22):2015–29.
[85] Stephenson PK, Freeman MA, Revell PA, Germain J, Tuke M, Pirie CJ. The effect of hydroxyapatite coating on ingrowth of bone into cavities in an implant. J Arthroplasty. 1991;6(1):51–8.
[86] Sun L, Berndt CC, Gross KA, Kucuk A. Material fundamentals and clinical performance of plasma-sprayed hydroxyapatite coatings: A review. J Biomed Mater Res An Off J Soc Biomater Jpn Soc Biomater Aust Soc Biomater Korean Soc Biomater. 2001;58(5):570–92.
[87] Cinca N, Vilardell AM, Dosta S, Concustell A, Garcia Cano I, Guilemany JM, et al. A new alternative for obtaining nanocrystalline bioactive coatings: study of hydroxyapatite deposition mechanisms by cold gas spraying. J Am Ceram Soci. 2016 Apr;99(4):1420–8.
[88] AL-Mangour B, Vo P, Mongrain R, Irissou E, Yue S. Effect of heat treatment on the microstructure and mechanical properties of stainless steel 316L coatings produced by cold spray for biomedical applications. J Therm Spray Technol. 2014;23(4):641–52.
[89] Dikici B, Ozdemir I, Topuz M. Cold spray deposition of SS316L powders on Al5052 substrates and their potential using for Biomedical applications. Int J Chem Mol Nucls Mater Metall Eng. 2016;10(4):483–7.
[90] Gardon M, Latorre A, Torrell M, Dosta S, Fernández J, Guilemany JM. Cold gas spray titanium coatings onto a biocompatible polymer. Mater Lett. 2013;106:97–9.
[91] El-Eskandrany MS, Al-Azmi A. Potential applications of cold sprayed Cu50Ti20Ni30 metallic glassy alloy powders for antibacterial protective coating in medical and food sectors. J Mech Behav Biomed Mater. 2016;56:183–94.
[92] Page K, Wilson M, Parkin IP. Antimicrobial surfaces and their potential in reducing the role of the inanimate environment in the incidence of hospital-acquired infections. J Mater Chem. 2009;19(23):3819–31.
[93] Rutala WA, Katz EB, Sherertz R, Sarubbi FA Jr. Environmental study of a methicillin-resistant Staphylococcus aureus epidemic in a burn unit. J Clin Microbio. 1983;18(3):683–8.
[94] White LF, Dancer SJ, Robertson C. A microbiological evaluation of hospital cleaning methods. Int J Env Health Res. 2007;17(4):285–95.
[95] Aycicek H, Oguz U, Karci K. Comparison of results of ATP bioluminescence and traditional hygiene swabbing methods for the determination of surface cleanliness at a hospital kitchen. Int J Hyg Env Health. 2006;209(2):203–6.
[96] Champagne VK, Helfritch DJ. A demonstration of the antimicrobial effectiveness of various copper surfaces. J Biol Eng. 2013;7(1):1–7.
[97] Da Silva FS, Cinca N, Dosta S, Cano IG, Couto M, Guilemany JM, et al. Corrosion behavior of WC-Co coatings deposited by cold gas spray onto AA 7075-T6. Corros Sci. 2018;136:231–43.
[98] Tazegul O, Dylmishi V, Cimenoglu H. Copper matrix composite coatings produced by cold spraying process for electrical applications. Arch Civ Mech Eng. 2016;16(3):344–50.
[99] Wang J, Wang C, Kang Y. The effects of annealing treatment on microstructure and contact resistance properties of cold sprayed Ag-SnO_2 coating. J Alloy Comp. 2017;714:698–703.
[100] Ashokkumar M, Duraisamy T, Chidambaramseshadri R, Pattabi T, Ranganathan S, Kaliyamoorthy M, et al. Enhancing the corrosion resistance of low pressure cold sprayed metal matrix composite coatings on AZ31B Mg alloy through friction stir processing. Coatings. 2022;12(2):135.
[101] Ashokkumar M, Duraisamy T, Sampathkumar D, Ranganathan S, Balachandran G, Kaliyamoorthy M, et al. Optimization of cold spray process inputs to minimize porosity and maximize hardness of metal matrix composite coatings on AZ31B magnesium alloy. J Nanomater. 2022:1–17.
[102] Rajendran PR, Duraisamy T, Chidambaram Seshadri R, Mohankumar A, Ranganathan S, Balachandran G, et al. Optimisation of HVOF spray process parameters to achieve minimum porosity and maximum hardness in WC-10Ni-5Cr coatings. Coatings. 2022;12(3):339.