MĀPAN-Journal of Metrology Society of India (December 2022) 37(4):859–879
https://doi.org/10.1007/s12647-022-00597-8

REVIEW ARTICLE

The Study of Assessment Parameters and Performance Measurement of Cold Spray Technique: A Futuristic Approach Towards Additive Manufacturing

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Received: 20 May 2022 / Accepted: 12 August 2022 / Published online: 6 October 2022

Abstract: In recent years, high-performance additive manufacturing (AM) is being extensively investigated by the virtue of its unique benefits over traditional manufacturing processes. Complex components of Ti, Fe, Ni alloys can be manufactured with ease; however, other nonferrous alloys such as Al alloys, Mg alloys, and Cu alloys have the melting tendency during processing by laser, electron beam, or arc, hence not appropriate to be manufactured using additive manufacturing. The most useful and powerful tool recognized in AM in the last decade is the cold spray process. This paper puts forth a review of recent research innovations and the concept to build new materials in the field of AM technology. The author has highlighted the important properties including retention of original feedstock particles and oxide-free surface deposits during the entire coating process. The present research work focuses on the basic principle, bonding mechanism and impact phenomenon, and effect of nozzle parameters on mechanical properties of deposits associated with cold spray additive manufacturing. Furthermore, the concept to develop well-bonded coated deposits and its metallurgical behavior have also been studied. Various aspects of repair and maintenance against corrosion and wear along with strength and geometry restoration have also been highlighted in this paper.

Keywords: Cold spray; Additive manufacturing; Composite coating; Feedstock material; Dimensional restoration; High velocity; Supersonic particle deposition

Abbreviations

CS	Cold spray
AM	Additive manufacturing
CSAM	Cold spray additive manufacturing
SPD	Supersonic particle deposition
SLM	Selective laser melting
EBM	Electron beam melting
LMD	Laser metal deposition
SOD	Standoff distance
HPCS	High-pressure cold spray
LPCS	Low-pressure cold spray
CMC	Ceramic matrix composites
MMC	Metal matrix composites
ASI	Adiabatic shear instability

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1. Introduction

Surface coatings play a vital role in improving the physical, chemical, and morphological properties of the material. These properties may include wear and abrasion resistance, corrosion, conductivity, etc. Since the substrate is the base material on which coating is applied, hence in context to surface properties, a substrate must be coated. Substrate material includes metals, plastics, and ceramics. The coating on a substrate cannot be only seen as an expensive tool. They can be inexpensive too. The substrate materials must be multifunctional so that they can be laminated with a high-performance coating. There are numerous methods to apply coatings on a substrate; a few of them include physical and chemical vapor deposition, electrochemical and supersonic particle deposition, thermal spray, sputtering, submersion, etc., Conventional thermal spray processes are not suited for the low-temperature sensitive material where a coating is required with an accuracy of few millimeters. A new class of thermal spray processes called cold spray or supersonic particle deposition (SPD) has been developed to overcome the limitations of these coating methods. Deposition of the particle with supersonic velocity commonly known as the SPD technique finds its application where subsequent layers of spurted powder particles form a coated deposit onto the substrate. SPD is an emergent process that is associated with a supersonic flow including gas and solid particles. Nowadays cold spray as a coating technology has been extensively used in various sectors including automobile, aerospace, energy, medical, marine, etc., In the last few years, the cold spray technique has prioritized itself and almost replaced the method and mechanism of additive manufacturing. The evolution of this technique leads to the evolution of the bright phase on traditional AM technologies and hence widens the area of applications. Materials like Ti, Fe, and Ni alloys are widely used to fabricate complex components through additive manufacturing. On the other hand, due to fusion, it is not suitable for nonferrous alloys like Al, Mg, or Cu alloys [1, 2]. Hence, an alternative AM technology is particularly necessary. A group of researchers has studied and investigated the relationship between the flows of two phases of an immersed body (particle). The key findings from their research were that the coatings from solid particles can be obtained even at room stagnation temperature [3]. The erosion behavior of the coated substrate was also studied. They concluded that erosion on the substrate can be noticed when spray particles reach beyond the critical velocity. During the process, the particle gets adhered to the substrate surface when the spray material reached critical velocity [4, 5]. SPD can be also known by different names such as cold spray, cold gas spray, micro-cold spray, cold gas dynamic spray, kinetic spray, or metal powder application [6]. Both thermal spray and CS processes are widely used for coating formation. However, the very common difference between the two is that the former utilizes both thermal and kinetic energies, while the latter uses only high kinetic energy for diffusion and bonding of powder particles. Apart from these, both the coating processes differ in broad areas of process parameters, coating materials, and surface coating properties. In recent years, the SPD technique has been promoted as a unique characteristic of multi-component coatings [7]. At present, this technique has been widely used to develop a surface coating over the metal substrate. Since the processing of substrate coating can be done well below the melting temperatures of spray particles, hence it can be termed a solid-state process. The process does not involve melting or evaporating the materials and is typically processed at low temperatures. As related to rudimentary thermal spray processes, temperature-sensitive and other oxidizing materials like polymers, nanocrystalline metals, aluminum (al), copper (Cu), etc., get benefitted through this solid-state processing [8]. During the process, the powder feedstock is fragmented within nanoseconds and possesses a high amount of kinetic energy. The high impact velocity generates some amount of heat and enforces both the substrate surface and sprayable powder particles to solidify and strengthen the coated deposits. Table 1 presents the significant capabilities of CS and CSAM techniques with recent references.

The deposition and coating behavior at the substrate interface can also be correlated with solid-state welding [9]. The cold spray process becomes favorable where dense and uniform coatings are required without substrate heating [10, 11]. Generally, nitrogen, air, and helium are used at high temperatures for the acceleration of powder particles. Powder particles are accelerated at a high impact velocity (more than 350 m/s) to impregnate the deposition and coating at the substrate surface.

Table 2 shows a brief comparison between CS and various fusion-based AM processes. While compared with other deposition techniques, supersonic powder deposition (SPD) or cold spray process offers various technological benefits that include.

I. Various materials like Al, Cu, Ni, Ta, Ti, Ag, Zn, stainless steel, and nickel-based alloys like Inconel, Hastelloy, etc., are used to develop non-porous, clean, solidified, and mechanically interlocked coated deposits.
II. Different subgroups of materials like metal composites—(Cu-W) or (Cu-Cr), cermet, metal carbides (Al-Sic, B_4C), and metal oxides (Al-Al_2O_3, NiCr-Al_2O_3) can be coated through a cold spray process for various applications.
III. This process has been widely used to develop shielded substrate coatings with enhanced ultra-thick layers.
IV. Types of deposits like MCrAlY coatings, corrosion resistant Al-Zn coatings, bond coats, and copper chrome coatings are extensively used for protection against elevated temperature, oil as well gas refinery, automotive, heat shield, and preventive layers for oxidation respectively.

2. Cold Spray Processes, Principles, and Methods

2.1. Process and Principles

The powder particles in the range of 1 to 50 µm are accelerated from a de Laval nozzle and are sprayed onto a substrate with a high impact of kinetic energy. Figure 1 summarizes the concept of cold spray methods where the

Table 1 Cold spray deposition mechanism attributes and its prominence as an additive manufacturing

S.No	CS and CSAM process attributes				Ref.
1	Process and methods				[12–16]
2	Improvements in the surface quality of additively manufactured metallic parts				[17, 18]
3	Deposition mechanism				[19–22]
4	Surface functionalization, art/decoration				[23]
	Sustainability towards CSAM				[10, 24]
	CS and CSAM process attributes	Materials	Capabilities and specific features	Uses	
5	Aerospace industry	Titanium and Nickel alloys	Higher coating density, less prone to oxidation, corrosion-resistant, High hardness value	Rocket engines, Nose wheel, steering actuator barrels, landing gears	[25–29]
6	Dimensional, restoration through CSAM	Nickel alloy, magnesium titanium, and other alloys	Restoration of required dimensions, replacing versus repairing, or addition of extra features to the existing component through CSAM	Intermetallic compounds for possible structural applications, cam bearing, the mounting pad of a large cast-iron engine mount, automotive and aerospace industry [refer Fig. 10 (b)]	[30]
7	Biological and Biomedical application	Ti,Ti-Mg,Ti–Al,Cu,Ti-Ta,Ta,Tio2,HA, Zn-Al–Mg-TiO2	Biocompatible coating, Bioactive coating, Anticorrosive coating, Touch surface antibacterial coating	Stents, anastomosis chips, embolic protection devices, implantable medical devices, orthopedic and dental implants, biosensors	[31–34]
8	Self-lubricating coatings & Neutron shielding	HCP-boron-nitride Ni & P alloys, B_4C/Al composite sprayed onto the 6061-T6 Al substrate	No damage before solid lubricants, reduce maintenance, Possesses superior ductile properties after heat treatment of coated deposits	Repair and restoration, nuclear industry to store used nuclear fuel	[35, 36]
9	Corrosion and wear	Al, SS, Muntz brass alloy (Cu60Zn40), hard ceramic, Al2O3, (WC)	Increased deposition efficiency, corrosion-resistant, improved coating quality, lower wear rate	Automotive and aerospace applications	[37–40]
10	Electrical components and carbon nanotubes	Copper and Al_2Cu powders	Better tribological properties, enhanced thermal as well as electrical conductivity, Anti-corrosion properties	Electronic and electrical industry, Reinforcement for SPD coatings, composites, batteries, shielding	[41–43]
11	Energetic material coatings	Nickel-clad aluminum powders	Stored chemical energy	Explosives, rocket fuels, pyrotechnics	[44, 45]
12	Material restoration and repairing through CSAM	Magnesium, Titanium, Aluminum, Nickel powder	Cost savings, Repair time reduction, Improved production yield, avoiding corrosive environments, and other enhanced properties include stiffness, density, thermal conductivity, and excellent machinability	Aerospace and automobile transmission system Boeing nose wheel, steering actuator, landing gears helicopters in Us defense Restoration of damaged transmission gearboxes [Refer to Fig. 10 (a, c)	[46–48]
13	Mechanical damage and metal sheet restoration through CSAM	Mg, Ni, Ti, and other alloys	Fatigue, accidental impact, overhaul, or improper operation may damage the structure	Large cast automotive parts Aircraft propeller blades [refer Fig. 10 (d, e)	[49–51]
14	Hybrid Repairing (CS + friction stir processing)	Cu–Zn alloy coatings with post-FSP, CSed MMC coatings	High-strength ultrafine-grained CSed deposits, improvement in mechanical properties, improve in wear and erosion properties	Repair and restoration	[52–54]

Table 2 A brief comparison of CSAM and other fusion-based additive manufacturing

Parameters	CSAM	SLM	EBM	LMD
Method of feeding powders	Direct deposition without any aid	At Powder bed	At Powder bed	Direct deposition without any aid
Feedstock limitations	Difficult to process high hardness and strength metals	Difficult to process high reflectivity and poor flowability metals	Problems with non-conducting and metal with a lower melting temperature	Problem with High reflectivity metals
Powder melting	No	Yes	Yes	Yes
Size of Product	Limited	Limited	Limited	Limited
Dimensional accuracy	Lower	Higher	Higher	Medium
Mechanical Properties (As Fabricated /After heat treatment	Lower	Higher	Higher	Higher
	Higher	Higher	Higher	Higher
Manufacturing time	Short	Long	Long	Long
Equipment flexibility	Higher	Lower	Lower	Lower
Suitability for repair	Yes	No	No	Yes

carrier gases like nitrogen, helium, or other compressed gases are generally heated to temperatures ranging from 300 to 800 °C depending upon the substrate materials. The propulsive gases then accelerate the powder particles and are carried through a de Laval nozzle to create a high impact on the gas jet. The materials like Zn, Al, Cu, Ni, and their alloys are widely used as coating materials having a low melting point and reduced mechanical strength like yield strength. This group of material and its alloys also show significant softening and plastic deformation at high temperatures. The operating temperature should be lower than the fusion temperature of powder materials. Since the process is solid-state and hence neither melting nor solidification of powder particles is experienced [55, 56], a target surface called substrate is located 25 mm away from the outlet of the nozzle. The distance between the target (substrate) and nozzle exit is called the standoff distance. Due to the collision between the spray particles at high velocity, heat is generated and plastic strain energy thereby reduces the effect of strain hardening. The increase in temperature of the powder particles due to collision ultimately softens the substrate materials. This phenomenon is also termed "adiabatic shear instability". The coated substrate will further experience mechanisms like oxidation, vaporization, and melting at high operating temperatures, along with re-crystallization and residual stresses.

2.2. Cold Spray System

The cold spray system can be categorized into two groups depending on the working principle: the pressure of carrier gases and the area of application. These are mainly high-pressure cold spray (HPCS) and low-pressure cold spray (LPCS) systems. Figure 1(a) shows the schematic diagram of an HPCS system. Propulsive and carrier gases are made to pass through two chambers, namely the gas heater and powder feeder simultaneously before entering the nozzle. The powder particles are heated to a temperature ranging between 300 and 800 °C in a gas heater. The flow of gases is mixed uniformly and enters into a converging–diverging nozzle where it is expanded isentropically. For successful impregnation of particles, carrier gas pressure should be higher than the propulsive gas pressure. The supersonic impact of powder particles diffuses to form a thick coating on a metal substrate, but well below the meting point of substrate materials. The unique design characteristics of both CS system permit them to operate at the same gas pressure. On contrary, even after this exclusive feature, only the HPCS system will operate at a similar gas pressure as the LPCS system, but the reverse is not true. In the case of HPCS, gases like nitrogen and helium, having low molecular weight, are utilized as a propellant, and typically generate very high impact velocity (1200–1400 m/s).

An HPCS system employs a gas pressure of not more than 5 MPa, and the powder particles are fed through a powder feeder longitudinally. Spray gun housing possesses a maximum feedstock temperature of 1100 °C. The high impact in the form of kinetic energy and fragmentation of powder particles during the process develops a very dense and uniform coating on a substrate [57]. Coating thickness may vary from a few hundredths of a millimeter to several centimeters. The powder particles are bonded together and are characterized by mechanical interlocking together with metallurgical features. However, the particles are not

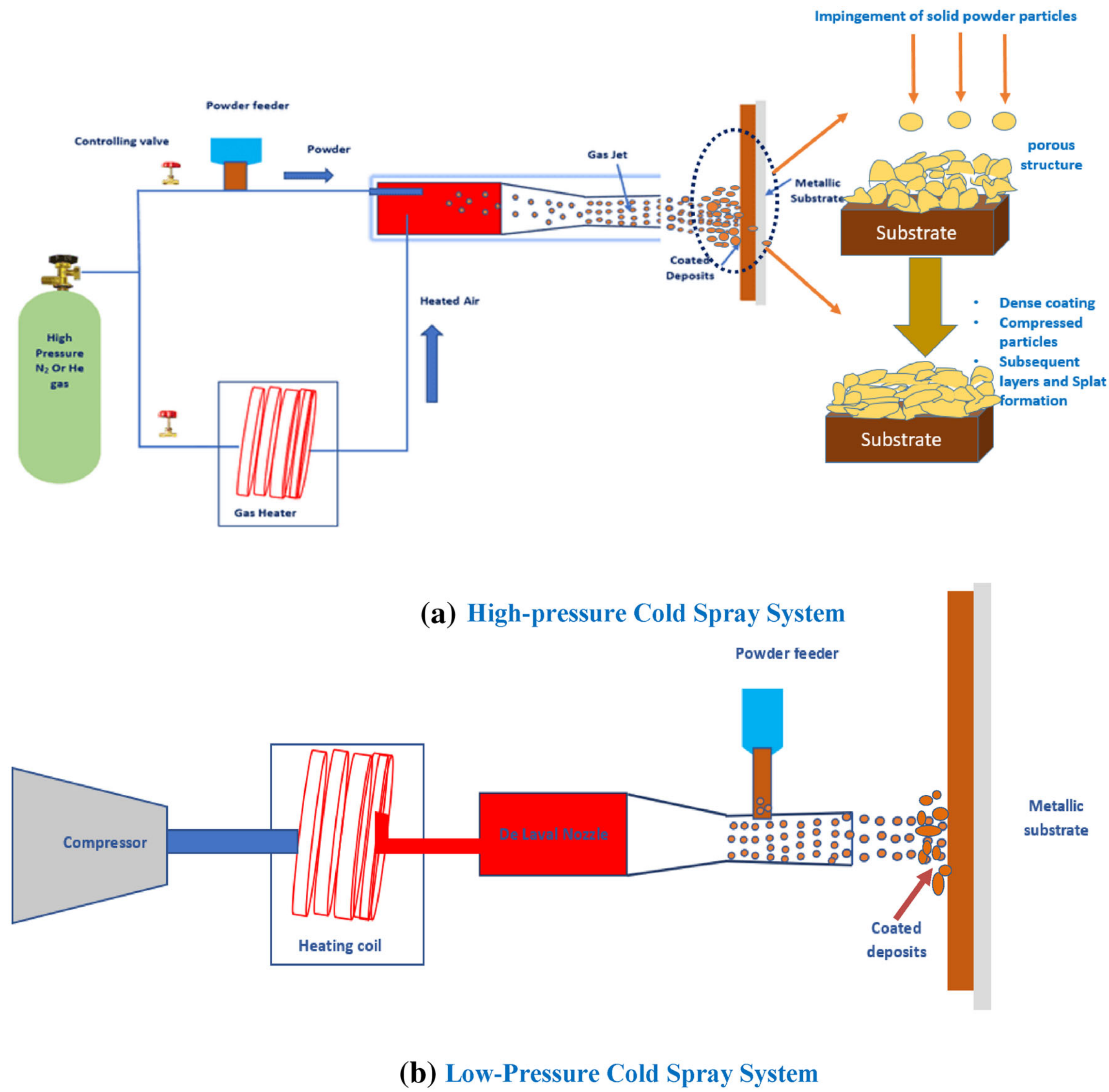


Fig. 1 **a** High-pressure Cold Spray System **b** Low-Pressure Cold Spray System

melted during the deposition process, thus induces low residual stress and lessens the chances of oxidation. The physiological properties of the original feedstock particles are retained during the entire coating process. Much more investigation is required for the materials like cermet and CMCs as there are very few process parameters available to work with these classes of material [58]. In the case of the LPCS system (refer to Fig. 1b), the powder particles are fed through a powder feeder which is placed at the diverging part of the nozzle. The nozzle design is restricted with a low value of Mach number (less than 3) and inlet gas pressure below 1 MPa, respectively. By doing so, the powder particle can be easily supplied to the nozzle at atmospheric pressure, thereby generating an impact velocity maximum of 600 m/s. Large powder particles (up to 250 microns) characterized by a smaller surface-to-volume ratio are allowed to adhere to the oxide layers of the substrate interface, thus reducing the risk of oxidation as a special benefit of the LPCS system. A comparison has been made between the two methods of cold spray system and is shown in Table 3.

3. Cold Spray Process Parameters

The bonding mechanism and impact phenomenon on the substrate materials rely heavily on various process parameters like propulsive gas (in terms of pressure and temperature), nozzle configurations, and its associated parameters like impact and erosion velocity, powder feed rate, substrate material as well as its morphology. Figure 2 depicts a schematic representation of various cold spray additive manufacturing (CSAM) processes parameters.

3.1. Impact Velocity

The common method employed to achieve high particle impact velocity is by using helium gas as a replacement for nitrogen and air or an increase in gas temperature rather than an increase in gas pressure [59]. It has been believed by several researchers from the cold spray community that enhanced coating properties can be obtained with a typical rise in particle velocity. Other performance parameters include deposition efficiency, porosity, cohesive and adhesive strength, etc., which are also likely to increase with the rise in impact velocity. These significant properties are characterized by reduced inherent defects and improved metallic bonding between the substrate and coated deposits [60–62]. The effect of performance parameters as a function of particle impact velocity on CSAM [63–65] Ti deposits is shown in Fig. 3 (a, b, c and d). Analysis has been done with different combinations of a metallic substrate (mild steel, Al, titanium itself), gas pressure, and propulsive gas (nitrogen and helium). Due to mechanical deformation in the microstructure of the metal, the enhanced strain-hardening effect increases deposit strength and hardness. Furthermore, because of enhanced plastic deformation of powder particles, residual stress in the coated substrate can also be increased with an increase in particle velocity [66, 67]. It has been found that an increase in gas temperature will reduce the effect of residual stress owing to the in situ annealing effect [68]. The effect of various process parameters on the mechanical properties of the bonded deposits is summarized in Table 4.

3.2. Powder Feed Rate

Powder feed rate can be defined as the number of powder particles fed to the nozzle per unit of time. In general, during the process, the rate of feeding the powder from the powder feeder is manually controlled and should not exceed the higher rate. Both coating thickness and powder feed rate vary linearly up to a certain extent and then after excessive residual stress is developed when the particles are impacted on the substrate for a prolonged period. This phenomenon leads to the separation of deposits from the substrate. By cumulative increase in the gun traverse speed, the peeling off coated deposits can be compensated [69]. The feed rate can be controlled with the help of a powder feeder. Various typical properties like deposition efficiency, porosity, strength, hardness, surface morphology, residual stress, etc., are influenced by feed rate. Some of them include: The movement of propulsive gases and powder particles through the nozzle are significantly affected by powder feed rate [70, 71]. Particle velocity also gets affected by the rate of feeding of powders. An increase in powder feed rate will decrease the particle velocity. This will lead to a decrement in hardness and tensile strength. Both porosity and deposition efficiency also get reduced with an increase in powder feed rate. Researchers have confirmed that for the ideal coating process in CSAM, the powder feed rate should range below 100 g/s. Generally, the characteristics of particle velocity are not affected at a feed rate that lies between 10 g/s and 30 g/s. The coating thickness and track profiles of the deposits are also affected by the rate of feeding of powders. Both thick and sharp track profiles can be generated by using higher feed rates [72].

3.3. Nozzle Parameters

3.3.1. Nozzle Traverse Speed

Nozzle traverse speed is an effective tool in determining the time duration and quantity of powder particles impacted on the target substrate. It directly influences the thickness of the coating as well as the location of single-track coated deposits [73–75]. Figure 4 shows a relationship between the width of the track, surface profile, and

Table 3 Comparison between the two methods of the cold spray system

Parameters	LPCSS	HPCSS
Gases	Portable air or nitrogen, a compressor may be used for propellant	Compressed gas, nitrogen, and helium are used as the propellant
Powder particles	Injected at the diverging part of a nozzle	Powder particles are fed through a powder feeder longitudinally
Cost	More flexible and cheaper	High cost
Pressure	5–10 bar	25-30 bar
Deposition efficiency	Maximum up to 50%	Maximum up to 70- 90%
Gas velocity	300–600 m/s	600–1200 m/s
Substrate Preheating temperature	550^0c	1000^0c

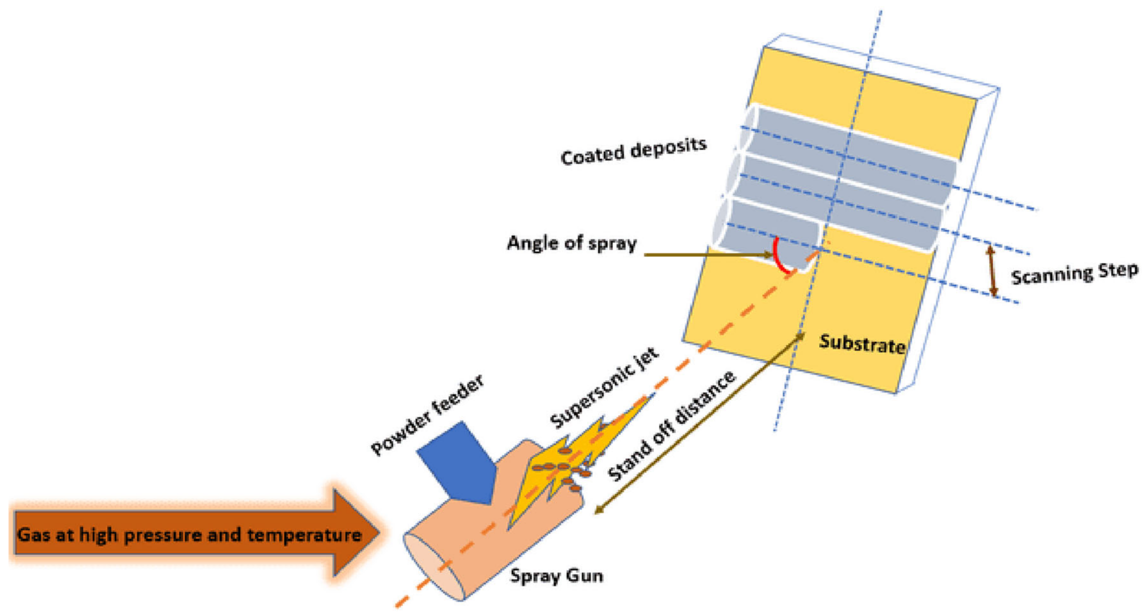


Fig. 2 Cold spray manufacturing parameters

Table 4 Effect of process parameter on substrate deposits

Parameters (↑)	Mechanical properties (↑/↓)				
	Porosity	Deposit strength	Adhesion strength	Residual stress	Deposition efficiency
Gas pressure	↓	↑	↑	↑	↑
Gas temperature	↓	↑	↑	↑	↑
Gas molecular wt	↑	↓	↓	↓	↓
Powder feed rate	↑	↓	↓	↑	↓
Traverse speed	↑	↑	↑	↓	↑
Spray angle	↓	↑	↑	↑	↑

scanning deposits step. The whole coating process is associated with the buildup of coating films. For a single layer coating, the final coating profile would be considered as an uninterrupted waviness nature of curve profile. The scanning step during the coating process has a major influence on the surface morphology and uniform deposition of powder particles at the substrate interface. It can be seen from the figure that the coating thickness is dependent upon the scanning step. Sharp and thickly coated layer deposits can be obtained with low traverse speed. The nature of the surface coating profile concerning coating thickness, scanning step, and nozzle traverse speed can be better understood with the help of Fig. 5. It is evident from Fig. 5, as the speed varies from 10 mm/s to 80 mm/s, track thickness significantly gets reduced from 2.35 mm to 0.35 mm. These changes in the cross section of coated deposits are also accompanied by the characteristics of carrier gases that pass through the nozzle at supersonic impact velocity.

For the general application of CSAM, desired coating thickness and the cross-sectional profile of several passes or tracks can be obtained by synchronization of nozzle traverse speed and the rate of feedstock. The microstructural changes and properties of deposits are also affected by traverse speed. The decrease in nozzle traverse speed, porosity, and other mechanical properties of coated deposits like Young's modulus, tensile strength, and adhesive force with the substrate also reduce [77]. Hence, it is not endorsed to work with low traverse speed in the case of CSAM, as it results in the development of high residual stress within the coated substrate. Nozzle scanning step on the other hand can be defined as the center-to-center distance between two consecutive single-track deposits. Both line-by-line, as well as layer-by-layer nozzle scanning, can be done systematically to understand the characteristics of CSAM deposits. Overlapping or stacking two single tracks with predefined widths is the most common scanning approach. The surface morphology and homogeneity in the

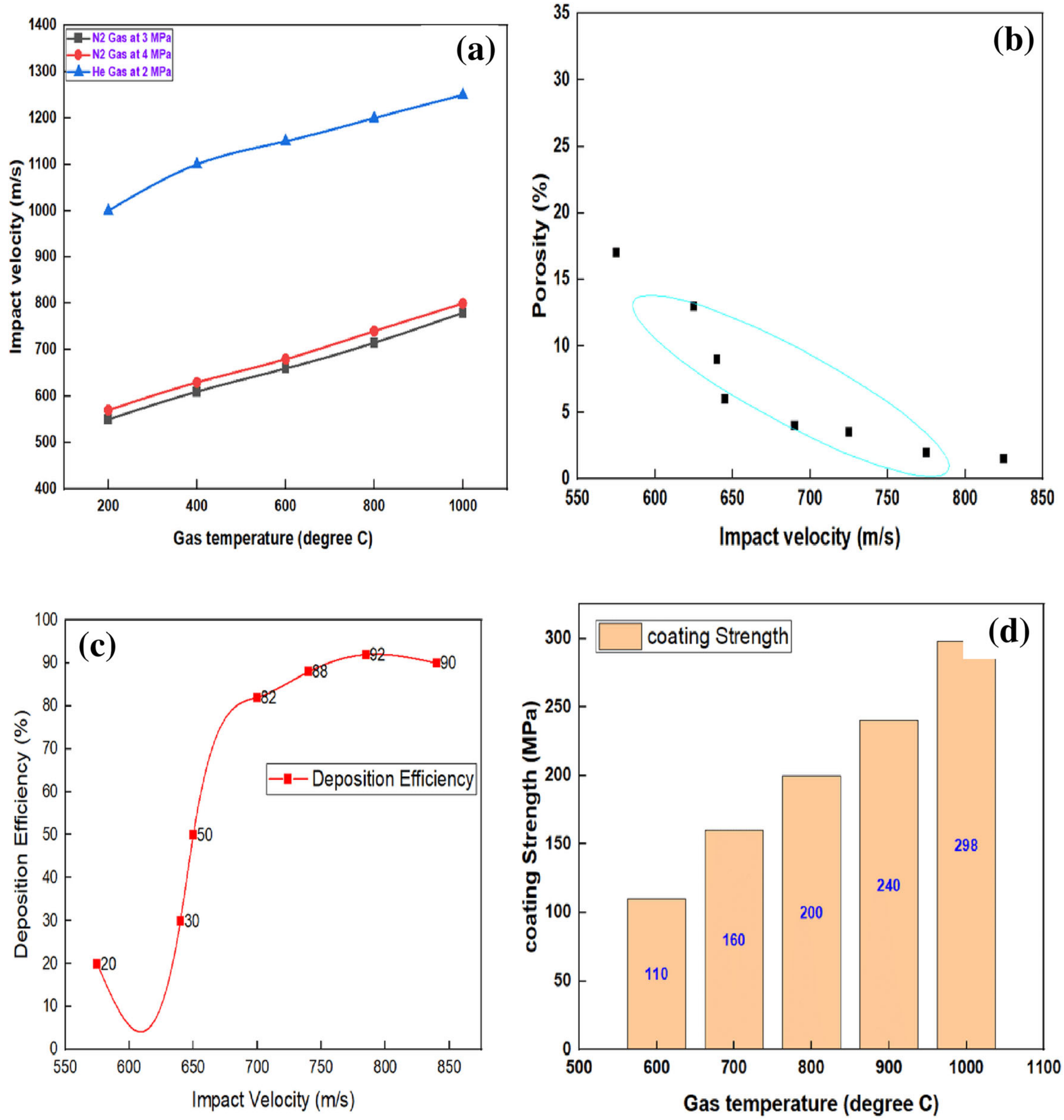


Fig. 3 **a**. Effect of particle impact velocity at a standoff distance of 30 mm as a function of propulsive gas parameers., **b**–**d**. The effect of performance parameters like porosity, deposition efficiency, and cohesive (tensile), as a function of particle impact velocity on CSAM Ti deposits [63–65]

coating thickness are significantly affected by the nozzle scanning step. It is highly recommended to select proper scanning steps for a better homogeneous deposit and smooth surface. From experimental investigation, it has been correlated that half of the width of a single track confirms flatness on the surface.

3.4. Standoff Distance

Standoff distance (SOD) is the standard gap between the nozzle outlet and target substrate. The impact velocity leaving the tip of the nozzle along the jet axis progressively decreases since the process is associated with momentum transfer between the high-velocity jet and particles present in a normal atmosphere [78]. When the carrier gas comes in contact with powder particles, a positive drag force is induced inside the jet core which accelerates the powder particles. A reduction in particle impact velocity can be observed when the propulsive gas leaves the tip of the nozzle. This is because negative drag force is created as the standoff distance is minimized. Pattison et.al [79] have strongly validated this phenomenon in their research work on the coating formation of Al, Cu, and Ti for CSAM. Li et al. [80] have also proposed that under optimum

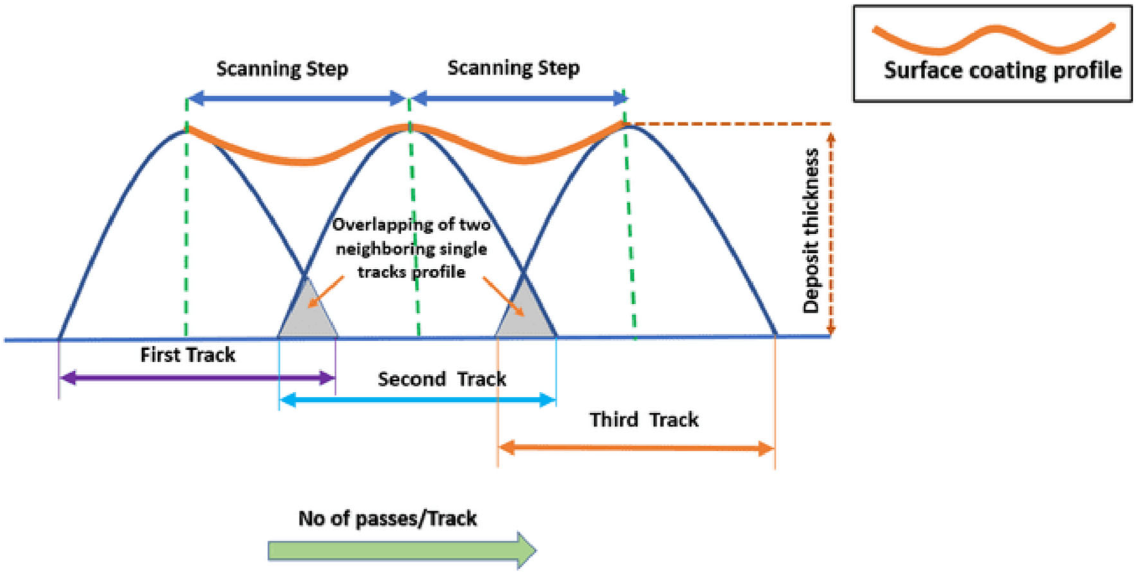


Fig. 4 Schematic diagram representing deposit thickness, surface coating profile, and scanning step

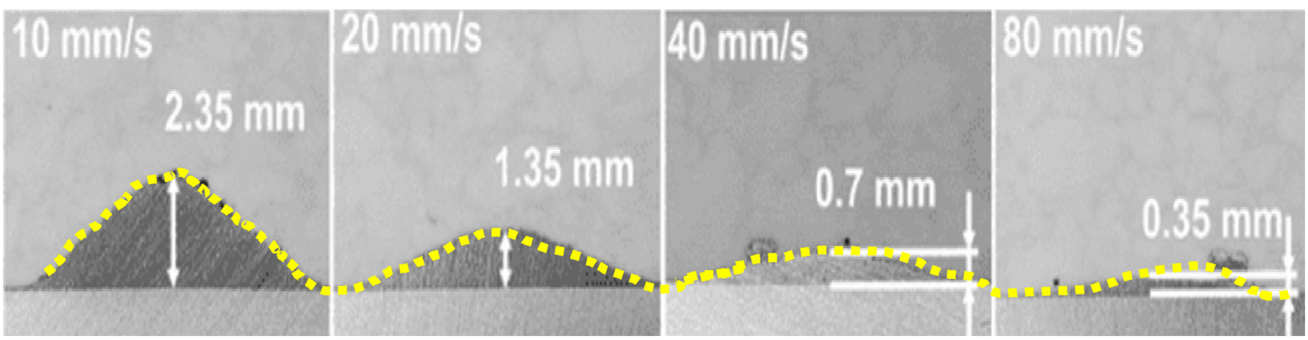


Fig. 5 Effect of nozzle transverse speed on the single-track deposit thickness and cross-sectional profile [77]

condition (10 mm to 110 mm), both impact velocity and efficiency of coated deposits increase with an increase in SOD and then reduce gradually.

3.5. Spray Angle

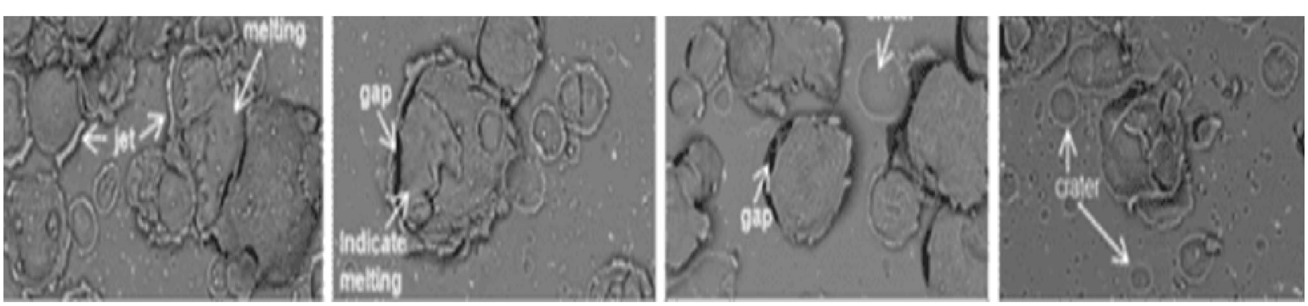
The spray angle is the opening angle that the nozzle jet of droplets forms at the moment when it leaves the nozzle diverging section and is one of the basic governing parameters for CSAM deposits. Both normal and tangential components of particle velocity are induced during the formation of the coating. Each component of impact velocity has its importance. During coating formation, the only normal component is responsible for coating deposits, while the tangential component is contrasting in nature and coated deposits tend to detach from the substrate [81]. A decrease in spray angle reduces the normal particle velocity and nevertheless increases the tangential component. There is a significant decrease in the quality of deposits and other performance parameters like deposition efficiency, cohesive and adhesive strength with a decrease in spray angle [82–84]. The component of particle velocity other than normal to the material substrate should not be preferred in any case. It has been concluded through research that in the case of copper and titanium deposits, the maximum deposition efficiency occurs at an angle between 80° to 90° and 70° to 90°, respectively [85]. Furthermore, the formation of coating is not possible at an impact angle (40° for copper and 50° for titanium). Within the mentioned range, the deposition efficiency decreases. Figure 6 (a, b, c and d) shows the variation in deposited particles of the Al 6061 series with spray angle. It is evident from the figure that with the decline of impact angle from 90 to 45-degree, the gap between substrate and deposits increases rapidly. Dense and effective coating with good bond strength (figure-a) can be obtained in the case of 90°. Bond gaps and craters are predominant at 60–45° (refer to figure: c, d). These gaps reduce the deposit's efficiency and mechanical bonding of coated deposits.

3.6. Surface Morphology and Its Properties

The performance characteristics of coated deposits depend on both spray particles and substrate material properties. Intermetallic bonding between the layers of deposits is highly influenced by substrate properties. This phenomenon is achieved in two different stages. Firstly, the substrate and primary coated layer interact, and then, subsequent layers of coated deposits tend to bond the particles. Both these interactions are equally important, as it provides adhesive and cohesive strength to the deposits for successful coating formation. As compared to hard substrate materials, soft substrate materials experience a better bonding effect due to adiabatic shear instability. Substrate temperature on the other hand also affects the coating quality and bond strength. Higher substrate temperature causes severe plastic deformation of powder particles, thus increasing the cross section profile of the track deposits. Preheating of the substrate is another common method employed to increase the coating quality as well as coating thickness [86]. Kumar et al. [87] have also suggested that there can be a significant impact of surface roughness on the bonding of deposits. For suitable bonding between the substrate and powder particles, the ideal surface roughness should lie within 50–75% of particle size. Generally, non-spherical with poor surface finish powder particles show diversified nature of bonding during impact. Plastic deformation at the powder particle interface will lead to the growth of localized shear stress, resulting in the formation of a metallurgical bond. The bonding will be further increased if a large cross-sectional area of irregular powder particles has interacted in the deformation process. Since the powder particles are not uniform and are irregular in shape, stress concentration may arise due to uneven distribution of load at the particle interface.

4. Bonding and Impact Phenomenon

In the case of the cold spray deposition technique, the powder particles are accelerated eventually at high pressure which ranges from 6.9 to 68 bar and are impacted at supersonic velocity (normally in the range of 300–1400 m s − 1) onto the metal substrate to form a suitable coating. Since the impregnation of the coating takes place at high-speed velocities and kinetic energy, the powder particles are plastically deformed and get deposited, thus producing bonded splats at the particle interface. The bonding mechanism in the case of the CS technique is a wide area of research and has to be further investigated. The adhesive and cohesive property between particle–substrate, and particle–particle is highly influenced by the bonding mechanism. There is a difference in coating behavior on the substrate material that is deposited directly and deposition onto already deposited coatings. The deformation of sprayed powder at the particle–substrate interface results in mechanical and metallurgical bonding employing adiabatic shear instability (ASI). In a general sense, the adiabatic process involves the transfer of energy without heat or mass transfer to the surrounding. In the case of the CS process, the heat generated at the particle substrate interface due to impact will remain at the interface. The classical model of ASI particularly states that firstly the powder particles get deform due to plastic deformation and the impact energy produced by supersonic jet velocity. During this stage, the powder materials at the substrate interface become viscous due to the thermal softening mechanism, and secondly, the plastically deform particles disrupt the deposited thin oxide layers, hence ensuring intimate connection with the base metal at substrate–particle interface. This mechanism of bonding in association with ASI behaves similarly to a well-known welding process called explosive welding, where dissimilar metals in a solid state can be welded. Since the powder particles are



(a) Impact at 90⁰ **(b) Impact at 75 ⁰** **(c) Impact at 60⁰** **(d) Impact at 45⁰**

Fig. 6 Effect of spray angle on deposited particles of Al 6061 series [55] deposited in the solid state, the microstructural features of the coated deposits will be retained. To comprehend the concept of bonding mechanism and interaction phenomenon between particle substrate interface, the whole mechanism can be divided into four stages as shown in Fig. 7 [24, 88, 89].

Stage I: Particle deposition in the form of a thin layer on the metal substrate due to direct initial contact. Coating formation relies heavily on both pre-processing of the substrate surface and its material properties.

Stage II: This phase is characterized by plastic deformation, increase in the contact area, and re-alignment of powder particles. A thick layer gets deposited and hence increases the densification parameter by overcoming the flow of plastically deformed materials into the voids or cavity. This phenomenon is also termed as the "peening" effect.

Stage III: Formation of strong metallurgical bond and occurrence of mechanical interlocking phenomenon between powder particles and substrate interface. Also, there is a reduction in atomic packing efficiency (voids).

Stage IV: The final stage features further densification, work hardening, and consolidation of metal powder. The consolidation of metallic powders in the CS process is highly affected by various geometrical as well as thermo-mechanical parameters. Geometrical parameters include surface contact area, width and depth of crater as well as nozzle geometry (diameter and impact angle).

On the other hand, plastic and shear strain, impact pressure, flow stress, and the temperature at the substrate interface are a few thermomechanical parameters. Both these parameters are directly or indirectly dependent on particle velocity. Hence, in a general sense, the particle velocity should be somewhere between critical and erosion These properties may include porosity, impact pressure and temperature, fusion temperature, impact strength, and hardness [90, 91]. A mechanism like mechanical interlocking also depends upon surface morphology at the substrate interface and ultimately affects the deposition efficiency. The substrate with high surface roughness leads to severe plastic deformation in the zone of increased surface area, hence enhancing the bonding strength as well as deposition efficiency. It is very difficult for the powder particles to adhere and form a strong bond between the smooth substrate and particle interface. There is also a reduction in deposited mass at the substrate [92].

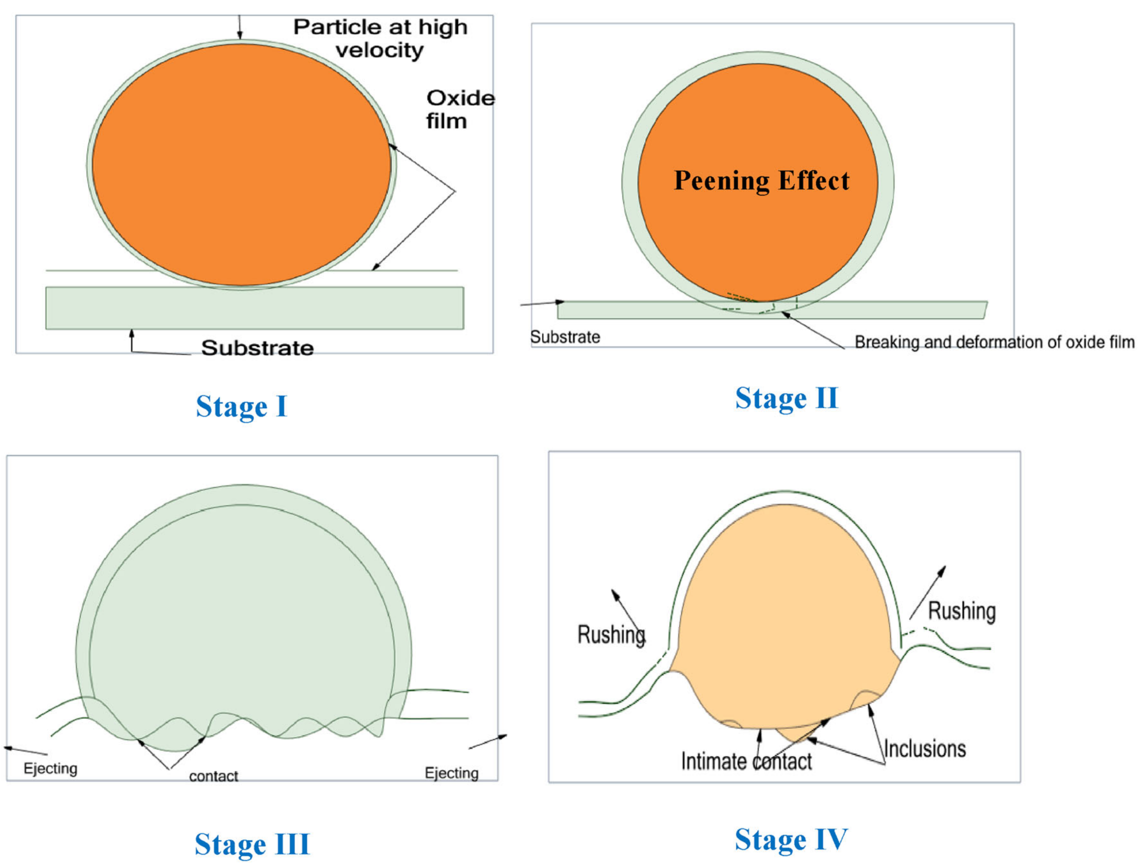


Fig. 7 Various stages of Mechanical bonding and impact phenomenon of CSAM

5. Mechanical and Metallurgical Aspects of CSAM Deposits

Several studies have been carried out to examine the mechanical and metallurgical properties of CSAM deposits. Since the cold-sprayed deposits own a limited ductility and tensile strength before any heat treatment process, hence by proper selection of heat treatment process, better strength could be achieved. Preprocessing of feedstock material and heat treatments of cold-sprayed deposits significantly affect the mechanical properties as well as metallurgical bonding between the interfaces. The ultimate tensile strength of preheated Fe powder particles becomes double and reaches a value of 109.42 ± 50.56 MPa from 64.58 ± 42.07 MPa. This is because preheated Fe particle deforms more extensively owing to the thermal softening and adiabatic shear instability mechanism as compared to the non-preheated powder. High dislocation density and formation of nano-oxides at the edges of splats lead to the brittle behavior of cold-sprayed preprocessed Fe powder particles [90].

Cold-sprayed zinc coatings have the potential to provide barrier as well as sacrificial protection to steels. Cold-sprayed zinc coatings on a mild steel substrate showed promising results in terms of hardness, Young's modulus, and corrosion behavior because of its anodic potential toward substrate material [93]. Moreover, the hardness, ultimate tensile strength, and percentage elongation of cold-sprayed Al coating with different percentages of Al203 showed a gradual improvement in these mechanical properties. A localized metallurgical bond is formed between the adjacent layers of Al particles due to the momentous hammering effect of Al_2O_3 resulting in the formation of a dimpled structure. With further increase in temperature, the particles diffuse together and the mechanical interlocked Al –Al particles form a metallurgical bond resulting in a significant improvement of the ductility of CS-AM deposits. Heat-treated Ti6Al4V composite coating also showed a significant improvement in the microhardness value with excellent adhesive bonding between powder particle and substrate [94]. Both shot peening and residual stress are interrelated. Residual stress in cold-sprayed coating develops due to the inhomogeneous plastic deformation of powder particles resulting in components cracking and shape distortions. Shot peening is a better example of inhomogeneous plastic deformation which involves the tensile nature of deformation on a surface layer. As-fabricated deposits of CS contain compressive residual stresses which occur due to the accumulation of peening stresses among successively deposited layers. Such compressive residual stresses in the CSAM deposits can be released via post-spray annealing. The formation of residual stresses and their effects on various groups of Ni-based super alloys like Inconel 718, 625, and others using different additive technology approaches like SLM, HVOF, and laser rapid forming have been broadly studied. Heat-treated In 718 and 625 is characterized by thermal softening and decrement in residual stress with

Table 5 Overview of some Common coating material, their benefits, and potential applications [35, 98–101]

Spray material	Benefits/Specific features	Applications
Tin	High hardness and adhesion, low surface tension, weldability, and ductility, excellent lubricity	Solderability
Zinc & its alloys	Galvanization results in protection from corrosion, oxidation, and sulfidation resistance	Bridges, ships, boilers, and other and other high-temperature use
Mg, Al & its alloys	Better bonding with similar strength to bulk material	Additive manufacturing, marine industry, Component repair
Cu & its alloys	Reduce friction and wear, Increased conductivity, and no oxidation	Tribological coating, Electronics Protection from corrosion, heat transfer
Steel	Magnetic properties, Comparable strength compared to bulk material, good resistance against corrosion	Repair, biomedical, and SPD tamping for softer particles
Ni & its alloys	Hot gas resistance, energetic material coatings, High-temperature corrosion	Aerospace, component repair, roller mills, hydraulic pumps, Automobile, glass and medical industry, agricultural components, etc.,
Fe-based alloys (Fe)	Improved wear resistance	Gas turbine and aircraft engines, water and steam turbine, steel rolling mill, cement industry, chemical processing, and textile industries, etc
Ti its alloys	Manufacturing components with little defects at substrate interface, corrosion resistance, and Biocompatibility	Biomedical applications, Additive manufacturing, tribological spray, marine applications

Fig. 8 Major areas of CSAM

very less visible cracks within the microstructure [95]. Another way to improve the surface behavior and mechanical property of CS deposits is by hybrid surface treatments. A combination of shot peening with nitriding and deep rolling is the best way to improve the fatigue life of CS coatings by the development of residual stress and inducing work hardening. The fatigue behavior of Al 6082 alloy was investigated using hybrid surface treatment concepts [96]. Microstructural characterization and mechanical properties of different structural materials altering the build direction using AM gas tungsten arc welding (GTAW) method using ER70S-6 filler wire have been studied. The results showed a significant improvement in mechanical properties like hardness, tensile strength, and impact strength. Microstructural characterization revealed the presence of ferrite as matrix phase, while pearlitic structure appears to be at the grain boundaries [97].

6. Cold-Sprayed Materials

Some of the common materials like boron carbide (B_4C), tungsten carbide (WC), carbon nanotubes, CO-based alloys, hard chromium, and ceramic coatings are dominantly used in the field of coating technologies because of their enhanced mechanical properties. These properties may include corrosion, wear, abrasion, high impact strength, thermal and electrical conductivity, etc. The use of such materials has drastically increased during the last decades in the field automobile industry such as piston and piston rings, engine cylinders, aircraft engine parts, plastic molds, etc. The emerging technology also finds importance in other areas like heat treatment furnaces, nuclear power plants, chemical processing equipment, heat exchangers, hydro- and steam turbine, valves for the offshore industry, aerospace, military industrial, and surgical components. A list of some coating materials, their benefits, and their potential application is highlighted in Table 5.

7. Application of CSAM for a Specific Purpose

Cold spray deposition techniques have been widely used to produce intricate free-standing shapes with additive features at a very high production rate with process flexibilities. To date, the process has been utilized mainly in the manufacturing and repairing sector and has the further potential to deposit various novel industrial materials onto the substrate like Al, Cu, bronze, Ni–Al, Ti, MMCs, and other superalloys. With the help of the CSAM approach, more recently one of the Australian manufacturing companies fabricated titanium drones of more than 1.8 m in diameter. Figure 8 shows the major areas of CSAM.

7.1. In the Field of Additive Manufacturing

Additive manufacturing (AM) technology has been widely used to build three-dimensional objects in a stacked manner. Complex and multifunctional components can easily be manufactured within the pre-defined time limit. Since the process completes in a single stage without any scrap waste, the overall cost of the final product gets reduced, thus promoting green manufacturing [102, 103]. Nowadays, additive manufacturing together with the cold spray coating process has gained so much importance in the field

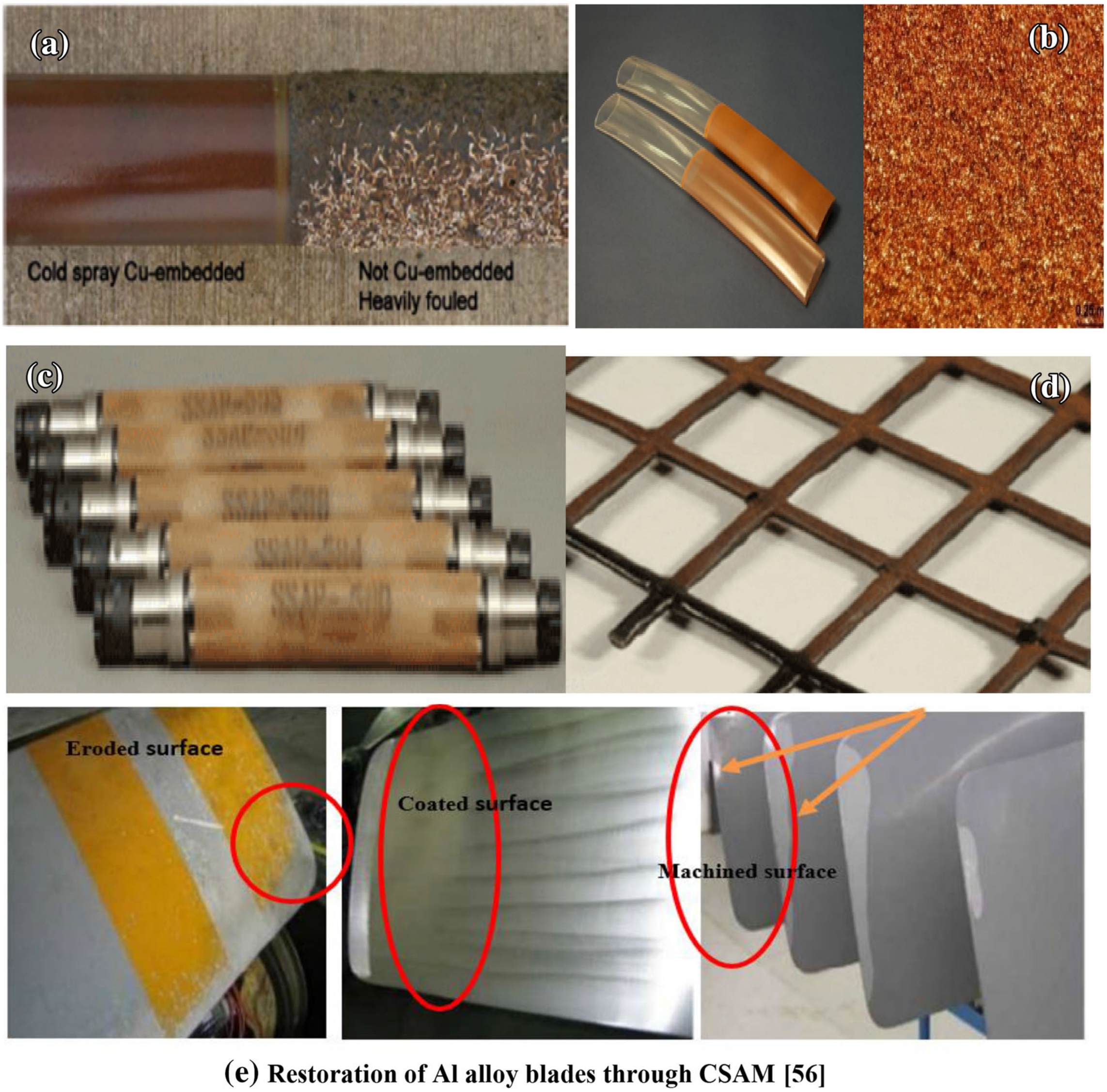


Fig. 9 **a** Comparison of Cu embedded and with Cu-embedded in streamer skin; **b** Cu deposition on polyurethane surface and its micrograph; **c**, **d** Cu particles embedded on cables and net for fish farms.[106–108]

of repair and restoration. Dense and thick coatings with good dimensional accuracy within the substrate interface are produced via CSAM. Still, very limited research has been accomplished in the field of CSAM to produce complex geometrical shapes at a single pace. Hence, to produce intricate manufacturing components, the study of various CS process parameters must be visualized. As compared to additive manufacturing and other conventional manufacturing processes, CS is advantageous due to the following facts [104, 105].

There is absence of metallurgical effect at substrate interface in the form of heat-affected zone (HAZ) interface. During the formation of oxide layers and coating deposition during the process, not much attention is required for shielding the atmosphere from oxygen-sensitive materials like Al and Ti alloys. A very little amount of waste is generated during the process. Cost-effective in terms of manufacturing and repair of small parts, depending upon usage, process parameters may be varied to increase deposition efficiency, deposition rate, coating thickness, and porosity.

7.2. In Antifouling as Functional Coatings

Biofouling may be defined as the growth of microorganisms like plants, algae, etc., over the surfaces such as ship and submarine hulls, devices such as water inlets, pipework, grates, ponds, and rivers that cause degradation to the primary purpose of that item. The accumulation of these micro-organisms over marine equipment will reduce

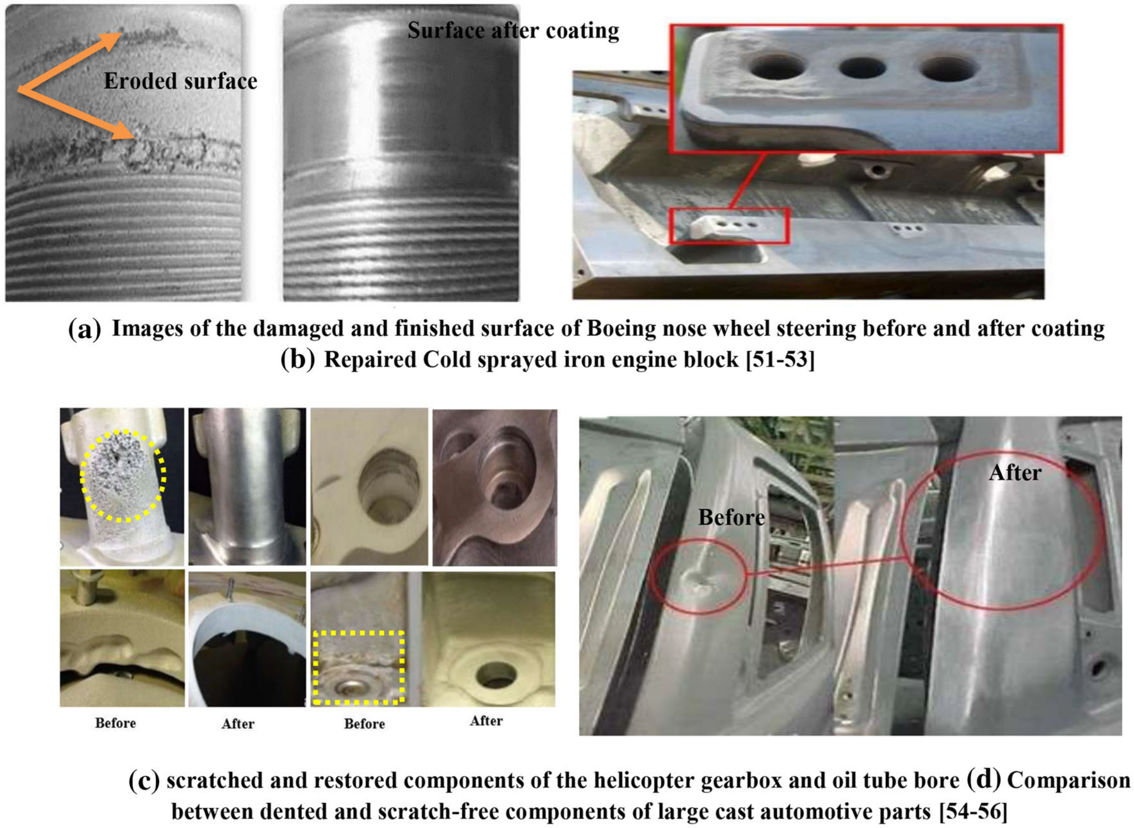


Fig.10 **a** Images of the damaged and finished surface of Boeing nose wheel steering before and after coating **b** Repaired cold-sprayed iron engine block [50–52] **c** Scratched and restored components of the helicopter gearbox and oil tube bore **d** Comparison between dented and scratch-free components of large cast automotive parts [53–55] **e** Restoration of Al alloy blades through CSAM [55]

the overall effectiveness in terms of surface friction, acceleration and de-acceleration of ships, fuel consumption, docking maintenance, and many more. Hence, it is essentially required to prevent and control the formation of marine biofouling. A group of researchers, biologists, and marine engineers studied the effect of biofouling on marine structures and developed some antifouling methods to significantly improve the overall performance. However, antifouling coatings possess some disadvantages too. The most common is the peeling off of organic antifouling paints in the case of submarine doors. Nowadays, the cold spray deposition technique (with Cu and Cu-based alloy) has been a widely accepted antifouling method. CSIRO Australia revealed that various large components and infrastructures also get benefitted from the cold spray antifouling technique [106]. Figure 9 (a, b, c and d) illustrates the cold spray copper deposition on the polyurethane surface, cable, and net for fish farms, respectively.

7.3. Cold Spray as Joining of Unlike Metals

Cold spray techniques have been widely used for joining various lightweight dissimilar materials, specifically metals and polymers. It has gained importance in the field of manufacturing various hybrid structures and mechanisms for industrial and engineering applications. The aerospace and automotive industry has revolutionized the use of lightweight materials to accomplish precise and improved versatility in these fields. Dissimilar metals can be joined based on tailored welded blank (TWB) with different combinations. Materials can be joined together through cold spray techniques by applying various sets of combinations for coating thickness. These combinations offer a significant improvement in the coating deposits. Homogeneous distribution of properties of materials in the finished part with adequate strength, cost-effectiveness, and reduction in weight of overall cast are some of the important highlights of this process [109]. Joining of fuselages skin of airplane (up to 2 mm), automobile panels (up to 1 mm), duct design (0.45–2 mm), and sheet bellows (0.15 mm) are a few areas where thin sheet metal joining can be possible with the aid of cold spray technique. As compared to conventional joining processes, the CS technique has evolved as an alternate solution for such applications where very little working temperature is associated. Various other areas like energetic material and self-lubricating coatings, aerospace industry, dimension, and mechanical damaged restoration also get benefitted from this innovative subclass of the thermal spray coating system.

7.4. Mechanical Damage, Repair, and Restoration

Most automobile and aerospace components are subjected to fluctuating mechanical load and harsh environments like pressure, temperature, air quality, speed of rotation, or accidental impact resulting in wear and corrosion of parts. This leads to the failure of parts, and it further requires either replacement or restoration. For the sustainability of the manufacturing industry, CSAM has emerged out to be one of the most favored technology in recent years. CSAM is a strong tool for sustainability over a broad range of modern manufacturing sectors by restoring rather than replacing the whole component. Figure 10 (a, b, c, d and e) shows the repair and restoration of damaged components of various parts of the helicopter, cast iron engine block, and Al alloy turbine blades. After successful surface restoration and processing of damaged parts, the components become smooth without any pores, cavities, or cracks.

7.5. Multifunctional Coatings for Biomedical Applications

The rising demand for high-performance anticorrosive and biocompatible coatings in the field of biomedical sciences has led to the emergence of various deposition techniques. CSAM is a versatile and cost-effective surface modification method that has been widely used in the medical industry to produce geometrically complex shapes. Some of the common products, namely dental implants, joint replacements prosthetic devices, surgical tools, artificial organs, tissue scaffolds, artificial muscles, and tendons, are fabricated with the CSAM technology. The pharmaceutical industry is not far behind and largely dependent upon AM technology because of several promising attributes like reduced production time, enhanced productivity, cost-effectiveness, customization, and personalization of products. Some of the common materials like Ti and its alloys, Cu, Ta, Co-Cr, Ni, and SS, are widely used on various biomedical devices. These groups of materials possess enhanced mechanical, chemical, and biological properties. Among these, Ti and its alloys have been used for decades because of their anti-corrosion and biocompatible nature. Since the advent of the COVID-19 pandemic, researchers and metallurgists have shifted their interest toward to use of copper and its alloys for biomedical applications because of its antiviral and antimicrobial properties. Co-Cr and nickel alloys have higher wear resistance properties with significant stiffness. Ceramic coatings also play a major role in biomedical applications because of their corrosion and wear resistance, impact toughness, and antimicrobial features [110, 111].

8. Current Challenges and Future Perceptions

In recent years, the cold spray deposition technique has shown a tremendous inclination toward additive manufacturing. Fabrication, restoration, and maintenance of individual components are important aspects of additive manufacturing. This is because the deposition process can retain the properties of the initial phase and avoid any subsequent effects related to the surface coating and substrate material. Experimental investigations and analysis of CSAM have established a strong relationship between mechanical and physical properties that allow it to be used in a varied range of applications. A few challenges associated with the cold spray deposition phenomenon are mentioned below.

8.1. Coating Material

At present, various investigations have been done primarily on Cu, Al and its alloy. This is because these materials have the unique capability of machinability and coating deposition on the target substrate. In the coming future, some other groups of materials are required to be studied, employed, and tested. These materials include nickel, cobalt, stainless steel, superalloys, titanium, ceramics, MMCs, etc. The unique characteristics like hardness, melting temperature, and high strength-to-weight ratio make a problematic condition to produce with suitable mechanical properties. Hence, it is highly recommended that more trials and research should be done on such types of materials.

8.2. Process Parameters and Material Deposit Properties

A systematic understanding of process parameters is another research area. Important parameters and their influence on the properties of coated substrates need to be further studied. A standard engineering approach for attaining optimum deposit and enhancement in mechanical properties should be recognized. Direction dependent phenomenon and its associated properties of coated deposits need to be investigated. The evolution of various advanced post-treatment approaches like surface treatment through laser, isostatic pressing at elevated temperature, and surface shot-blasting would aid in upgrading the abilities of CSAM.

8.3. Post Machining Treatment

The final products made from CSAM methods require post-machining treatment. Also, the surface properties of coated deposits were significantly improved by this method. Hence, further investigation into the post-machining process is required.

8.4. Fabrication of Intricate Shapes

The purpose of CSAM for synthesizing and developing multifaceted structures is exciting and interesting research. Very few researchers have worked in the field of complex structure fabrication.

8.5. Application

At present, CSAM is mainly focused on the field of the aerospace industry, repair, and restoration of damaged products. So, it is highly recommended that other specific areas should be explored.

9. Conclusions

CS technology has shown great potential in the field of additive manufacturing. The current study focuses on a comprehensive review, of recent research innovations, current challenges, and future perceptions of CSAM technology. The deposition technique has been widely used for developing compact, clean, thick, dense, and well-bonded metallurgical deposits. With the advancement of new coatings technologies, the process has gained importance and occupied the remanufacturing and repair market up to large extent. Still, there are possibilities to discover and innovate a few shortcomings to accomplish this process as the fastest, most economical, and improved one as compared to other existing deposition techniques. From the trials of R&D to the various industrial sector, CS has gained importance worldwide. A wide range of materials (including Mg, Al & Ti alloys, even superalloys, MMCs, etc.) are projected to be deposited for manufacturing with the evolution of recent technologies and advanced CS equipment. Additionally, the damages like scratches, cracks, and cavities can be restored by CS. SPD has emerged as an advanced and refined technique for coating substrates where multiple layers of spurted particles are deposited. Surface defects such as wear and tear, corrosion, and electrical conductivity can be enhanced through the coating substrate. Consequently, coated substrate relies heavily on properties, substrate materials, and various processing parameters (like feed rate, gas pressure, temperature, nozzle parameters, etc.,). The efficiency of the coating is measured in terms of deposition efficiency (DE). A higher value of DE is always preferred because it is more effective and profitable. Impact velocity adversely affects the irregularity of sprayed particles. Deposition efficiency will be higher when the velocity will be high. The coating quality can also be assessed through impact angle. The spray particle should be pre-processed to enhance the morphological changes of the finished coating. Generally, cold working of particles is preferred over non-cold working as it produces fine microstructure. As compared to nitrogen, compressed air, and other inexpensive gases, helium can also be used as a carrier gas. A wide range of coating materials is used in the metallic and mechanical interlocking bonding mechanisms which are the highlights of the CS technique. Each mechanism is equally responsible for both geometrical and strength restoration at the substrate particle interface. The major challenges during the CS process are to overcome voids or cavities. Shot peening is generally preferred for tamping down the cavities. The shape of the particles is equally important to characterize the coating efficiency. Cold spray technology is still in its initial phase; nevertheless, it has many specific and potential applications which include energetic material coatings, electrical and electronic components, marine, tribological coatings, biomedical, aerospace, nuclear industries component repair, self-lubricating composite coatings, additive manufacturing, and more.

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