Thermal Spray Technology: From Cold Spray to AI-Driven Innovations

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Abstract — A variety of coating techniques fall under the umbrella of thermal spray technology, such as the more contemporary cold gas dynamic spray, in which solid powder particles are driven by a de Laval nozzle to strike and form a bond with a substrate without melting. The principles, benefits, and drawbacks of several thermal spray techniques—such as cold spray, high-velocity oxygen fuel (HVOF) spraying, wire arc spraying, and plasma spraying—are thoroughly discussed in this study. Additionally, it goes into great length about the background and uses of cold spray. The potential of Artificial Intelligence (AI) and Machine Learning (ML) to transform thermal spray processes through process optimisation, coating quality prediction, defect detection, and material design is also introduced in this paper, acknowledging the growing importance of data-driven approaches in materials science and opening the door for intelligent coating solutions.

Keywords: Cold Gas Dynamic Spray (Cold Spray), History, Applications

I. INTRODUCTION

Previously, cold spray was gas dynamics. Cold spraying is a solid-state spraying technique that uses ballistic impingement to create a coating on a work piece using solid powder particles, often metals. A work piece positioned around 25 mm from the nozzle's exit is sprayed with metal powders with a diameter of 1 to 50 µm that have been accelerated in a high velocity gas jet to extremely high speeds of up to 300 to 1200 m/s. The solid powder particles required to create the layer are introduced into the nitrogen or helium jet stream, which accelerates the particles as they expand in the de Laval nozzle's divergent section. The carrier gas's temperature ought to be lower than the feedstock material's melting point [1]. The solid particles undergo a permanent shape change and form a consolidation of metallurgical and mechanical connections with the surrounding material if the impact speed of the powder particles exceeds a critical limit. Many of the drawbacks of thermal spray techniques, such as high temperature oxidation, melting, crystallisation, evaporation, residual stresses from chemical reactions that are undesirable, and gas release, are reduced by cold spray. Low-temperature coating deposition speeds up the formation of oxides and other inclusion-free coatings as well as fine microstructure [1]. The layers created by cold gas dynamic spray are less porous, more homogeneous, harder, less shrinking, less oxide formation, and have greater Young's moduli than those created by thermal spray coating [2].

A. Types Of Cold Gas Dynamic Spray

The two primary categories of cold gas dynamic spray processes are low pressure cold spray and high-pressure cold spray. As illustrated in Figure 1(a), the working gas (helium, nitrogen, or air) and powder stream are both injected before the de Laval nozzle throat in a high-pressure cold spray process. The pressure is higher than 1.5 MPa, the gas flow rate is between 50 and 150 m3/h, the gas preheat temperature is between 20 and 800°C, and the particle speed is between 800 and 1400 m/s. In the low-pressure cold spray method, a low-pressure gas (0.5 to 1.0 M Pa), a flow rate of 15 to 30 m3/h, a gas preheat temperature of 20 to 550°C, and particle velocities of 300 to 600 m/s are used to inject the powder into the diverging region of the de Laval nozzle.as shown in Figure 1(b).

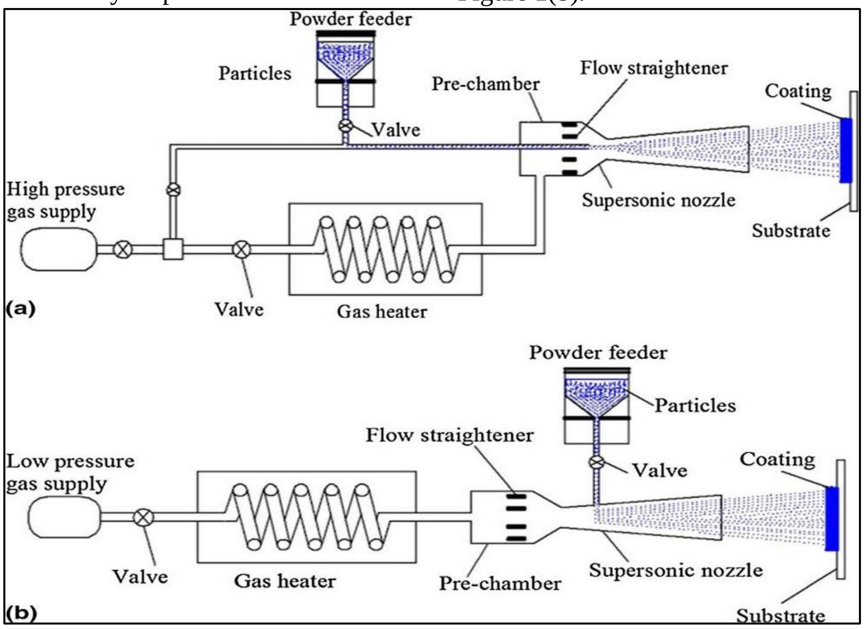

Fig. 1: Schematic presentation of cold gas dynamic spray processes (a) High pressure cold spray(b) Low pressure cold spray.

II. COLD GAS DYNAMIC SPRAY SYSTEM:

The cold spray system can be built as a robotic or stationary system, or as a manual or portable system, depending on the application area. Dry air (79%N2–21%O2), nitrogen (N2), helium (He), and their mixes are the most often utilised carrier gases. [3] Powder feeder (power 1 to 50 µm in dia.), compressor source for compressed gas supply, gas heater to preheat the carrier gas, de Laval nozzle), spraying chamber, and temperature & pressure measurement & regulating system are the primary components of a cold spray system.

A. HISTORY OF THE INVENTION

Early in the 20th century, the fundamental idea behind cold spray was trademarked. Schoop is credited with discovering the cold gas dynamic spray method. However, for at least a century, the idea of employing the K.E. of the particle rather than thermal energy to produce a coating by accelerating solid particles with a compressed gas stream has been in use. When models were used in Russia to analyse the supersonic flow of gas and solid particles in a wind tunnel, it was discovered that when the impact speed exceeded the critical limit, the solid particles adhered to the material surface and underwent irreversible deformation. A concise description of the development of cold spray process from 1900-2017 is as follow [4].Thurston received a patent for "a way of carrying out the process of depositing a layer of one metal on another metal" on August 12, 1902. 1915: On March 30, 1915, Schoop received a patent for a thermal spray method. 1970–1980: Prof. Anatolii Papyrin developed the cold spray gas dynamic spray, or simply cold gas dynamic spray, processes at the Institute of Theoretical and Applied Mechanic of the Siberian branch of the Russian Institute of Science in Novosibir in the middle of the 1980s [5].1990–2000: A US patent addressing the viability of cold spray for a variety of applications was granted in April 1994 [6].1995: A European patent for the effective deposition of a wide variety of pure metals, alloys, polymers, and composites onto a variety of work piece materials was granted in January 1995 [7].2003–2004: Morich, M. Grujicic, et al. suggested that "adiabatic shear instability," which happens when the speed of the spray particles surpasses the critical speed, is the primary bonding process in cold gas dynamic spray. A pressure field is created when the spray particles strike the work piece because of their fast speed. Thus, a shear load is created, which causes the material to accelerate laterally. This results in shear straining phenomena at a specific location, which accelerates to adiabatic shear instability under specific circumstances [8-10].2000–2017: In June 2004, Steenkiste and Smith used a kinematics spray method to create a tantalum (Ta) coating. The tantalum (Ta) coating's examination showed that it decreased porosity and increased cohesiveness, adhesion, and hardness [11]. There aren't any studies on depositing copper and its alloys in the literature[12-20], Aluminum and its alloy [12, 21-26] and Zn and its alloy [27-29]. Li Chang-Jiu, Yang Guan-Jun, and colleagues used cold spray to deposit the nanostructured tungsten carbide-cobalt coating in December 2007. The outcome revealed a backed microstructure in the coating's spray powder with complete preservation of the original nanostructure[30]. Cold spray applications in the automotive, petrochemical, electrical, medical, and aerospace industries were proposed by M. Trexler in 2010[31].V.K. Champagne described some new methods and applications that are currently being explored in May 2004. Among these are bio-ceramic and hydroxyapatite, which are mostly utilised in orthopaedic and dental implants. It was demonstrated that Ti could be cold sprayed onto hydroxyapatite powder to create a thick layer [32]. Various researcher show the successful deposition Ti and its alloy [33-38], stainless steel [39], Ni and its alloys [40-42], &Ta [43-46]. A multi-layered cylindrical titanium-copper item with its sliced section created by cold spraying was displayed by Moog Brochure in August 2017[47]. In order to further reduce material waste caused by over-deposition, Chen et al. developed a spiral trajectory approach that follows the nozzle's movement inside the sprayable area[48].

III. ADVANTAGES OF COLD GAS DYNAMIC SPRAY

For a variety of applications, cold gas dynamic spray is a successful technique for coating metals, alloys, metal matrix composites, ceramics, polymers, and nanostructure powders. When compared to thermal spray techniques, the primary advantages of cold spray are its low temperature and lack of a heat-affected zone, which reduces the possibility of a state phase transition and maintains the particles in their initial condition. Additional benefits include the absence of oxide formation, low porosity (less than 1%), high density, high electrical and thermal conductivity, increased coating hardness, enhanced resistance to wear and heat abrasion, high impact strength, oxidation, and corrosion.

A. Limitation Of Cold Gas Dynamic Spray

The powder feeders used in HPCS are often larger and therefore more expensive. Although the carrier gas (helium) in cold spray is very costly until recycled, another disadvantage of HPCS is related to nozzle clogging and wear, which is caused by high temperature and particle velocity.

IV. APPLICATIONS OF COLD GAS DYNAMIC SPRAY

Applications for cold spray include production and restoration [49] in the automotive, petrochemical, electronics, aerospace, medical, marine, and machine maintenance industries [50]. For producing dense, thick, pure, and well-bonded layers of various metals and alloys, such as aluminium, copper, nickel, silver, tantalum, zinc, nickel base alloys, stainless steel, and bond coatings (MCrAlYs), cold spray coating is most frequently utilised [51].

Coating	Uses
Ceramic coatings (SiC, Al_2O_3, TiC, glass, WO_3, cement linings)	Solar cells, sterilisation, cancer treatment, heat treatment equipment, furnace parts, chemical processing equipment, condenser, protection for machining tools, rocket motor nozzles, engine exhaust manifolds, photoelectrodes, jet engine parts, oxidation resistance at high temperatures, and nuclear power plant parts, among other things.
Hard chromium coatings	Applications that call for greater depth of hardness and resistance to

	oxidation and corrosion. These include cylinders and pistons, parts for aeroplane engines, piston rings, and uses in medicine, among other fields.
Zinc-aluminum alloys	Steam generators, bridges, roof coverings, ships, and other large constructions, steel corrosion prevention, and other high-temperature applications, etc.
Cobalt based alloys	Used in areas that need hardness, corrosion resistance, and erosion resistance due to extreme conditions. It can also be utilised in applications like gate valves and lighting where high temperature strength is necessary. Steam turbines, hydraulic turbines, internal combustion engines, etc.
Nickel based alloys	Used in situations where a long-term corrosion-free life is necessary. Additionally, it can be applied to wear-resistant applications, mill rolls, gas turbines, pumps, chemical plants, glass moulds, and dimensional restoration and repair. heat exchangers, wearing plates, pump bushings, medical devices, automotive, oil refining, aerospace, and agricultural, among other industries.
Iron based alloys	Chemical processing facilities, steel rolling mills, gas turbines, hydraulic and steam turbines, and transient cardiovascular applications, among others.
Cu, Al, Ag & Ti alloys	Utilised in applications such as aerospace and military, dimensional restoration and repair, improved erosion and corrosion resistance, and electrical conductivity.
Organic coatings	Agricultural harvesting parts, machine maintenance, oil drilling components, biomedical applications, infrastructure, anti-fouling, aerospace, and military applications, among others.
Nano crystalline coatings	Applications in automotive, aerospace, and aviation Increasing hardness and resisting oxidation behaviour are general applications for thermal barrier coating on parts that are exposed to extremely high temperatures in order to enhance their performance, longevity, and tribological qualities. Examples of these components are boiler tubes and gas turbine parts.

Table 1: Applications of cold gas dynamic spray coating materials [52–69].

Although cold gas dynamic spray is typically used to coat materials like Cu and Al, high strength temperature-resistant materials like Stellite 6, Inconel 625, Waspaloy, and Inconel 718 are now frequently used to restore the coating's microstructure and hardness due to ongoing improvements in the spraying procedure and parameters.

Surface modification techniques, including thermal spray processes like HVOF and plasma spraying, play a crucial role in enhancing the performance and extending the lifespan of engineering components. Research has extensively investigated the oxidation and erosion-corrosion behavior of coatings applied to boiler steels using these techniques [70-73], as well as the broader impact of surface modification on preventing failure in IC engine parts [74]. In particular, cold spray technology has demonstrated effectiveness in combating wear in hydraulic turbine steels, with studies focusing on the deposition behavior and cavitation erosion performance of WC-Co coatings [75, 76]. Furthermore, comprehensive reviews have highlighted the importance of carbide-based thermal-sprayed coatings for boiler steel protection [77] and the potential of high entropy alloy-based coatings across various applications [73], demonstrating the breadth of research dedicated to improving material performance through advanced coating solutions. The insights gained from these studies are vital for informing the development and optimization of coating processes, an area where AI/ML can play an increasingly significant role in the future. Various researchers [78-85] reported that thermal spray coatings are influenced by processing conditions. Research focuses on combating hot corrosion in boilers using these coatings, analyzing performance factors like process parameters and heat treatment. Studies also examine coating behavior in boiler environments, including erosion-corrosion and oxidation of wire arc sprayed coatings.

V. Role of Artificial Intelligence (AI) and Machine Learning (ML)

Applications of machine learning (ML) and artificial intelligence (AI) in manufacturing and materials science are growing. AI/ML can be applied to thermal spray processes for material design, defect identification, coating quality prediction, and process optimisation [86]. This paper will also provide a brief overview of the potential applications of AI/ML in thermal spray."

VI. Role of AI and ML in Thermal Spray

A. *Process Optimization*

Large datasets produced by thermal spray techniques can be analysed by AI/ML algorithms to determine the best settings for obtaining the required coating qualities.[87]For instance, ML models can forecast how coating properties (porosity, hardness, and adhesion) and spray parameters (temperature, gas flow rate, and powder feed rate) will interact. This can improve process efficiency and lessen the need for trial-and-error experiments.[88]

B. *Coating Quality Prediction*

In-situ monitoring data can be used to train machine learning models that predict coating quality in real-time. AI can forecast coating characteristics and identify any flaws throughout the spraying process by evaluating data from sensors that measure temperature, particle velocity, and other process variables. This makes it possible to take corrective action and guarantee high-quality coatings. [89]

C. Defect Detection

Defects in thermal spray coatings can be automatically detected using computer vision and deep learning techniques. By identifying cracks, porosity, or other flaws in photos or other sensor data, AI systems can enhance quality control and lessen the need for human inspection. [90]

D. Material Design

Additionally, AI/ML can help with the creation of novel coating materials with improved qualities. Artificial intelligence (AI) can recommend new materials or optimise current ones for particular thermal spray applications by evaluating data on the relationship between material composition, microstructure, and performance.[91]

E. Challenges and Future Directions

Even though AI/ML has a lot of promise for thermal spray, there remain obstacles to overcome. These include the intricacy of thermal spray processes, the requirement for sizable and superior datasets, and the creation of strong and trustworthy AI models. [92] In order to develop intelligent thermal spray systems, future research should concentrate on resolving these issues and investigating the integration of AI/ML with other cutting-edge manufacturing technologies."[92]

VII. CONCLUSION

For a variety of applications, thermal spray methods offer a flexible way to apply coatings. In this industry, cold spray is a crucial technology that provides special advantages. The capabilities and influence of coating technologies across sectors will continue to grow as a result of the continuous advancement of thermal spray techniques and the growing role of AI/ML.

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