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PERSPECTIVE

How to Unleash the Remarkable Potential of Cold Spray: A Perspective

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Abstract Cold spray is a solid-state, powder-based consolidation technique for deposition of coatings, component repair and near-net-shape additive manufacturing. Its unique attributes have propelled the development and commercialization, yet cold spray has only experienced limited deployment. In fact, cold spray technology could be extended to a considerably broader range of applications and achieve a much higher level of industry adoption by focusing on innovative ways to unlock current roadblocks that prevent it from reaching its full potential. Cold spray R&D efforts have doubled during the last decade and along with new industry applications and novel demands provide both a strong body of knowledge and market pull to identify and address these roadblocks. This paper offers the authors' perspective on what are the next steps to be taken in cold spray R&D to unleash its remarkable potential.

Keywords cold gas dynamic spraying · cold spray · feedstock preparation · in situ monitoring · laser surface treatment · optical diagnostics · optical sensors

Introduction

In the cold spray process, micron size powder particles are accelerated to supersonic velocities by a high-pressure gas jet passing through a convergent-divergent de Laval type nozzle (Ref 1-5). The solid-state particles undergo high strain rate plastic deformation upon high kinetic energy impact on a substrate at temperatures below their melting point and bond to the surface to form a layer. Due to the low heat input, the powder material does not experience undesirable phase transformation or chemical reactions and oxidation is typically minimal. In addition, the low thermal load on the substrate enables the use of this process for repair without inducing excessive thermal stresses on the part. Although the concept of consolidating powders using kinetic energy was reported over a century ago, the cold spray process as a viable technology resulted from a study, performed in a wind tunnel, on the effect of supersonic impact of particles of different nature onto objects (Ref 1). The intriguing behavior of such particles, either sticking to the surfaces or rebounding, led to a rapidly expanding research field as evidenced in Fig. 1, showing the number of peer-reviewed publications per year since the first paper published by Alkimov et al. in 1990 (Ref 6) and then later after the development of the cold spray process technology (Ref 7). Since the introduction of the first commercial cold spray system in the 2000s, significant improvements have been made that allow application of dense deposits of a larger variety of materials by virtue of higher operating pressure and temperature capabilities, in addition to innovative nozzle materials, geometries and nozzle-injector assembly designs.

Compared to conventional additive manufacturing (AM) techniques, cold spray offers the advantage of multi-material buildup at high rates. It can be strategically used in

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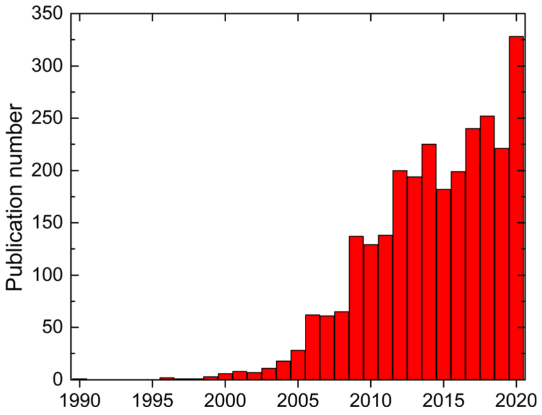

Fig. 1 Publication on cold spray by year from search on Scopus with the following search strategy ("cold spray" or "cold spraying" or "cold sprayed" or "gas dynamic spray" or "gas dynamic spraying" or "gas dynamic sprayed" or "kinetic spray" or "kinetic spraying" or "kinetic sprayed" or "kinetic metallization" or "supersonic deposition"). Results were reviewed those irrelevant to cold spray technology were removed

combination with conventional manufacturing technologies to fabricate functional components on parts, reducing material waste and costs while increasing both material and part design flexibility. Moreover, the cold spray process operates under normal atmospheric conditions and is thereby inherently scalable to large parts as no inert gas or vacuum environment is required. These characteristics of cold spray give rise to a new degree of freedom in AM that can lead to innovation in manufacturing. Therefore, the cold spray technique is viable for a wide range of applications in diverse sectors. These applications include thermal and nuclear power plants, protective coatings, catalysts, high power line connecting switches, sputtering targets, induction heating cookware, to name a few. Currently, one of the main applications of cold spray is the dimensional restoration of damaged parts, for example corroded or worn, in particular for expensive aircraft parts. This extends to other industrial parts, such as bearings, pistons, valves and pump components. Dimensional restoration can be performed in a robotized cold spray cell but also by using portable systems with handheld operated guns. Most of these repairs have simple geometries, where the material is deposited using a raster movement over a surface or a linear movement on the part placed on a rotating table or lathe. The deposited materials generally need to meet strict dimensional requirements for the application and, therefore, machining or grinding to the final dimension is performed, post-cold spray.

The first barrier for a broader deployment of the cold spray technique is deficient properties of the as-deposited material, with cold spray deposits generally exhibiting poor strength and ductility as compared to bulk counterparts. For free-standing parts where good inter-particle interfaces and very low porosity is obtained, it is possible to perform a heat treatment to improve the deposited material to reach bulk properties. However, for deposits on a base material or substrate, heat treatment of the whole part could degrade the base material properties and, in some cases, would be impractical. Innovative ways to improve the as-deposited properties and/or to perform localized heat treatment on the deposited material could lead to a significant breakthrough for this technology. It should also be noted that most current industrial cold spray applications are using feedstock materials with a "reasonable" level of ductility/deformability and hence, are relatively easy to deposit. Despite demonstrations of hard material deposition are of great interest, they remain, however, anecdotal.

Another challenge is the relatively low geometrical control and precision of the final dimensions of the deposits. For coating applications using cold spray, the coating procedure is relatively well established. The cold spray gun (nozzle) is scanned over the surface using a small overlap between spray tracks, with masking sometimes employed to protect against overspray and better define the deposit outline. During path planning, the track overlap can be optimized to produce a uniform thickness by accounting for the spray track width and profile. The minimum spot size of typical commercial cold spray nozzles is $\sim$4 mm and a profile is obtained across this diameter due to variations in the gas/particle flow from the nozzle center to wall (Ref 8). However, the size and profile of spray tracks, along with the lack of robust toolpath planning tools, limit the use of cold spray for more geometrically complex AM applications. Finally, the cold spray technique consistency and reliability need to be improved for its broader adoption for mass production applications and to facilitate the development of cold spray as an AM technology.

Cost of equipment, consumables and powder as well as limitations in terms of operating gas temperature and pressure besides nozzle clogging issues are other barriers responsible for slow deployment of the cold spray technology.

This paper presents core elements that are required for the future development and industrial adoption of the cold spray technology for a broader range of applications, including (1) tailoring powders specifically for cold spray, (2) developing a hybrid cold spray approach and (3) integrating Industry 4.0 concepts (digital twin of a cold spray manufacturing cell). These core elements are the basis of the research program at the McGill-NRC cold spray facility. Topics presented in (1) and (2) are at the outmost importance for the rapid and wide acceptance of cold spray by many sectors of the industry while topic (3) aims to position the technology within the era of Industry 4.0, where the integration of cyber-manufacturing and state-of-the-art machine learning methods is expected to greatly improve process efficiency and reliability, product quality and domain knowledge discovery.

Tailoring Powders Specifically for Cold Spray

Cold spray users mostly relied on using powder feedstocks designed or optimized for other processes, mainly conventional powder metallurgy (e.g., pressing and sintering, MIMS, HIP) or thermal spray. Concomitant with the strong adoption of laser and electron beam powder bed fusion based metal AM techniques, more spherical powders produced by gas or plasma atomization, exhibiting narrower particle size distributions and higher purity are becoming available and can be used advantageously for cold spray. With these commercially available powders, the three metrics typically used for powder specifications for cold spray are size distribution, morphology and chemistry. Beyond these three metrics, powder microstructure (and therefore mechanical properties) and surface state are paramount to maximize the cold sprayability and consistently obtain the targeted properties. Indeed, cold spray of non-optimized powders imposes limitations on the range of sprayable materials, prevents achieving optimal deposit properties and may lead to low deposition efficiencies, powder losses and additional processing costs. Clearly, in order to accelerate commercialization and industrialization of cold spray, powder feedstocks need to be specifically designed for cold spray. Powder feedstock characteristics need to be manipulated to maximize (1) cold sprayability, (2) deposit properties, and (3) manufacturing reproducibility, all while maintaining control of costs.

Cold Sprayability

Powder cold sprayability encompasses (1) powder flowability and (2) powder ability to deposit.

Powder Flowability

Powder flowability depends on various factors such as powder morphology, size, surface roughness and chemistry (Ref 9-11). Good flowablity is essential for a proper and constant powder feeding during the cold spray process and, thus, to ensure a uniform deposited thickness per pass/layer. It is also a key factor in preventing powder feeder, injector or nozzle clogging issues that could arise by a sudden change in the feed rate. The flowability of a powder can change over time, for example, due to the presence of moisture resulting from the powder storage and handling conditions. Lack of good and constant flowability is a roadblock for full industrialization of the cold spray process for specific materials, as it is one of the factors limiting cold spray reliability as a precise AM technology.

Powder Ability to Deposit

The ability of powder to deposit depends on its acceleration by the gas jet and its subsequent deformation and adhesion upon impact to the substrate or the previously deposited particles. It is generally accepted that within the window of deposition, the ratio of particle velocity over critical velocity, the minimum velocity beyond which the particles deposit (Ref 12, 13), should be maximized to obtain, not only high deposition efficiency, but also strong inter-particle bonding, yielding optimal deposit properties (Ref 14). For a given material and set of cold spray process parameters, powder characteristics, such as particle size, shape and surface roughness, can be optimized to maximize the particle velocity. Powder microstructure and surface chemistry profoundly impact the cold spray process characteristics and coating properties. For example, changing the surface by formation of superficial oxide scale on copper powder results in an increase in the critical velocity and therefore reduced sprayability (Ref 15). Variability in powder characteristics such as size and surface state can also cause nozzle or powder injector clogging. Powder density also directly influences the plastic deformation behavior at impact. In other words, for a given velocity, two particles of the same material with the same size but different densities, for instance due to the presence of engineered porosities, will deform differently. Furthermore, powder microstructure depends on the powder processing route and can be controlled during production through parameter adjustment and by post heat treatments. Thus, for the same material, tailoring powder microstructure can make the difference between no deposition and the deposition of a dense deposit with good inter-particle bonding allowing the attainment of bulk-like properties (or better) after an appropriate heat treatment (Ref 16).

Powder engineering is an approach that presents high potential in enhancing the ability of powder to deposit. For low pressure cold spray, ceramic particles additives have shown a strong effect on improving the deposition efficiency of metallic powders (Ref 17, 18). Likewise, metal-alloy powder blends can provides significant improvement for both sprayability and deposit properties in high-pressure cold spray due to a combination of tampering from the hard particles and improved deformation and retention of hard particles by the softer ones forming a continuous matrix. For example, it has been shown that adding a small amount of Ti to Ti6Al4V led to a significant decrease in deposit porosity (Ref 19), addition of SS316L to Fe powder has been shown to improve the deposition efficiency (Ref 20) and addition of a low amount of Al binder has allowed for the deposition of brittle NdFeB magnetic material for the fabrication of complex-shaped permanent magnets (Ref 21). In another approach, loosely agglomerated and porous particles has been shown to accelerate more and deform more easily upon impact (pseudo-deformation), producing denser and thicker cold spray deposits (Ref 22, 23). Cladding the surface of hard powder particles with softer and more ductile materials has been shown to also improve powder cold sprayability and deposit properties, which is consistent with the cold spray bonding theory based on localized deformation at the surface of the impacting particles (Ref 24, 25). Softening metallic powders via microstructural transformations through heat treatment demonstrated significant improvements in cold sprayability of different materials (Ref 26). Cold spray deposition of Al alloy powders was improved by homogenization (Ref 27) or solutionizing (Ref 28-30) heat treatments.

Deposit Properties

For a given material, deposit properties depend on the powder sprayability and the cold spray process parameters. For functional, non-structural materials, the as-deposited properties are often acceptable for industrial applications. For example, electrical and thermal properties of copper deposits were measured to be 60-80% (Ref 31, 32) and 55-80% (Ref 32) of bulk values, respectively, depending on the process conditions. Due to high strain hardening and the presence of inter-particle interfaces and micropores, the mechanical strength is, however, generally lower than that of bulk, while deposits exhibit typically very low ductility, although, some improvement can be obtained by optimizing the powder sprayability and by using He as propelling gas (Ref 27). These functional and mechanical properties can be drastically improved by performing post-process treatments (Ref 33, 34). The efficacy of post-treatments depends on the quality of the inter-particle bonding and density of the as-sprayed deposit (Ref 35-37). However, heat treatments could also affect the base material, which may be detrimental. As a consequence, cold spray structural repair or add-on structural fabrication using conventional alloys is still very limited. One possible approach is the development of new alloys tailored for cold spray that would provide high structural deposit properties. Indeed, current alloy compositions have been partly determined by conventional manufacturing limitations, such as the need for liquid metal flowability for casting, that are not relevant for cold spray. Cold spray preservation of powder microstructure due to solid-state deposition is a unique advantage over classic AM or powder metallurgy techniques, where the powder microstructure is significantly altered by melting or high-temperature sintering. Exploiting this advantage, powders tailored for cold spray could be developed to produce deposits that require minimal post-treatment. The success of this approach could lead to a breakthrough in AM and cold spray technology. Besides developing new alloy compositions, another method could consist of modifying the microstructure of commercially available powders, for instance via powder heat treatment.

Furthermore, the development of deposits from novel materials known for their exceptional properties, such as functional and structural materials comprised of nanostructured (Ref 38), amorphous alloys (Ref 39) or advanced composites materials (Ref 40) could also benefit from tailored powders that better suit the cold spray process and that would results in enhanced properties.

Manufacturing Reproducibility and Cost Efficiency

Once the key powder characteristics are identified for a given cold spray application, appropriate powder specifications should be defined relying on practical quality control tools to ensure manufacturing reproducibility. Surface state control can be particularly challenging due to the lack of simple characterization tools as well as due to its potential alteration under storage (powder aging) as most metallic powders oxidize over time and absorb moisture, yielding major variability in flowability and sprayability. In addition to storage under inert atmosphere, which may not be always practical, mitigation strategies, such as powder additives or modification of powder surfaces, for example, by addition of protective thin films, could be considered to ensure a controlled surface state.

Powder characteristics leading to good cold sprayability may, however, differ from those yielding optimized coating properties. In that context, finding the correct balance between the process cost reductions associated with higher deposition efficiency and coating properties meeting the application requirements would be the key to the development success. Ultimately, a broad adoption of feedstocks specifically designed for cold spray will also depend on the feasibility of producing them on a large scale at reasonable costs.

Accelerated Development of Tailored Cold Spray Powders

Tailoring cold spray powders is a complex and expensive task where numerous characteristics need to be taken into consideration. The ability to accelerate this R&D process while reducing costs can be drastically improved by using a comprehensive set of lab scale equipment that is the foundation of a powder development “factory”. This includes equipment that can manipulate different powder characteristics, test rigs and cold spray equipment that require only a small amount of powder for assessing the impact/deformation/consolidation behavior, and equipment for collection of reliable data to develop a fundamental understanding of the variables involved. The collected data can be used for validating and refining numerical models that can further accelerate the powder development.

Figure 2 schematically presents the proposed cold spray powder development cycle: powder tailoring or manufacturing and evaluating its cold sprayability. Powders can be acquired off the shelf and then modified, or can be produced in various compositions in a laboratory scale atomizer. These powders can then be sorted to specific size distributions in a powder classifier and their microstructures can be changed through mechanical alloying in ball milling equipment or in fluidized bed or rotational furnaces. They could be spheroidized or doped in a plasma reactor. Their surface can be changed by thermal or chemical etching, applying a thin film of a different material using a powder coater or new nanostructured or amorphous alloys can be produced through mechanical alloying.

With the evolution of high-speed imaging equipment, supersonic impact of single particle has recently been made possible and used to investigate the deposition of powder particles with size and velocity in the range used in cold spray (Ref 41). Such equipment, together with common microstructural characterization tools, could be used for evaluating the high-speed impact, deformation and bonding of single particles having various characteristics. For a set of powder characteristics, studying the impact behavior at different velocities and on different substrates could be performed with a very small amount of powder. The next step would be the use of a cold spray system with a powder feeder specifically designed to allow the injection of a few grams of powder during a very short period of time (typically 1 s). High-speed cameras can be used to image the deposition of an ensemble of particles forming a deposit at different cold spray conditions without the need for spraying kilograms of powders or meeting any flowability constraints. Powder flowability can therefore be addressed using conventional or adapted Hall or Carney flowmeter funnels still using a relatively small amount of powder for each condition (Ref 9, 11). When optimized powder characteristics and cold spray parameters are found, a larger amount of powder can be made and used in an actual cold spray system for producing coupon-scale deposits that will be tested for targeted properties.

Hybrid Cold Spray Manufacturing Cell

Although a range of cold spray equipment is available to fill various market needs, the current generation of high-pressure cold spray systems faces challenges in achieving (i) the targeted deposit material properties and (ii) the geometry control demanded by additive manufacturing. This has spurred investigations into various hybrid manufacturing routes (Ref 42).

Hybrid Cold Spray-Laser Powder Consolidation

The literature clearly indicates that, for current hard-to-spray materials, high-pressure cold spray in isolation is insufficient to obtain mechanical properties equivalent to conventional cast or wrought products (Ref 34). A hybrid cell, which pairs laser technology with cold spray, will have considerable potential for improving the properties of the as-consolidated material, although defining the process-property relationships is very challenging.

The realization of clean interfaces, without cracks and entrapped grit, is likely to be critical for effective material response to post-spray processing (e.g., heat treatment) and associated improvement in material consolidation by diffusion-related mechanisms such as “sintering” across the interfaces (Ref 33, 43). Pulsed laser ablation has been shown to have a high potential to increase the bond strength of cold spray deposition onto a substrate surface

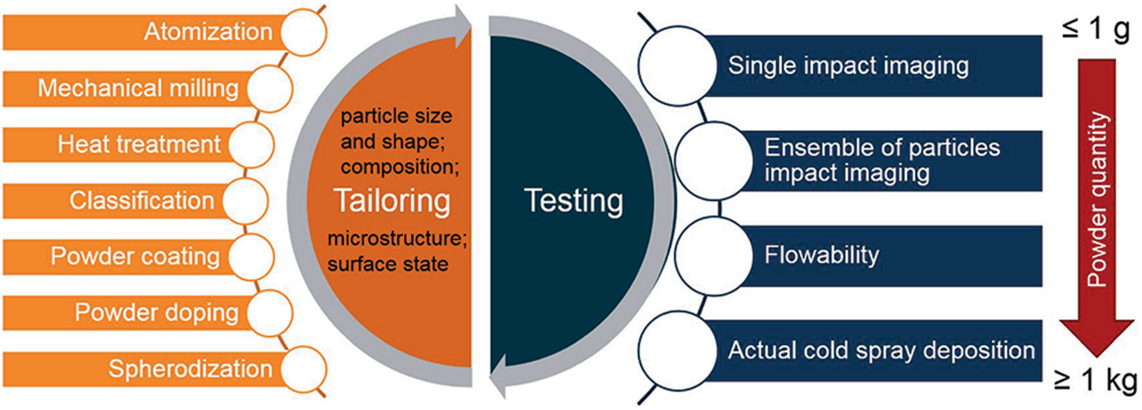

Fig. 2 Schematics cold spray powder development cycle

by removing the native oxide at the substrate surface (Ref 44-46). This non-contact, non-abrasive process also includes the important benefit of eliminating the need for chemicals or blasting media and is, of course, an excellent fit for this hybrid process. In addition to laser ablation for surface preparation, laser-assisted cold spray can be effective for improving cold sprayability (e.g., deposition efficiency) and deposit properties (e.g., bond strength, porosity) (Ref 44, 47-50). However, this type of laser-assisted spray processing is challenging because it is very difficult to accurately measure conditions at the target surface due to changing deposit emissivity during the process; thus, process modeling will be critical.

Combined Additive-Subtractive Manufacturing

For cold spray additive manufacturing (CSAM), building 3D structures featuring freeform geometry and low tolerances introduces a significant layer of complexity versus that required for typical cold spray coatings. For example, a tessellation concept can be used for producing vertical walls (Ref 51–53). In practice, the effectiveness of such build concepts is highly dependent on the capability to accurately realize the previewed evolution of the deposit throughout the build process. This presents a few general requirements: the capability to perform precise robotic manipulation of the spray gun through the complex spray paths of a cold spray AM build strategy; management of residual stresses to minimize distortions/defects; online evaluation of the deposited tracks; a means to bring the geometry back into tolerance as needed.

A hybrid cell focusing on an additive (robotic cold spray)—subtractive (robotic machining) manufacturing process, supported by lasers, combines the best attributes of CSAM (i.e., high build rate, multi-materials, solid-state) with the finishing precision and quality of advanced machining, maximizing speed, flexibility and quality, while minimizing waste.

CSAM employs a conventional AM build strategy, i.e., starting with a computer-aided design (CAD) drawing, slicing the CAD geometry into layers, and performing a layer-by-layer build (Ref 52). However, the path/trajectory planning and robot programming are challenging due to, for example, the size and profile of deposits obtained, line-of-sight and suitable nozzle access to the spray location, continuous deposition needed to maintain stable powder feeding (versus instant on/off), temperature evolution within the part/substrate. Moreover, since cold spray can be used to build features on existing parts, another complication is that the associated spray surface will not necessarily be flat; this needs to be accounted for in CSAM. The development of unique tool paths for every type of material deposit can require extensive experimentation in the absence of mass and heat transfer models.

Residual stress occurs in cold spray deposits because the process involves significant plastic deformation of powder particles. As a result, cracking within the deposit, delamination between spray layers or from the initial substrate, can occur. The hybrid cell laser (described above) can be used as a standalone tool (without simultaneous cold spray) to investigate the capacity to relieve residual stress, as well as other applicable heat treatments during the build (e.g., after a sprayed track(s), sprayed layer(s), etc.). A recent study showed the potential of the technique by stress relieving single tracks of cold sprayed copper (Ref 54). As an alternative to localized stress relieving, an industrial infrared (IR) system can also be used to investigate managing residual stress by heating over a larger area. This can be through heating the substrate, which is akin to heating the build plate in other additive manufacturing processes, and/or heat treating the cold spray deposit itself. A recent study reported using an IR system that could reduce the hardness of single tracks of cold sprayed 6061 aluminum alloy (Ref 55). Temperature monitoring and control can be performed using a two-color / dual-wavelength high-speed infrared camera or pyrometer, which can provide an accurate temperature measurement even when emissivity is not constant during the deposition process, for example with copper, or in the case of a multi-material component (Ref 56).

Integrated Non Destructive Inspection (NDI) and Process Monitoring

While development of effective build strategy and toolpath is critical for cold spray to move toward delivering near-net-shape parts, inspection and quality control of such cold sprayed complex parts becomes a challenge. New strategies have to be developed, not only for off-line, but also for online inspection. Having solutions to monitor online the geometry of added features and, furthermore, their quality, through assessment of representative properties is paramount; for this purpose, optical techniques for dimensional analysis combined with laser ultrasonics for volume probing of cold sprayed 3D structures are promising approaches (Ref 57).

Optical coherence tomography (OCT) system (Ref 57), can be used to perform online dimensional inspection at defined stages of the buildup (deposition) process and will allow rapid adjustment of the process parameters as soon as any profile discontinuities or deviations are detected. This is essential for enabling a feedback control loop in situ and dynamic adjustment of deposit thickness by adjusting robot path parameters, powder feed rate, robot machining, etc. In this way, compounded errors associated with the removal and repositioning of the substrate/workpiece between inspections will also be avoided.

As a complement to a dimensional inspection system, a laser ultrasonic system (LUT) can be used for online NDI of the integrity (e.g., adhesion, flaws, porosity) of each deposited layer (Ref 57). One particular benefit of such a capacity is in the incidence of "catastrophic" flaws; detection of such flaws during the build will allow corrections of the affected zone to be made using robot machining, as opposed to scrapping the part at the end of the build. The LUT also will greatly enhance the efficiency of experimental campaigns, yielding characterization and testing on an optimally fabricated part that also will allow for establishing a predictive flaws detection model based on machine learning algorithms employed with data generated by the numerous process control and industrial internet of things (IIoT) sensors, which will be discussed in the next section.

Robot-assisted AM is still in an early developmental stage with challenges to the hybrid cell such as: (i) combined control of the machining and CSAM robotic systems (lack of compatibility between robots and the slicing algorithms, CAD/CAM software, etc.) and (ii) the low accuracy and rigidity of robot systems relative to CNC machines (Ref 58). For hybrid cold spray, an important distinction can be made in the objectives for in-process machining versus those for the finished part. A critical factor for the former is the ability to "reset" the geometry, e.g., bring into planned tolerances with the requirement that it can be subsequently built upon without introducing a weak interface at that machined surface. The development of process automated, laser ablation as a surface preparation method within the cell (described above for substrate surfaces) will be also investigated for robotic machined surface as more suitable technology for hybrid processing (Fig. 3).

Cold Spray 4.0: Digital Twin of a Cold Spray Manufacturing Cell

Cyber-physical integration is the core of future smart manufacturing for Industry 4.0. Two concepts are cyber-physical systems (CPS) and digital twins (DTs) (Ref 60). CPS relies on integration and collaboration of computing, communication and control known as "3C." The system provides real-time sensing, information feedback, dynamic control, etc. DT integrates and supports these capabilities by incorporating high-fidelity virtual models of the physical objects in the virtual space to simulate and predict their behaviors and to perform analytics. With a complete digital footprint of the equipment and product, DT can also support product lifecycle management (PLM). DT is being explored by companies such as General Electric, Siemens and Tesla, despite several known challenges, e.g., a lack of standardization of IoT technologies (Ref 61).

For thermal spray, cyber-physical integration has been investigated in only a few studies, particularly in the form of an expert system (ES) for air plasma spray deposition. In brief, an ES emulates human expertise based on given input parameters. Kanta et al. (Ref 62) and Choudhury et al. (Ref 63) proposed an Artificial Neural Network (ANN) based method to develop a predictive model for the in-flight particle characteristic from process parameters. Kanta et al. (Ref 64) and Liu et al. (Ref 65) explored the idea of combining the ANN model with a fuzzy logic control scheme to develop an ES that can adjust and optimize the operating spray process parameters as a function of the measured in-flight particle characteristics. To the best of our knowledge, no similar work has been reported for cold spray, nor any development of a DT in general for thermal spray. For a complex process such as a hybrid cold spray manufacturing, the complete virtual model must be realized by integrating a series of sub-

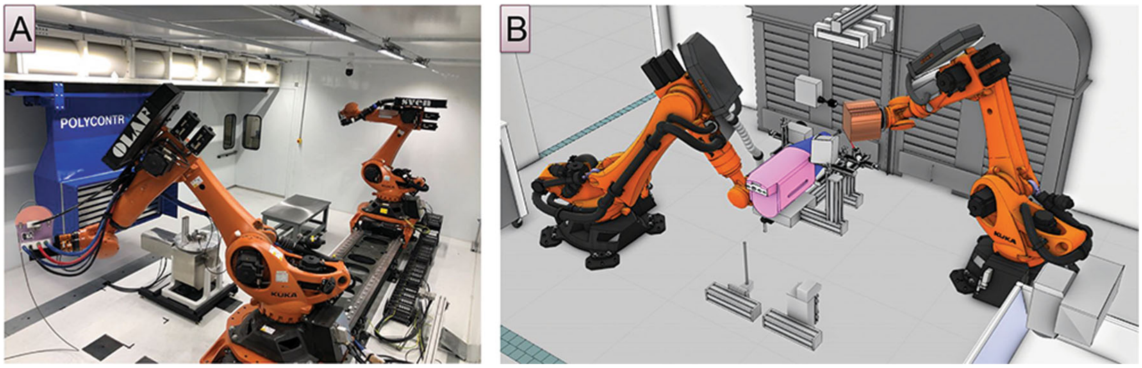

Fig. 3 Hybrid CSAM cell concept (A) picture of the POLYCSAM facility; dual robot configuration one for cold spray and one for robot machining (Ref 59) and (B) 3D drawing of the new McGill-NRC hybrid cold spray cell (Canadian Foundation for Innovation) to be commissioned in 2022; dual robot configuration one for cold spray holding laser heads and sensors and one for manipulating the part that can be brought sequentially to a stationary spindle, to the LUT and to the OCT

models, e.g., the powder feeding process, gas and particle flow, the laser processing, robotic machining and dimensional control, etc. In addition to these sub-models paired from every hardware asset of the physical process, the DT will be continuously interrogating the equipment operation input data and handling the component-to-component interaction. Furthermore, under the digital twin concept, human expertise can also be incorporated as a sub-model, similar to the ES. These sub-models can be formulated using either physics-based mathematical modeling or machine learning techniques.

Input parameters for the cold spray process may be of various forms, e.g., numerical and categorical values and sound signals or images (2D or 3D). Both structured (e.g., text and numeric) and unstructured (e.g., video images, sound) data need to be acquired, streamed, processed and exchanged in real time among the various physical and cyber components.

A sensor platform for hybrid CSAM processes monitoring could be upgraded to include directivity of acoustic sensors (microphones), spectral and imaging improvement of optical sensors (cameras and photodetectors), and continuous or pulsed narrowband illumination of the jet of particles, electrical impedance and gain refinement of sensors. The cold spray process environment is dusty and noisy, which is challenging for in situ sensing technologies. At the same time, ambient spray booth conditions should be recorded (e.g., temperature, humidity, ventilation) and bundled with the process and equipment records (e.g., robot acceleration, deceleration, vibrations). It will be important to identify what spray parameters can be monitored in situ and in real time to deliver useful data toward analytics and prediction of production problems before they occur.

Having an efficient framework to support the information exchange, including the communication network, protocols and/or database is essential. Due to its real-time nature, the DT may be deployed in a decentralized manner, i.e., a few sub-models may run at the "edge" level and a few sub-models at the server level, connected through the network. Having all the relevant information of the processes from the beginning to the end, it is evident that the DT can support the aspects of process and equipment monitoring and control and / or for instance anomaly detection. The cyber-physical infrastructure behind the "digital twin" facilitates and augments the logging, recording and storage of relevant information in databases that in turn may lead to advance the domain knowledge and furthermore to potentially new knowledge discovery (Fig. 4).

Several immediate benefits of sub-model development can be envisioned. For instance, one key challenge in the cold spray process is to maintain consistency in the powder feedstock delivery. This can be influenced by a number of aspects, including ambient temperature, moisture content, etc. By incorporating novel sensors for the cold spray equipment, vital process data, such as powder flow, propellant gas pressure and temperature, spray gun/robot movement, surface pressure and temperature on the part and in its vicinity, sound detected from the process operation, can be collected, streamed simultaneously and continuously (from various sources), and captured into a data storage system such as a SCADA-type industrial data management platform. After applying appropriate data preprocessing (data de-noising, feature extraction, etc.), these data become candidate features in a feature-selection/ranking framework to identify the most relevant ones that control the powder feedstock delivery. The appropriate feature-selection approach should be determined based on the number of available training data and candidate features (Ref 66). Techniques such as Random-Forest and Gradient-Boosting, can also highlight the relative importance of the parameters in the collected data set (Ref 67). Critical parameters may then be monitored in real time using dashboards designed via commercially available data management platform for mobile devices and/or personal computers. Ranking of the parameters also provides better direction of the next round of experiments, thus making the overall investigation more effective than the traditional design of experiment (DOE) approach.

Employing computational fluid dynamics (CFD) modeling enables the analysis of the gas flow and the particle dynamics inside the gun nozzle and even at impact with the substrate during the spray process (Ref 68). This approach can facilitate process parameter optimization through reduced DOE aimed at the optimization of the physical parameters such as particle impact velocity and temperature. Furthermore, reduced order models (e.g., using proper orthogonal decomposition (POD) methods) can be extracted from the complete CFD model for the digital twin to be used in real time. Experience gained in modeling the nozzle flow field will eventually support the investigation, for example, of another concern in cold spray that is the wear of the spray nozzle due to particle erosion. Machine learning techniques could be very effective for predicting the cold spray deposition quality and efficiency related to a specific set of factors, including the nozzle inlet, throat and exit diameter (Ref 38). Such a machine learning framework could be built based on ANN in which the input neurons are connected to the factors and the output neuron predicts outcomes such as deposition quality and efficiency (Ref 69, 70).

A key challenge in cold spray is the assessment and the design of the robotic-driven spray path for the optimization of the layer-by-layer deposition/buildup. Presently, the build strategy in cold spray employs the conventional AM

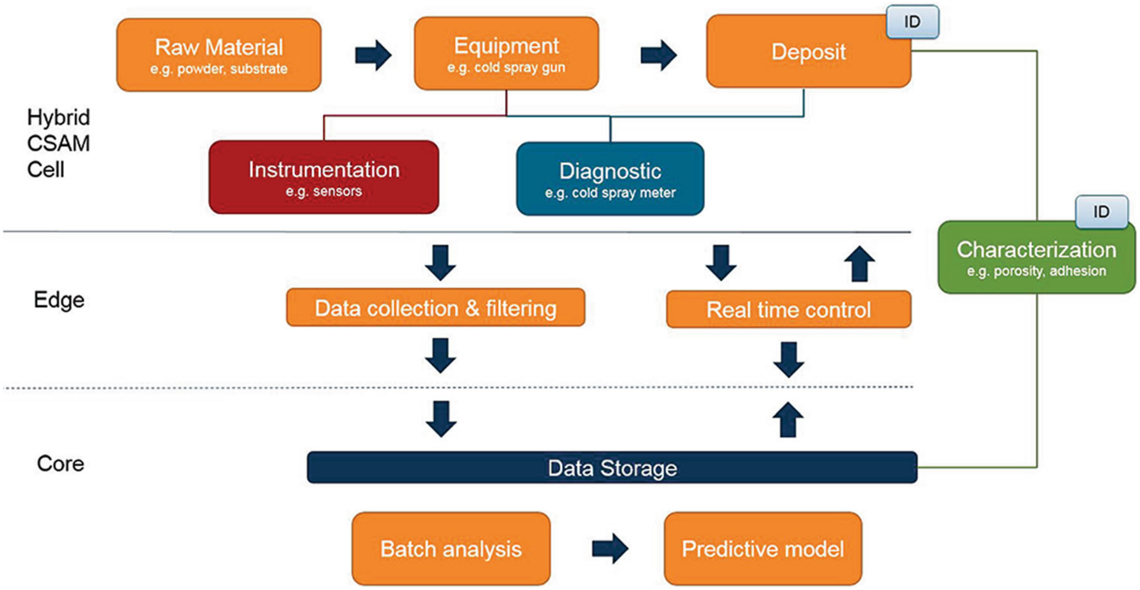

Fig. 4 Data information exchange overview

strategies but has problems specific to cold spray that require the development of unique toolpaths for every type of material deposited, which becomes even more complex with the hybrid approach. Toolpath planning could be implemented using a data-driven approach (Ref 71), or in a longer term via computer vision technology and AI based on reinforced learning. Since the build strategy is a sequential operation, the optimal toolpath for a specific geometry can be obtained by employing the advanced machine learning concepts of recurrent neural networks (RNN), such as long-short-term memory (LSTM) learning techniques (Ref 72) by which, the temporal relationship across the performance/features of sub-layers can be modeled. Considering the continuous nature of the cold spray process, deep reinforcement learning techniques can effectively control the robotic-driven spray path. As previously mentioned, for such an application of dynamic control, a two-stage analysis implementation may be needed: a fast responding analysis at the “edge” for rapid local feedback control and a batch analysis at the central server to develop the toolpath planning model.

In summary, the development of a digital twin for a cold spray hybrid cell would provide a dynamic framework for capturing the information of the spray and machining equipment and the parts, analyzing the process data of various natures, as well as optimizing process monitoring and control strategies. The DT will support and enable the CSAM experts to use data-driven approach to advance domain knowledge. Thus, the development of a DT for a hybrid CSAM cell will have a valuable impact for both the scientific and industrial communities interested in unleashing the remarkable potential of cold spray.

Conclusion

Cold spray is performed at high deposition rates in atmospheric conditions, offers multi-material AM capabilities and preserves the feedstock microstructure and phase composition while avoiding the creation of heat affected zones. Due to these unique attributes, during the past 20 years, cold spray has been receiving constantly growing attention from the research community as well as several industries, yielding significant commercial potential. Over the years, it has evolved from a coating process to a dimensional restoration tool to an additive manufacturing technique. It can now be used, for example, to produce add-on features on large parts manufactured by traditional means. This extends to the modification of parts that are manufactured out of specifications or that require a design change, or to repair damaged or worn parts, providing advantages such as shorter turnaround time, reduced material waste and lower costs. New advances in cold spray also enable deposition of a new range of materials, such as nanostructured or amorphous materials, that would be detrimentally transformed due to melting in powder bed fusion or most other direct energy AM techniques. Cold spray exhibits a unique potential for large-scale deployment addressing several industrial needs. The commercial potential of cold spray is, however, not fully exploited due to a number of technological roadblocks.

One roadblock is the relatively narrow range of materials that can be deposited due to either lack of powder sprayability or availability in the form of powder. Another roadblock is deficient properties of the as-deposited material. The low strength and ductility as compared to bulk, alongside the difficulties relative to performing heat treatment without affecting the base material, limit using this technique for structural repair and AM applications. The relatively low geometrical control and precision of the final dimensions of the deposits along with the lack of robust toolpath planning tools are additional roadblocks to the broader deployment of cold spray for more geometrically complex AM applications. Finally, consistency and reliability issues prevent broader adoption of cold spray for mass production applications and constrain its development as an AM technique.

To unleash the remarkable potential of cold spray, powder feedstocks need to be tailored specifically for cold spray at a competitive cost. Such customized powders would allow improving cold sprayability, as-deposited properties and manufacturing reproducibility, while significantly extending the range of materials that could be effectively deposited. A hybrid approach to the cold spray technique that combines laser-assistance, NDI techniques and robot machining for improved deposit integrity and dimensional control together with IIoT sensors for in-process monitoring and control would trigger the next wave of commercial deployment for industrial applications. Construction of a digital twin of the hybrid cold spray cell will allow data-driven decisions on new equipment and powder development, further unlocking potential applications with a higher level of complexity.

References

1. A. Papyrin, V. Kosarev, K.V. Klinkov and V.M. Fomin, *Cold Spray Technology*, Elsevier Ltd., Amsterdam, 2006.
2. V.K. Champagne, *The Cold Spray Deposition Process: Fundamentals and Applications*, Woodhead Publishing Ltd., Sawston, 2007.
3. R.G. Maev and V. Leshchynsky, *Introduction to Low Pressure Gas Dynamic Spray: Physics & Technology*, WILEY-VCH Verlag GmbH & Co, KGaA, 2008.
4. J. Villafuerte, *Modern Cold Spray: Materials, Process, and Applications*, Springer International Publishing, Berlin, 2015.
5. V.K. Champagne Jr., V.K. Champagne III. and C. Widener, *Cold spray applications, Cold-Spray Coatings: Recent Trends and Future perspectivesed*, Springer International Publishing, Berlin, 2017.
6. A.P. Alkhimov, V.F. Kosarev and A.N. Papyrin, A Method of 'Cold' Gas-Dynamic Deposition, *Sov. Phys. Dokl.*, 1990, **35**(12), p 1047-1049.
7. E. Irissou, J.G. Legoux, A.N. Ryabinin, B. Jodoin and C. Moreau, Review on Cold Spray Process and Technology: Part I - Intellectual Property, *J. Therm. Spray Technol.*, 2008, **17**(4), p 495-516.
8. J. Villafuerte, Considering Cold Spray for Additive Manufacturing, *Adv. Mater. Proces.*, 2014, **172**(5), p 50–52. (**in English**)
9. W. Wong, P. Vo, E. Irissou, A.N. Ryabinin, J.G. Legoux and S. Yue, Effect of Particle Morphology and Size Distribution on Cold-Sprayed Pure Titanium Coatings, *J. Therm. Spray Technol.*, 2013, **22**(7), p 1140-1153. (**in English**)
10. R.C.V. McGee, Y. She, A. Nardi, D. Goberman and Z. Dardas, Enhancement of Ti-6Al-4V Powder Surface Properties for Cold Spray Deposition Using Fluidized Gas-Nitriding Technique, *Mater. Lett.*, 2021, **290**, p 129429. (**in English**)
11. B. Young, J. Heelan, S. Langan, M. Siopis, C. Walde and A. Birt, Novel Characterization Techniques for Additive Manufacturing Powder Feedstock, *Metals*, 2021, **11**(5), p 720. (**in English**)
12. H. Assadi, F. Gartner, T. Stoltenhoff and H. Kreye, Bonding Mechanism in Cold Gas Spraying, *Acta Mater.*, 2003, **51**(15), p 4379-4394.
13. T. Schmidt, H. Assadi, F. Gartner, H. Richter, T. Stoltenhoff, H. Kreye and T. Klassen, From Particle Acceleration to Impact and Bonding in Cold Spraying, *J. Therm. Spray Technol.*, 2009, **18**(5–6), p 794-808.
14. H. Assadi, T. Schmidt, H. Richter, J.O. Kliemann, K. Binder, F. Gärtner, T. Klassen and H. Kreye, On Parameter Selection in Cold Spraying, *J. Therm. Spray Technol.*, 2011, **20**(6), p 1161-1176.
15. C.J. Li, H.T. Wang, Q. Zhang, G.J. Yang, W.Y. Li and H.L. Liao, Influence of Spray Materials and Their Surface Oxidation on the Critical Velocity in Cold Spraying, *J. Therm. Spray Technol.*, 2010, **19**(1–2), p 95-101.
16. D. Poirier, Y. Thomas, B. Guerreiro, M. Martin, M. Aghasibeig and E. Irissou, Improvement of Tool Steel Powder Cold Sprayability via Softening and Agglomeration Heat Treatments, *J. Therm. Spray Technol.*, 2021 https://doi.org/10.1007/s11666-022-01320-4
17. E. Irissou, J.G. Legoux, B. Arsenault and C. Moreau, Investigation of Al-Al 2O 3 Cold Spray Coating Formation and Properties, *J. Therm. Spray Technol.*, 2007, **16**(5–6), p 661-668. (**in English**)
18. A. Sova, A. Papyrin and I. Smurov, Influence of Ceramic Powder Size on Process of Cermet Coating Formation by Cold Spray, *J. Therm. Spray Technol.*, 2009, **18**(4), p 633-641. (**in English**)
19. H. Aydin, M. Alomair, W. Wong, P. Vo and S. Yue, Cold Sprayability of Mixed Commercial Purity Ti Plus Ti6Al4V Metal Powders, *J. Therm. Spray Technol.*, 2017, **26**(3), p 360-370. (**in English**)
20. X. Chu, H. Che, C. Teng, P. Vo and S. Yue, Understanding Particle-Particle Interactions from Deposition Efficiencies in Cold Spray of Mixed Fe/316L Powders with Different Particle Size Combinations, *J. Therm. Spray Technol.*, 2020, **29**(3), p 413-422. (**in English**)
21. J.M. Lamarre and F. Bernier, Permanent Magnets Produced by Cold Spray Additive Manufacturing for Electric Engines, *J. Therm. Spray Technol.*, 2019, **28**(7), p 1709-1717. (**in English**)
22. P.H. Gao, Y.G. Li, C.J. Li, G.J. Yang and C.X. Li, Influence of Powder Porous Structure on the Deposition Behavior of Cold-Sprayed WC-12Co Coatings, *J. Therm. Spray Technol.*, 2008, **17**(5–6), p 742-749.
23. T. Sonoda, T. Kuwashima, T. Saito, K. Sato, H. Furukawa, J. Kitamura, D. Ito, Super hard WC cermet coating by low pressure

cold spray based on optimization of powder properties, Proceedings of the International Thermal Spray Conference, 2013, pp 241-245.

24. J. Wang, J. Villafuerte, A novel method to spray tungsten carbide using low pressure cold spray technology, Ceramic Transactionsed., 2009, p 161-168.
25. G.P. Bracker, E. Hodges, M. Scott, R. Berdos, J. Rigali, V.K. Champagne and R.W. Hyers, TMS 2020 149th annual meeting and exhibition of the minerals, metals and materials society, *Electroplating Powder for Cold Spray Applications*. Z. Peng, J.Y. Hwang, J. Downey, D. Gregurek, B. Zhao, O. Yucel, E. Keskinkilic, T. Jiang, J. White, M. Mahmoud Ed., Springer, Cham, 2020, p 769-774
26. W.D. Callister, *Materials Science and Engineering: An Introduction*, Wiley, Hoboken, 2000.
27. M.R. Rokni, A.T. Nardi, V.K. Champagne and S.R. Nutt, Effects of Preprocessing on Multi-Direction Properties of Aluminum Alloy Cold-Spray Deposits, *J. Therm. Spray Technol.*, 2018, **27**(5), p 818-826. (**in English**)
28. A. Sabard, H.L. de Villiers Lovelock and T. Hussain, Microstructural Evolution in Solution Heat Treatment of Gas-Atomized Al Alloy (7075) Powder for Cold Spray, *J. Therm. Spray Technol.*, 2018, **27**(1–2), p 145-158. (**in English**)
29. W.A. Story and L.N. Brewer, Heat Treatment of Gas-Atomized Powders for Cold Spray Deposition, *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.*, 2018, **49**(2), p 446-449. (**in English**)
30. T. Liu, W.A. Story and L.N. Brewer, Effect of Heat Treatment on the Al-Cu Feedstock Powders for Cold Spray Deposition, *Metall. Mater. Trans. A*, 2019, **50**(7), p 3373-3387.
31. T. Stoltenhoff, C. Borchers, F. Gartner and H. Kreye, Microstructures and Key Properties of Cold-Sprayed and Thermally Sprayed Copper Coatings, *Surf. Coat. Technol.*, 2006, **200**(16–17), p 4947-4960.
32. Y. Itoh, S. Suyama and H. Fukanuma, Thermal and Electrical Properties of Copper Coatings Produced by Cold Spraying, *Zairyo/J. Soc. Mater. Sci. Japan*, 2010, **59**(2), p 143-148.
33. W. Sun, A.W.Y. Tan, K. Wu, S. Yin, X. Yang, I. Marinescu and E. Liu, Post-Process Treatments on Supersonic Cold Sprayed Coatings: A Review, *Coatings*, 2020, **10**(2), p 123. (**in English**)
34. W. Li, K. Yang, S. Yin, X. Yang, Y. Xu and R. Lupoi, Solid-State Additive Manufacturing and Repairing by Cold Spraying: A Review, *J. Mater. Sci. Technol.*, 2018, **34**(3), p 440-457. (**in English**)
35. W. Wong, E. Irissou, P. Vo, M. Sone, F. Bernier, J.G. Legoux, H. Fukanuma and S. Yue, Cold Spray Forming of Inconel 718, *J. Therm. Spray Technol.*, 2013, **22**(2–3), p 413-421. (**in English**)
36. R. Huang, M. Sone, W. Ma and H. Fukanuma, The Effects of Heat Treatment on the Mechanical Properties of Cold-Sprayed Coatings, *Surf. Coat. Technol.*, 2015, **261**, p 278-288. (**in English**)
37. P. Vo, D. Goldbaum, W. Wong, E. Irissou, J.G. Legoux, R.R. Chromik and S. Yue, *Cold-Spray Processing of Titanium and Titanium Alloys, Titanium Powder Metallurgy: Science, Technology and Applicationsed*, Elsevier Inc., Amsterdam, 2015.
38. A. Moridi, S.M. Hassani-Gangaraj, M. Guagliano and M. Dao, Cold Spray Coating: Review of Material Systems and Future Perspectives, *Surf. Eng.*, 2014, **30**(6), p 369-395. (**in English**)
39. Q. Wang, P. Han, S. Yin, W.J. Niu, L. Zhai, X. Li, X. Mao and Y. Han, Current Research Status on Cold Sprayed Amorphous Alloy Coatings: A Review, *Coatings*, 2021, **11**(2), p 206.
40. L. He and M. Hassani, A Review of the Mechanical and Tribological Behavior of Cold Spray Metal Matrix Composites, *J. Therm. Spray Technol.*, 2020, **29**(7), p 1565-1608. (**in English**)
41. M. Hassani-Gangaraj, D. Veysset, K.A. Nelson and C.A. Schuh, In-situ Observations of Single Micro-particle Impact Bonding, *Scr. Mater.*, 2018, **145**, p 9-13. (**in English**)
42. W. Li, C. Cao, G. Wang, F. Wang, Y. Xu and X. Yang, 'Cold spray +' as a New Hybrid Additive Manufacturing Technology: A Literature Review, *Sci. Technol. Weld. Join.*, 2019, **24**(5), p 420-445. (**in English**)
43. P. Vo, E. Irissou, J.G. Legoux and S. Yue, Mechanical and Microstructural Characterization of Cold-Sprayed Ti-6Al-4V After Heat Treatment, *J. Therm. Spray Technol.*, 2013, **22**(6), p 954-964. (**in English**)
44. M. Perton, S. Costil, W. Wong, D. Poirier, E. Irissou, J.G. Legoux, A. Blouin and S. Yue, Effect of Pulsed Laser Ablation and Continuous Laser Heating on the Adhesion and Cohesion of Cold Sprayed Ti-6Al-4V Coatings, *J. Therm. Spray Technol.*, 2012, **21**(6), p 1322-1333.
45. R. Kromer, S. Costil, C. Verdy, S. Gojon and H. Liao, Laser Surface Texturing to Enhance Adhesion Bond Strength of Spray Coatings – Cold Spraying, Wire-arc Spraying, and Atmospheric Plasma Spraying, *Surf. Coat. Technol.*, 2018, **352**, p 642-653. (**in English**)
46. D.K. Christoulis, S. Guetta, E. Irissou, V. Guipont, M.H. Berger, M. Jeandin, J.G. Legoux, C. Moreau, S. Costil, M. Boustie, Y. Ichikawa and K. Ogawa, Cold-Spraying Coupled to Nano-pulsed Nd-YaG Laser Surface Pre-treatment, *J. Therm. Spray Technol.*, 2010, **19**(5), p 1062-1073.
47. L. Yang, Z. Li, C. Huang, P. Wang and J. Yao, Producing Hard Material Coatings by Laser-assisted Cold Spray: A Technological Review, *Cailiao Daobao/Mater. Rev.*, 2018, **32**(2), p 412.
48. D.J. Barton, V.S. Bhattiprolu, G.B. Thompson and L.N. Brewer, Laser Assisted Cold Spray of AISI 4340 Steel, *Surf. Coat. Technol.*, 2020, **400**, p 126218. (**in English**)
49. D.J. Barton, B.C. Hornbuckle, K.A. Darling, L.N. Brewer and G.B. Thompson, Influence of Surface Temperature in the Laser Assisted Cold Spray Deposition of Sequential Oxide Dispersion Strengthened Layers: Microstructure and Hardness, *Mater. Sci. Eng. A*, 2021, **811**, p 141027. (**in English**)
50. E.O. Olakanmi and M. Doyoyo, Laser-Assisted Cold-Sprayed Corrosion- and Wear-Resistant Coatings: A Review, *J. Therm. Spray Technol.*, 2014, **23**(5), p 765-785. (**in English**)
51. J. Pattison, S. Celotto, R. Morgan, M. Bray and W. O'Neill, Cold Gas Dynamic Manufacturing: A Non-thermal Approach to Freeform Fabrication, *Int. J. Mach. Tools Manuf*, 2007, **47**(3–4), p 627-634.
52. P. Vo, M. Martin, Layer-by-layer buildup strategy for cold spray additive manufacturing, International Thermal Spray Conferenceed., DVS Media GmbH, Düsseldorf 2017, p 714-718.
53. A. Vargas-Uscategui, P.C. King, S. Yang, C. Chu and J. Li, Toolpath Planning for Cold Spray Additively Manufactured Titanium Walls and Corners: Effect on Geometry and Porosity, *J. Mater. Process. Technol.*, 2021, **298**, p 117272.
54. B. Hunter, B. Aldwell, R. Jenkins and R. Lupoi, A Study on the Feasibility of Laser Annealing to Relieve Residual Stresses in Cold Spray Coatings, *Proc. CIRP*, 2018, **78**, p 91-96.
55. R. Jenkins, B. Aldwell, S. Yin and R. Lupoi, Modelling and Experimental Testing of a Novel Focused Infrared Heater for Use with Cold Spray, *Proc. CIRP*, 2018, **78**, p 97-102.
56. F. Di Carolo, L. Savino, D. Palumbo, A. Del Vecchio, U. Galietti and M. De Cesare, Standard Thermography vs Free Emissivity Dual Color Novel CIRA Physics Technique in the Near-Mid IR ranges: Studies for Different Emissivity Class Materials from Low to High Temperatures Typical of Aerospace Re-entry, *Int. J. Therm. Sci.*, 2020, **147**, p 106123.
57. C.V. Cojocaru, P. Vo, D. Levesque, C. Bescond, M. Rivard, J. Boisvert, G. Lamouche, M. Martin and E. Irissou, Dimensional analysis and laser-ultrasonic inspection of cold spray additive manufacturing components, *Cold Spray in the Realm of Additive Manufacturing*. S. Pathak, G. Saha Ed., Springer, Cham, 2020

58. P. Urhal, A. Weightman, C. Diver and P. Bartolo, Robot Assisted Additive Manufacturing: A Review, *Robot. Comput.-Integr. Manuf.*, 2019, **59**, p 335-345.
59. J. Oberste-Berghaus, E. Irissou, M. Martin, L. Pouliot, F. Caio, S. Desaulniers and B. Monsarrat, Polycsam: Boosting Cold Spray Additive Manufacturing Into Full-Scale Production: A Joint Canadian Venture Launches a New Facility with an Innovative Hybrid Approach to Cold Spray Additive Manufacturing, *Adv. Mater. Process.*, 2020, **178**(3), p 39–80 (**in English**).
60. F. Tao, Q. Qi, L. Wang and A.Y.C. Nee, Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison, *Engineering*, 2019, **5**(4), p 653-661.
61. N. Higgins, K. Fowler, C. Fowler, S. Singh, E. Shehab, T. Tomiyama, Challenges of Digital Twin in High Value Manufacturing, ed., SAE International, 2018.
62. A.F. Kanta, M.P. Planche, G. Montavon and C. Coddet, In-flight and Upon Impact Particle Characteristics Modelling in Plasma Spray Process, *Surf. Coat. Technol.*, 2010, **204**(9–10), p 1542-1548.
63. T.A. Choudhury, N. Hosseinzadeh and C.C. Berndt, Artificial Neural Network Application for Predicting In-flight Particle Characteristics of an Atmospheric Plasma Spray Process, *Surf. Coat. Technol.*, 2011, **205**(21-22), p 4886–4895.
64. A.F. Kanta, G. Montavon, C.C. Berndt, M.P. Planche and C. Coddet, Intelligent System for Prediction and Control: Application in Plasma Spray Process, *Expert Syst. Appl.*, 2011, **38**(1), p 260-271.
65. T. Liu, M.P. Planche, A.F. Kanta, S. Deng, G. Montavon, K. Deng and Z.M. Ren, Plasma Spray Process Operating Parameters Optimization based on Artificial Intelligence, *Plasma Chem. Plasma Process.*, 2013, **33**(5), p 1025-1041.
66. N. Armanfard, J.P. Reilly and M. Komeili, Local Feature Selection for Data Classification, *IEEE Trans. Pattern Anal. Mach. Intell.*, 2016, **38**(6), p 1217-1227.
67. R.K. Yu, C.V. Cojocaru, S. Tremblay, F. Ilinca, E. Irissou, On the consideration of electrodes ageing for the prediction of in-flight particle characteristics of atmospheric plasma spray using decision tree model, International Thermal Spray Conferenceed., ASM International, 2019.
68. S. Yin, M. Meyer, W. Li, H. Liao and R. Lupoi, Gas Flow, Particle Acceleration, and Heat Transfer in Cold Spray: A review, *J. Therm. Spray Technol.*, 2016, **25**(5), p 874-896. (**in English**)
69. Z. Cheng, H. Wang and G.R. Liu, Deep Convolutional Neural Network Aided Optimization for Cold Spray 3D Simulation Based on Molecular Dynamics, *J. Intell. Manuf.*, 2021, **32**(4), p 1009-1023. (**in English**)
70. H. Canales, I.G. Cano and S. Dosta, Window of Deposition Description and Prediction of Deposition Efficiency via Machine Learning Techniques in Cold Spraying, *Surf. Coat. Technol.*, 2020, **401**, p 126143. (**in English**)
71. D. Ikeuchi, A. Vargas-Uscategui, X. Wu and P.C. King, Data-efficient Neural Network for Track Profile Modelling in Cold Spray Additive Manufacturing, *Appl. Sci. Switzerland*, 2021, **11**(4), p 1654. (**in English**)
72. T.N. Sainath, O. Vinyals, A. Senior, H. Sak, Convolutional, Long Short-Term Memory, fully connected Deep Neural Networks, ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing - Proceedings, 2015, pp 4580-4584.