Int J Adv Manuf Technol (2013) 69:2269–2278
DOI 10.1007/s00170-013-5166-8

ORIGINAL ARTICLE

Potential of cold gas dynamic spray as additive manufacturing technology

A. Sova · S. Grigoriev · A. Okunkova · I. Smurov

Received: 27 March 2013 / Accepted: 28 June 2013 / Published online: 2 August 2013

Abstract In this paper, the application of cold spray (CS) coating deposition technology as additive manufacturing technique is discussed. Absence of material melting during CS deposition permits to obtain deposits with low value of residual stresses and to preserve the phase composition of source material which is a very important advantage. In this paper, the latest developments in the field of cold spray such as micronozzle device and new multimaterial deposition approach permitting to significantly enlarge the potential of cold spray as additive manufacturing technology is discussed.

Keywords Cold spray · Additive manufacturing · Freeforming · Nozzle

1 Introduction

Additive manufacturing (AM) also known as rapid manufacturing is the technology of freeform fabrication of components and parts based on layer-by-layer approach. In this approach, the part is constructed by consecutive deposition of layers corresponding to the part cross-sections. AM technologies enable the production of functional components in a single step, where the time and cost of manufacture does not depend of component complexity [1, 2]. Nowadays, several different types of AM technologies such as selective laser melting (SLM), selective laser sintering, direct metal deposition (DMD), and others are applied for fabrication of metallic freeforms for space, aviation, automotive, and other industries directly from metal powders without using any intermediate binders or any additional processing steps [3, 4]. In these technologies, energy of laser radiation is used for melting and resolidification of powder [5].

Previous studies demonstrated that cold gas dynamic spray coating deposition technology or simply cold spray (CS) could be adapted for performing of 3D object fabrication [6, 7]. In this process, the particles of deposited material are accelerated to high velocities by supersonic gas flow delivered by supersonic nozzle. If the particles velocity exceeds certain critical value, the energy of particle–substrate impact leads to intensive plastic deformation of particle and, in some cases, surface of substrate. This process breaks thin films on substrate and particles surface formed from oxides and establish intimate contact between “clean” chemically active materials of substrate and particle that leads to the creation of strong bonding. The advantage of this technique is that the amount of heat transferred to the powder or to the substrate is relatively small. Therefore, retention of the microstructure as well as the mechanical and chemical properties of the feedstock powder is facilitated [8–11]. This advantage of CS process permits to use it for deposition of temperature sensitive materials such as nanocrystalline and amorphous materials [12–14] as well as oxygen-sensitive materials like aluminum, copper, and titanium [7, 15–21].

The objective of the current paper is to analyze the advantages and disadvantages of CS as a method of freeform fabrication taking into account the latest developments made in the field of cold spray.

2 Cold spray principle

One of the possible schematics of cold spray process is presented in Fig. 1. A high-pressure (1–5 MPa) working gas

A. Sova · I. Smurov
National Engineering School of Saint-Etienne, DIPI Laboratory,
University of Lyon, Saint-Etienne, France

S. Grigoriev · A. Okunkova
MSTU Stankin, Moscow, Russia

A. Sova (✉)
ENISE/DIPI, 74 rue Des Aciéries, 42000 Saint-Etienne, France
e-mail: sova.aleksey@gmail.com

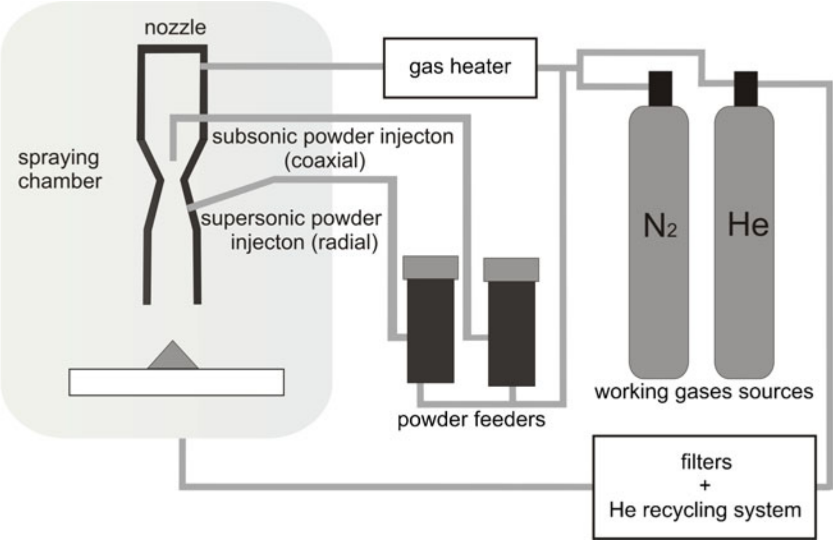


Fig. 1 Schematic view of cold spray installation with two powder feeders and two working gas sources

at flow rate ~0.5–2 kg/min is fed from the tank to a gas heater. In the gas heater, the gas flow is heated up to 1,000 °C (depending on the type of spraying material, but always lower than its melting point) and fed to the prechamber of the supersonic nozzle. A carrier gas, also fed from the high-pressure tank, transports the spraying powders from one or several powder feeders to the nozzle unit and injects the particles to its subsonic or supersonic region of the nozzle. Generally, the injection of the powder is performed coaxially; however, the radial injection could also be applied [22–24]. Application of several powder feeders permits to perform separate injection of different materials in case of deposition of multicomponent coatings. The high velocity gas/powder jet exits the nozzle and impinges with the substrate. The level of noise generated by the interaction of supersonic jet with the substrate could reach 90 dB, so the spraying should be performed in sound-protected booth.

In cold spray, the gas preheating is applied in two main reasons. Firstly, increasing of gas temperature leads to augmentation of gas flow velocity and therefore increasing of particle in-flow velocity. Secondly, due to the heat transfer between hot gas and particles, the particle temperature increases that by turn augment their plasticity and ameliorates particles deformability during impact. The Assadi equation of critical velocity shows the relationship between impact velocity and impact temperature that particle should achieve in order to adhere to the substrate [10]. In some cases, to increase the particle impact temperature, special powder preheaters are applied [25, 26].

The typical particles impact velocity and temperature in cold spray lay between 400 and 1,500 m/s and 273–1,100 K, respectively, depending on the nozzle design, gas stagnation temperature, gas stagnation pressure, particles density, and the type of working gas [8, 11]. The nozzle/substrate displacement is typically controlled by robot and rotating table that permits to make deposition on substrate of complex shapes.

Selection of working gas strongly influences on the properties of obtained deposits. Typically, three types of gases are applied as working gas in CS: air, nitrogen, and helium. Application of air as a working gas permits to decrease the operational costs but significantly increases the oxides content in the deposits in comparison with feedstock material. The velocity of sound in air is relatively low: 331 m/s at $T=273$ K. Therefore, in order to increase the particles impact velocity, the heating to a relatively high temperature is needed. Nitrogen has practically the same velocity of sound as air (~334 m/s at $T=273$ K) and also demands preheating. However, the powder oxidation in this case in minimal and mainly occurs because of air admixture from the atmosphere to the free jet. The operational costs in this case are higher than for air but still is reasonable. Application of helium as working gas permits to obtain deposits with superior quality at low gas preheating thanks to chemical neutrality of helium and its high velocity of sound (~965 m/s at $T=273$ K). The operational costs increase in several times in comparison with air or nitrogen. However, installing of helium recycling system could help to make helium more competitive [7].

3 Geometrical characteristics of spraying tracks

3.1 Spatial resolution

A very important characteristic of the AM technologies is their spatial resolution that defines precision of component manufacturing. For example, in SLM technology, the spatial resolution is defined by dimensions of laser beam and granulometry of powder [5]. The spatial resolution of cold spray is mainly defined by the dimensions and shape of the nozzle exit. Typically in cold spray, different axisymmetric nozzle is applied [27, 28]. The scheme of the supersonic axisymmetric nozzle is presented in Fig. 2.

It is important to note that all nozzle dimensions are related with each other and could not be simply varied in random manner. First of all, the ratio between the nozzle throat and the nozzle exit defines the nozzle Mach number M, and therefore the gas velocity at the nozzle exit is in accordance with the following isentropic relationship [29]:

$$\frac{d_{exit}^2}{d_{cr}^2} = \frac{\left(1+\frac{k-1}{2}M^2\right)^{\frac{k+1}{2(k-1)}}}{M\left(\frac{k+1}{2}\right)^{\frac{k+1}{2(k-1)}}}$$

Here, M is Mach number at nozzle exit, k is gas specific heat, d_{exit} and d_{cr} are nozzle exit and nozzle critical section diameter correspondingly. The same relationship defines Mach number of the gas flow at any cross section of the nozzle by replacing of d_{exit} by the value of nozzle diameter at desirable point of the nozzle. Secondly, the length of the supersonic part L_{sup} of the nozzle should be sufficient to provide necessary "accelerating path" for the particles during its movement in the gas flow. Thirdly, the relationship between the length of supersonic part and nozzle exit diameter L_{sup}/d_{exit} should not be too high. In the nozzle with high relative length, the influence of boundary layer growing on the nozzle wall on the mean gas velocity increases together with increasing of L_{sup} value that could finally lead to gas flow decelerating and even to its transition from supersonic flow regime to the subsonic one [30, 31]. And finally, the length of subsonic region strongly influences on outlet particle temperature. It is known that the heat exchange between particles and gas is most intensive in the subsonic region of the nozzle [11]. Therefore, the length of the subsonic section should be properly chosen in order to provide the optimal heating of spraying powder if injection is performed in the subsonic region of the nozzle.

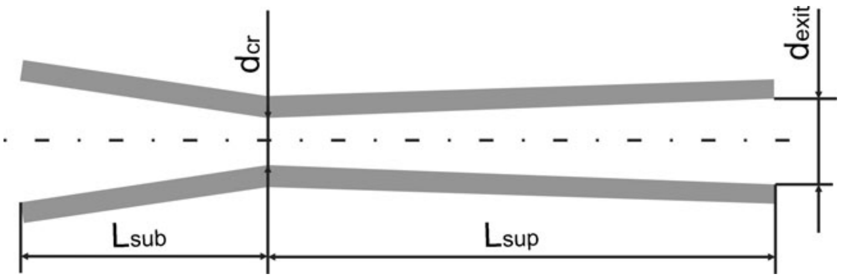
Typical exit diameters of convenient cold spray axisymmetric nozzles lay in range 4–10 mm with throat diameter of 1.5–3 mm and length 100–200 mm [8, 11, 23, 27]. Dispersion of the supersonic jet after leaving the nozzle exit is low (<0.1 d_{exit}) if the spraying distance lies in the range 1–8 d_{exit}, therefore, the diameter of spraying spot and, consequently, width of single spraying track is practically the same as the nozzle exit diameter [8]. The borders of spraying spot are narrow also due to the low dispersion of supersonic biphasic gas–particle flow, and therefore the minimum possible single track width is equal to the nozzle exit diameter and equal ~4–10 mm for convenient cold spray systems.

The last researches conducted by the authors in the field of development of cold spray nozzles show that spatial resolution of cold spray nozzle cold be significantly improved by application of so-called micronozzles with exit diameter of 1 mm or less. The study proofing and feasibility of such approach gave promising results [32, 33]. It was demonstrated that simultaneous decreasing of the nozzle length and nozzle diameter permits to create a small nozzle capable to produce narrow spray spots with a diameter less than 1 mm. In Fig. 3, photos of micronozzle and nozzle unit of micro-cold spray system with mounted micronozzle are presented. Figure 4 a, b demonstrates the photo of single spot (aluminum) deposited by micronozzle and its cross-section. One can see from the figure that the diameter of the spot does not exceed 1 mm. The coating cross-section shows that the deposit consist of strongly deformed aluminum particles; however, its porosity is elevated in comparison with convenient cold spray deposits due to smaller acceleration path. The principle limit of this approach is the necessity to apply powders of small granulometry because the length of the nozzle is not sufficient for acceleration of large particles.

It is also important to note that the nozzles of other shapes could be applied for cold spray deposition. In particular, the rectangular nozzles are applied for deposition of relatively large tracks [31]. The nozzle with special profile and gas flow swirling could be also used for deposition of coating tracks of special shape like for examples fan-shape or star-shape tracks [34]. Such nozzle design approaches also could find specific applications in cold spray additive manufacturing for fabrication of deposits with special shapes.

One can conclude that spatial resolution of cold spray as well as the shape of spraying spot and therefore of the single track could be controlled by the application of special nozzles with geometry adapted for the given demands. However, adaption of cold spray nozzle is a very complex task involving specifics of supersonic gas/powder flows.

Fig. 2 Schematic view of axisymmetric cold spray supersonic nozzle



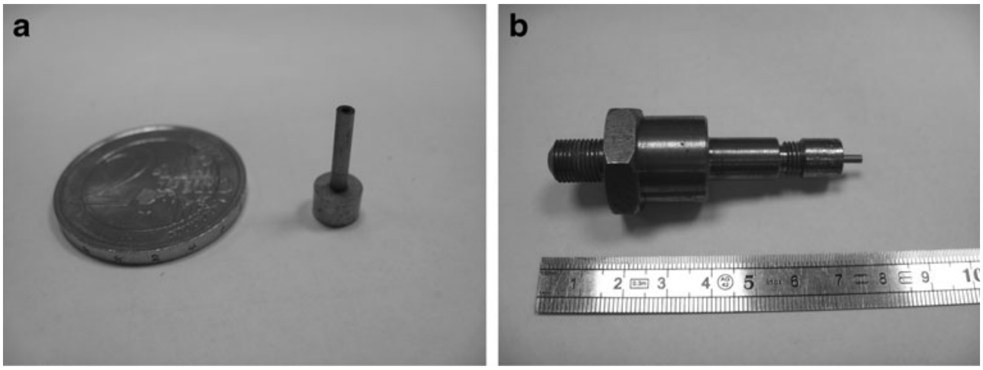


Fig. 3 Photos of cold spray micronozzle (**a**) and cold spray nozzle unite with mounted micronozzle (**b**)

3.2 Track profile

The thickness of cold spray deposits could be varied from ~10 μm to several hundred millimeters. The rate between the volume of spraying material V and the track length *F*

$$K = \frac{F}{V}$$

could be changed by controlling the nozzle traverse velocity and powder feeding rate. The particular feature of cold spray is the shape of deposits; if the *K* value is low then thin, flat tracks are obtained. If the *K* value is high, the tracks become rounded and eventually develop a sharp triangular profile [7]. It is important that such shape of thick track could not be avoided by variation of nozzle traverse speed or powder feed rate. In other words, several "rapidly" deposited consecutive tracks will lead to the formation of this triangular shape as well, as one "slow" track. Pattison et al. [7] explain this feature by influence of the following factors: Firstly, the particle distribution in the jet is quasi-Gaussian [35]. Secondly, deposition efficiency decreases with distance from the center of the jet due to the particle velocity profile across the nozzle exit and the increasing angle of impact [7, 35, 36]. When these factors combine, a greater degree of deposition is observed in the center of the jet that eventually causes the track profile to become triangular. In this situation, building of vertical wall by consecutive deposition of tracks seems to be impossible. However, in the same work, authors propose an original solution permitting to construct vertical walls. In particular, they suggest applying a 4/5-axis system. The advantage of this type of system is that by tilting the nozzle, so that it sprays normal to the inclined surface of a previous track, the material may be deposited in the correct orientation to generate a vertical surface [7]. Combination of this approach with micronozzle discussed above seems to be a promising solution for creating complex shape objects, including vertical walls with high spatial resolution.

Another way of deposition of tracks with narrow vertical walls is the combination of cold spray deposition with conventional milling technology. In this case, the deposited tracks are machined by milling cutter that permits to maintain desirable precision and shapes of deposits. An example of a successful "coupling" of cold spray device and milling machine could be found in [7].

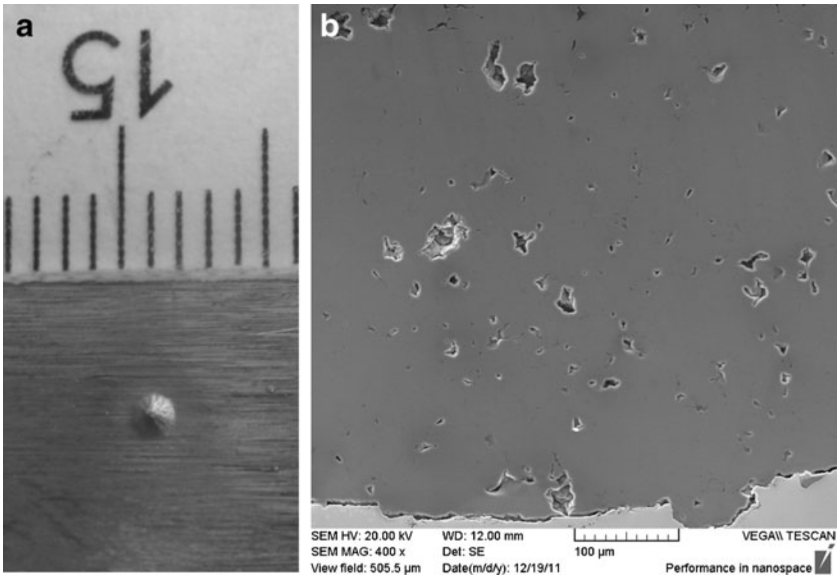


Fig. 4 Cold spray deposit obtained by in spraying aluminum powder (granulometry −35+5 μm) in one point using micronozzle: **a**—overview, **b**—cross-section. Spraying parameters: p_0=20 bar, T~300 K

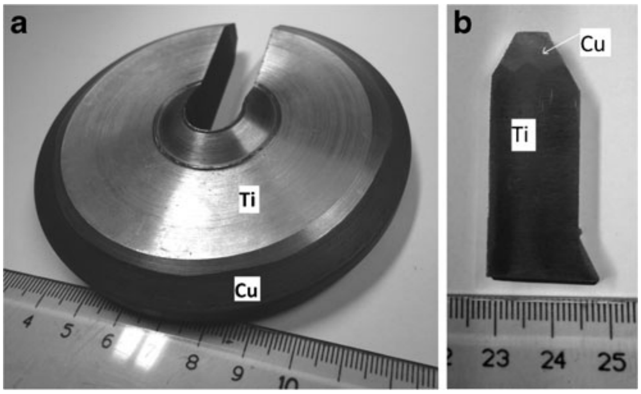


Fig. 5 Multilayer Ti–Cu object (**a**) and its cut fragment (**b**) fabricated by convenient cold spray system. Surface of part was machined by turning after cold spray deposition

4 Spraying materials

4.1 Multilayered coatings

Cold spray is able to deposit a wide range of metals and alloys like aluminum [17], zinc [37], copper [19], titanium [21], nickel and its alloys [38–40], steel [41, 42], tantalum [43], magnesium [44], silver [45], and in some cases cermet powders [25, 26]. However, the principle limit of this technology is the difficulty or impossibility to spray materials with low plasticity such for example pure ceramics [11].

The advantage of cold spray is the possibility to spray a wide range of materials on different types of substrates. For example, in SLM technology, creating of multilayered objects using materials with different coefficient of thermal conductivity and thermal expansion is an important technological problem [5]. Another issue typical for AM technologies involving material melting is creating of brittle intermetallic phases on the borders between layers of different materials that diminish mechanical properties of fabricated part.

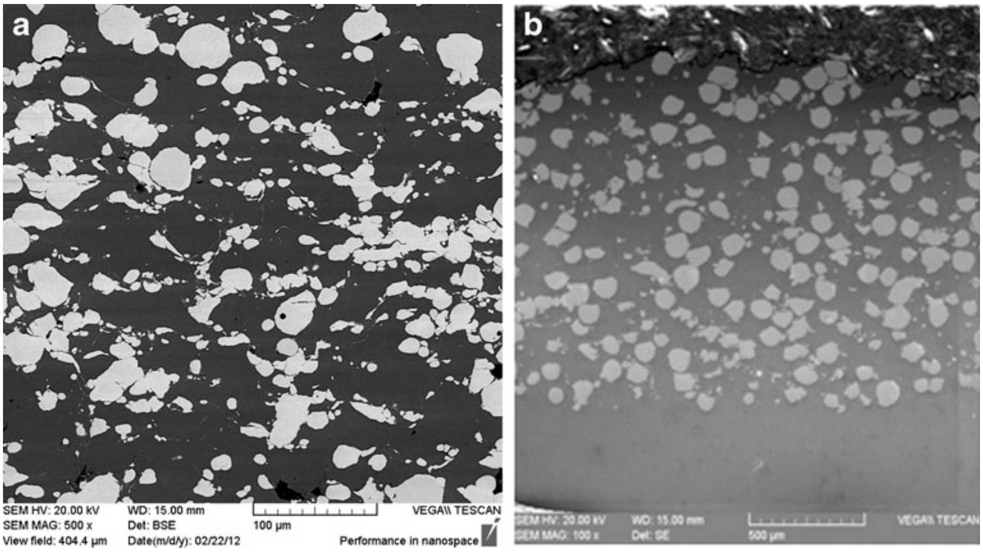
In cold spray, deposition occurs from material in solid state, and therefore the problem of materials incompatibility is not as important as for other AM techniques. Practically all available cold spray powders could be deposited as consecutive layers at any desirable combination and thickness. An example of multilayered coatings deposited by cold spray could be found in literature [46, 47]. In Fig. 5a, b, an example of multilayered Ti–Cu cylindrical object and its cut fragment manufactured by cold spray is presented. Interface between titanium and copper layers is uniform without any local detachments.

4.2 Multimaterial and graded coatings

Cold spray could be applied for the creation of so-called “multimaterial” or “mixed powder feed” deposits. It is known from the literature that these deposits could have elevated functional characteristics in comparison with single-component ones. For example, the coatings Co–Cr+316 L stainless steel have higher mechanical properties and better corrosion resistance than pure 316 L deposits [48].

Currently, multimaterial coatings are usually sprayed using preliminarily prepared powder mixtures [45, 49–51]. Examples of coatings obtained in this way are presented in Fig. 6a, b. Although this method is straightforward, it has several drawbacks. The first major drawback is the impossibility to change the components ratio in the powder mixture during the spraying process. This makes it impossible to spray coatings with through-thickness compositional gradient. Second drawback is the impossibility to provide optimal spray parameters for each spraying components if the mixture consists of two or more materials demanding significantly different spraying parameters for effective deposition. However, another method of mixed powder feed coatings by cold spray exists. In this case, each component of spraying mixture is injected in proper point

Fig. 6 Microstructures of multimaterial cold spray deposit obtained from spraying of previously prepared mixtures: **a**—Ti–Ni, **b**—stainless steel 316 L + Al



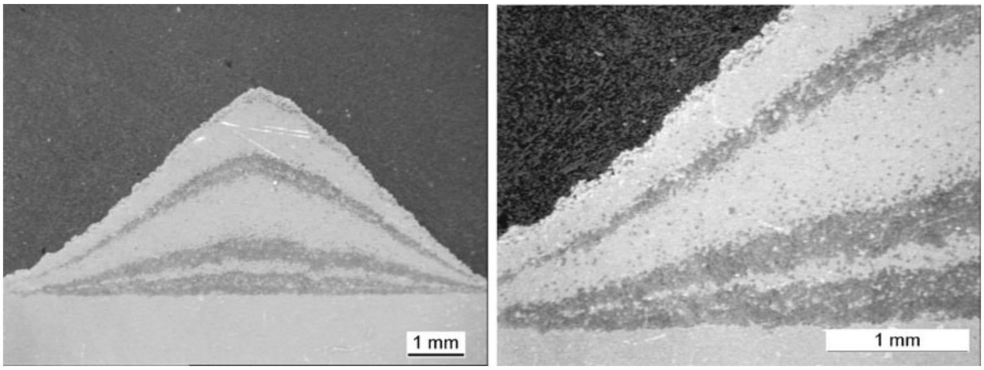


Fig. 7 Graded Ti–Al cold spray deposit fabricated by the application of multi-injection approach

of the nozzle [52]. Location of injection point strongly influence on powder outlet parameters, so for different components of spraying mixture, an optimal location of injection in the nozzle could be found that permits to provide optimal particle impact parameters for each mixture components but at the same gas flow parameters. Feeding of each mixture component is performed from separate powder feeders. As the components mixing takes place in the gas-dynamic channel, the components ratio in the coating may be set by changing the powder feed parameters. Compositionally graded deposits with varying through-thickness concentration of one of the components can be obtained using well-controlled powder feeders. An example of such coating is presented in Fig. 7. Evidently, such approach with separate powder feeding could be applied for cold spray additive manufacturing for the fabrication of 3D objects with graded structure.

It was mentioned before that non-plastic powder (ceramics, oxides, etc.) in their pure state produce no coating but erode the surface. However, being mixed with metal phase, the ceramic powders could be successfully deposited. In this case, a metal coating with ceramic inclusions can be formed (Fig. 8). Such composites have specific properties differing from ones of pure metals [53–56].

5 Properties of deposits

5.1 Porosity

Porosity of cold spray deposits varies from less than one to several tens of percents depending on spraying conditions and type of spraying powder [8, 19, 21]. For example, titanium and its alloys could be deposited with very low coating porosity if helium is applied as working gas. Application of nitrogen as a working gas leads to a significant porosity increase. In Fig. 9,

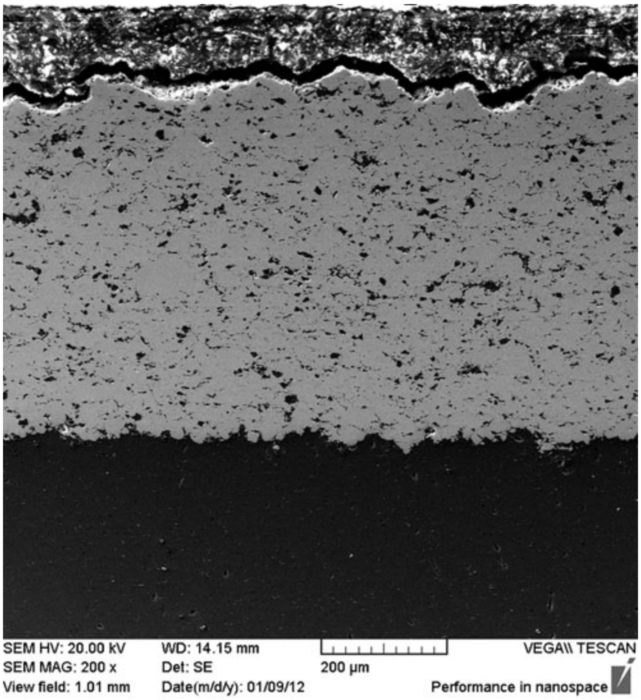


Fig. 8 MMC cold spray deposit Inconel 625+SiC

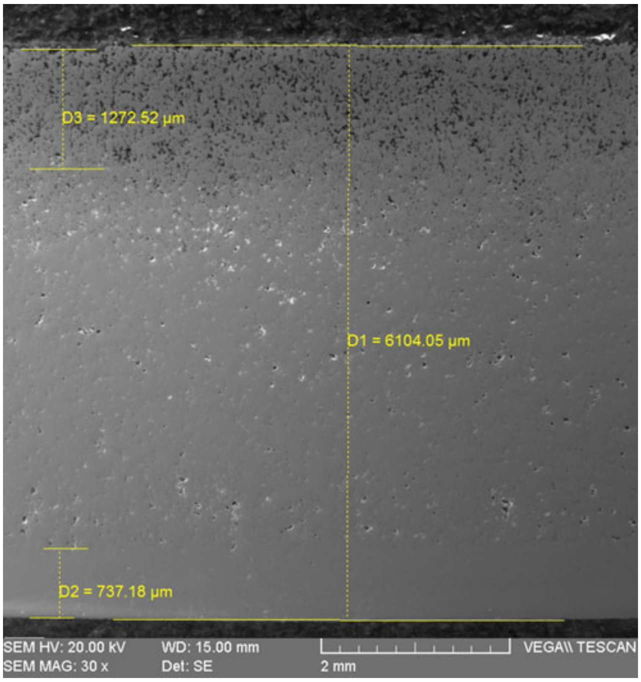


Fig. 9 Cross-section of titanium cod spray deposit with graded porosity, SEM

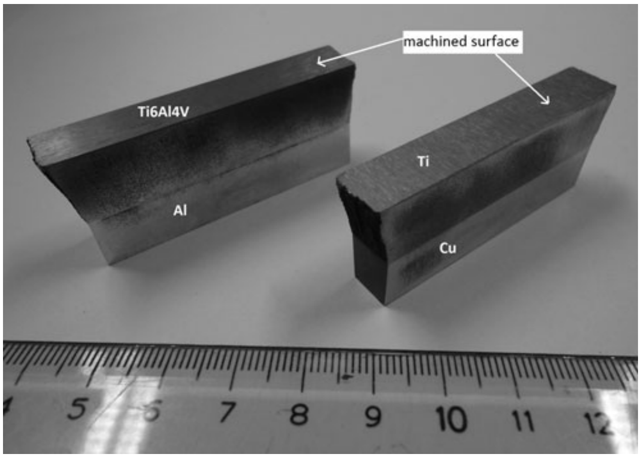


Fig. 10 Fragments of bimetal Ti6Al4V-Al and Ti–Cu plates fabricated by cold spray and machined by milling after spraying. Parameters of milling: axial depth of cut 0.4 mm, radial depth of cut 2.5 mm, spindle speed 800 rpm, feed per tooth 0.0833 mm/tooth

the 6-mm thick titanium deposit with gradient porosity is presented. The first low-porous layer was sprayed using helium as a working gas (4 MPa, 600 °C). The second medium porous layer (~10 %) was deposited on the first one using nitrogen as a working gas (4 MPa, 800 °C). The third layer with the highest porosity (~20 %) was obtained by spraying titanium at lower nitrogen temperature (600 °C). One can conclude that in some cases, cold spray permits to fabricate deposits with controlled and graded porosity that could find an application, for example, in implant fabrication industry.

5.2 Machinability

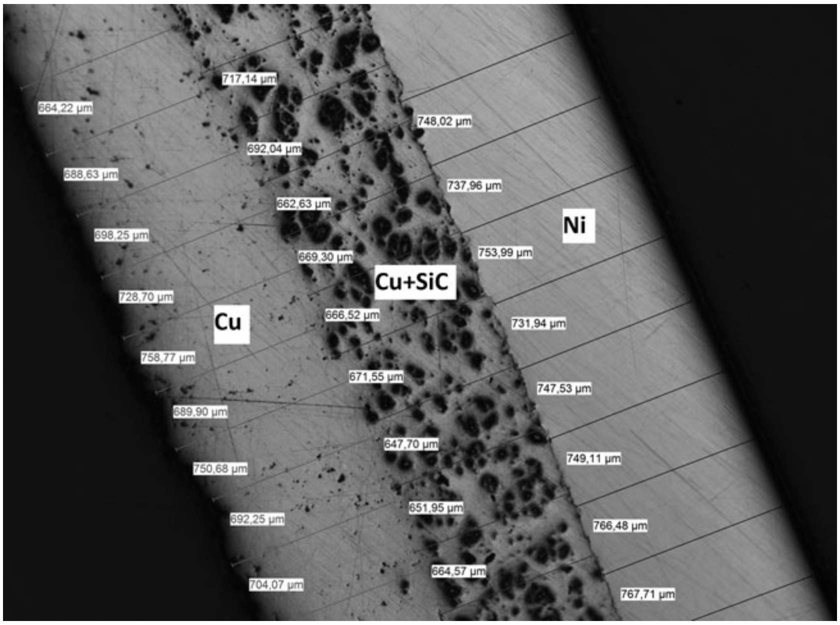
Obviously, machinability of deposits is a very important property in terms of application of cold spray for AM. It is known that mechanical properties of cold spray deposits differ from properties of rough material. In particular, the plasticity of cold spray deposits is significantly lower than for the bulk materials, whereas tensile strength could be higher [57]. One can suggest that increase in material fragility could embarrass machining of deposits. However, the results presented in literature shows that as-sprayed cold spray deposits have satisfactory machinability and could be treated by turning or milling. For example, in [58], authors successfully performed machining of aluminum cold spray coating using the same operating parameters as for bulk material. In Fig. 10, the photos of fragments of bimetallic Ti6Al4V-Al and Ti-Cu plates fabricated by cold spray and machined after spraying are presented.

Two different strategies of application of machining in case of cold spray AM could be considered. The first one is the final machining of near-net shape object made by cold spray. In this case, the process could be divided in two stages as follows: the fabricating of the object using cold spray and final treatment by machining in order to achieve required dimensions and tolerances and the application of machining process during cold spray deposition. In this case, the machining tool is integrated in the spraying system in order to provide the finishing of each layer directly after its deposition.

5.3 Stresses

Regardless of absence of high thermal impact and material melting, the value of stresses in cold spray coatings is not negligible. It is known from the literature that cold spray coatings are in compressive stresses [59–62]. In [59], authors suggest that the main contribution (85 %) to the stress level

Fig. 11 Wall of experimental mold fabricated using a combination of electroplating and cold spray techniques



was the high velocity of impact of the solid particles on the substrate. Similar conclusion was made in [60], where distribution of stresses in A1 coating was studied. Authors stated that the residual stress profile is dominated by the peening process. The contribution of thermal mismatch is not significant. These particularities of stress distribution in CS deposits should be taken into account during designing of strategy of freeform fabrication.

5.4 Compatibility with other AM techniques

The important property of cold spray process is its compatibility with other additive manufacturing techniques involving metals as source materials. One can suggest that complex multifunctional 3D objects could be fabricated by consecutive application of several AM technologies. For example in Fig. 11, the cross-section of wall of injection mold prototype for fabrication of plastic parts is presented. The mold was fabricated in three steps. Firstly, the ~750-um thick nickel shell of required shape was constructed by electroplating technology [63]. After that, in order to improve heat transfer from nickel wall of mold, the Cu–SiC and pure copper layers were deposited. The intermediary layer of Cu–SiC was deposited in order to improve adhesion between pure copper and pure nickel.

Hybridization of cold spray freeform fabrication with selective laser melting technology also looks promising for fabrication of multimaterial parts. For example, it is known that copper and its alloy as well as pure titanium could be applied in SLM only with certain limitations. One can imagine the application of hybrid technology where part of the object is fabricated by SLM and another part could be fabricated by cold spray with or without finishing machining.

6 Conclusion

Cold spray deposition process has a significant potential to perform nonthermal freeform fabrication and could be assumed as perspective additive manufacturing technology. In comparison with other additive manufacturing methods, cold spray involves neither high-temperature processing as for example SLM and DMD nor ecologically unfriendly chemicals as electroplating.

New developments in the field of cold spray such as increasing of spatial resolution by application of micronozzles as well as optimization of spraying strategy permits to elaborate freeform 3D objects with reasonable precision. The great advantage of cold spray is its ability to fabricate multimaterial, intermetallic, and functionally graded components that were demonstrated by authors as well as by other research groups. However, further work is needed to develop the process and to address challenging technological issue such as stable powder feeding and optimization of spraying strategy.

Acknowledgments The study was supported by the grant from the Government of Russian Federation (decree N220).

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