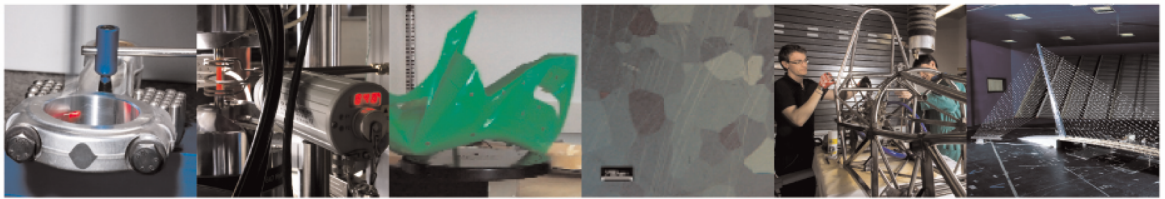




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Revolutionizing Repair and Production: an integrated modular cold spray additive manufacturing system

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Abstract

As an emerging additive manufacturing process, cold spray additive manufacturing (CSAM) has attracted considerable attention from researchers. It allows for near-net-shape fabrication of workpieces, but its accuracy and properties often do not meet the user requirements. Additionally, the development of a generalized manufacturing strategy for workpieces with complex geometries is imminent. To address this challenge, various processes involving the entire manufacturing process cycle, from design to delivery, can be integrated. However, few researchers have conducted studies in this area. Therefore, this study developed an efficient and flexible integrated modular CSAM system for the fabrication of workpieces. The system consists of two components: software for modeling and simulation, and hardware for precise fabrication. The software component primarily facilitates the reverse engineering modeling of the workpieces, as well as forming control of the deposits, including automation of path generation and deposits shape prediction before spray. The hardware component, supported by the software's informational groundwork, actualizes the manufacturing of the workpieces to meet expected quality. The developed system provides a generalized strategy for precision manufacturing of workpieces in CSAM.

Keywords: cold spraying additive manufacturing, module, hardware, software, information

exchange

Abbreviation

CSAM: cold spray additive manufacturing

AM: additive manufacturing

CAD: computer-aided design

SLM: selective laser melting

SLS: selective laser sintering

EBM: electron beam melting

CS: cold spray

SoD: stand-off distance

DE: deposition efficiency

AI: artificial intelligence

ANN: artificial neural network

DED: directed energy deposition

HCSAM: hybrid cold spray additive manufacturing

SM: subtractive manufacturing

PSS: Product Service Systems

RE: reverse engineering

CAM: computer-aided manufacturing

HPCS: high-pressure cold spray

LPCS: low-pressure cold spray

Introduction

Additive manufacturing (AM) or three-dimensional (3D) printing is the construction of a 3D object from a computer-aided design (CAD) model or a digital 3D model. As a manufacturing process based on a layer-by-layer strategy, it can be conducted in a variety of processes in which material (such as polymers, metals, ceramics, or liquids) is joined, solidified, or deposited under computer

control. The main differences between processes are the way in which the layers are deposited and the materials used in the fabrication of workpieces. Therefore, AM can be grouped into several categories, such as binder jetting, directed energy deposition (DED), material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (Ref 1). Due to the advantages of design for AM, it is now beginning to make significant inroads, especially in metalworking. Currently, metal manufacturing technologies, such as selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM) have been widely used to fabricate workpieces (Ref 2–4). However, high-frequency laser radiation or high-powered electron beam can alter nature of raw materials or adversely affect the deposits through mechanisms such as oxidation, grain growth, residual thermal stress and phase transformation.

Cold spray (CS) or cold gas-dynamic spray is a solid-state deposition technique that produces a solid deposit using powder feedstock. The powder particles are injected into a supersonic gas jet stream based on a de Laval nozzle and accelerated to a velocity between 300 and 1500 m/s. Typically, air, nitrogen or helium is used as propellant gas. Severe and highly localized plastic deformation occurs when the particles impact a substrate surface, which triggers bonding between the particles and the substrate. The most important benefits of CS over other processes are its higher deposition rate (up to 500 g/min) and lower heat input, as the material is not melted. This makes CS particularly suitable for the deposition of a wide variety of materials, especially heat-sensitive ones (Ref 5,6). Additionally, CS is relatively environmentally friendly, as it produces virtually no toxic fumes or other harmful emissions (Ref 7,8).

In recent years, investigations and applications regarding CSAM have been widely reported, although it is still an emerging technology. It is well known that efficient deposition of the powder depends mainly on whether the flight velocity of powder particles exceeds a critical velocity.

Therefore, numerous previous studies have emphasized increasing the critical velocity to facilitate the powder deposition (Ref 9,10). In addition, some studies have focused on optimizing process parameters, such as suitable stand-off distance (SoD), gas temperature and pressure, and the use of helium with a high specific gas constant as propellant gas (Ref 11). Some researchers have also aimed to optimize structure of nozzle (primarily expansion and divergent length) (Ref 12,13). These studies have shown that optimizing these parameters can significantly improve powder deposition efficiency (DE) and deposits properties.

Pattison et al. (Ref 14) proposed a triangular-tessellation technique to deposit a vertical wall. However, a typical triangle-like shape deposit can result in low DE. Wu et al. (Ref 15) proposed a strategy of building layer by layer for 3D shape forming. Vaz et al. (Ref 16) developed a new strategy named metal knitting for CSAM. However, these strategies have not been further investigated for AM of complex-shaped parts such as multi-features. Lamarre et al. (Ref 17) adopted a complex robot toolpath to produce permanent magnets for electric engine. Nevertheless, the premise of this approach is that an aluminum cylinder needs to be machined into the required hourglass shape to serve as a sacrificial substrate. Nault et al. (Ref 18) proposed a gradient-descent-based tool path optimization algorithm to enable the manufacture of arbitrary convex deposit shapes. However, the study did not investigate spray trajectory planning for complex structural components.

Some researchers have begun to work on simulation of deposits formation processes. Tzinava et al. (Ref 19) developed a coating thickness simulator that can accurately handle complex parts of arbitrary geometry. However, the model can simulate one-layer coating deposition, but cannot handle the deposition simulation of stacking of multiple layers. Venturi et al. (Ref 20) proposed a convolution-based approach to predict surface finish of deposits to minimize post-deposition treatment. The problem to be solved is how to build a model that can observe evolution of the deposits.

In addition, artificial intelligence (AI) has also been applied in the deposit simulation. Ikeuchi et al. (Ref 21) presented a neural network predictive model of a single-track profile to improve geometric control of components during CSAM process. Liu et al. (Ref 22) employed an artificial neural network (ANN) model to describe and predict multi-layer profile of deposits. However, in the current state of the art, no CS shape prediction AI model has yet been expanded to predict 3D deposits.

Another point that has attracted a lot of attention is how to improve manufacturing accuracy of deposits. In contrast to other DED technologies, where parts can be manufactured with an accuracy of several tens of microns, the accuracy of CSAM products is usually greater than one millimeter due to its lower spatial resolution (Ref 23–25). Vargas-Uscategui et al. (Ref 26) focused on understanding how tool path planning strategy and robot kinematics affect the geometry and porosity distribution in a 3D object. Sova et al. (Ref 24) developed a micronozzle with a 0.5 mm throat diameter and a 1 mm exit diameter for deposition of aluminum powder. They improved the shape precision of the deposits by path planning and employing small-sized nozzles, respectively. Each of these methods has made some progress in improving the accuracy of CSed products. Subsequent machining is still required to remove the excess coating. Combining CSAM with other processes, known as hybrid CSAM, presents itself as a promising new manufacturing technique.

Recent challenges for hybrid CSAM

In fact, the term “hybrid” has been widely used in many additive manufacturing areas (Ref 27–30). A hybrid process for component remanufacturing was developed (Ref 31), integrating reverse engineering, pre-repair process, laser-assisted DED, and material testing. A proposed CS repair system offers individualized repair for aircraft components (Ref 32). This system encompasses digital data acquisition of damaged part, pre-processing of the part, spray path planning, real-time monitoring of the process, and post-processing to enhance deposits characteristics. Despite advancements, the industry still lacks a universal and efficient CSAM system capable of fabricating or repairing workpieces with intricate geometries. The initial development of the hybrid CSAM

(HCSAM) system was based on the combination of the CSAM system with a single other process, such as subtractive manufacturing (SM), pre-treatment process, or post-treatment process (Ref 33–35). The subtractive process can be used for final finishing of workpieces. It can also be used to calibrate shape of the workpiece being manufactured in real time during deposition. The pre-treatment module facilitates deposition by treating raw material and substrate prior to deposition, while the post-treatment module improves the shape precision and deposits properties to meet the requirements. CSAM has been in development for more than 20 years, but the process is still in its infancy and is only used to manufacture parts with simple geometries. The system is still inadequate to solve many of the practical problems of CSAM process. Therefore, incorporating deposits shape evolution prediction and path planning into this system may be an effective methodology to take CSAM products from concept to delivery.

Integrated modular cold spray additive manufacturing system

In the current digital economy, the time to market of a product has a significant impact on its profitability. Bringing products that meet consumer expectations to market faster has developed into a constant battle between companies competing with each other. How to make the manufacturing process more intelligently integrated, namely a CSAM system involving the entire manufacturing process from design to delivery, is the focus of this study. Therefore, this paper contributes an integrated modular CSAM system shown in Fig. 1 that consists of two components: the software that performs modeling and simulation, and the hardware that performs precise fabrication. The following sections describe the two components of the current system in detail. It should be noted that each component has its own modules; these modules do not run independently but are coupled to each other through direct physical links or indirect decentralized and event-driven manners. In addition, there is information exchange between hardware and software components, which ensures real-time

feedback.

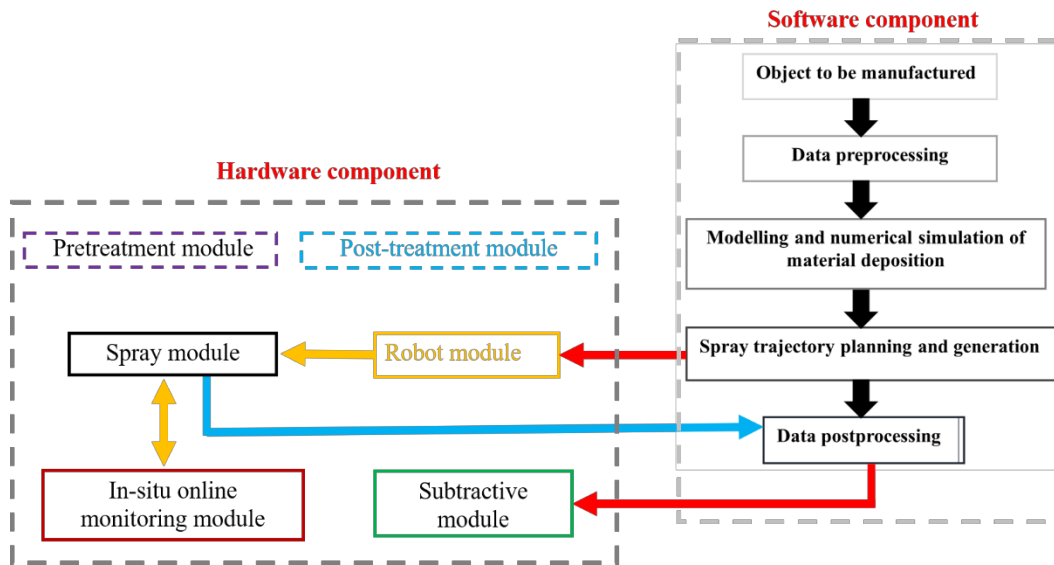


Fig. 1 Integrated modular CSAM system

Software component

CSAM is currently only used to fabricate components with simple geometries such as rotationally symmetrical shapes or walls. However, it is also well-suited for developing components with relatively complex structures or multiple features. A mature CSAM industry chain should include at least the following modules: data preprocessing; modelling and numerical simulation of material deposition; spray trajectory planning and generation, as well as data postprocessing of initially manufactured deposits.

Data preprocessing

Data preprocessing refers to acquisition and preprocessing of digital model of fabricated object. The digital model of the manufacturing object is the starting point of the CSAM process. For a workpiece with a simple structure, it can be modeled based on the known given dimensions or measurement method. However, in some cases, the dimensions are not available for modeling. In such cases, digitizing the physical workpiece using a noncontact vision sensor combined with reverse engineering (RE) technology is one approach that can be considered for modeling. A high-resolution

digital model of the workpiece can be obtained by a series of preprocessing and model reconstruction processes. The EinScan SE Desktop 3D Scanner (by SHINING 3D in China) with an accuracy less than 0.1 mm was used to conduct RE of the workpiece in this study, as shown in Fig. 2a. There are two scanning modes, fixed and turntable, both with a maximum scanning range of 700×700×700 mm and 200×200×200 mm, respectively. The latter mode was selected to obtain comprehensive structural information considering complexity of the workpiece. The scanner adopts a 3D reconstruction technology based on phase-shifted structured light. After projecting a grating on the surface of the object, the camera captures the image that produces distortion, and uses phase decoding to obtain the phase information of each point to perform the measurement of 3D contour of the object surface.

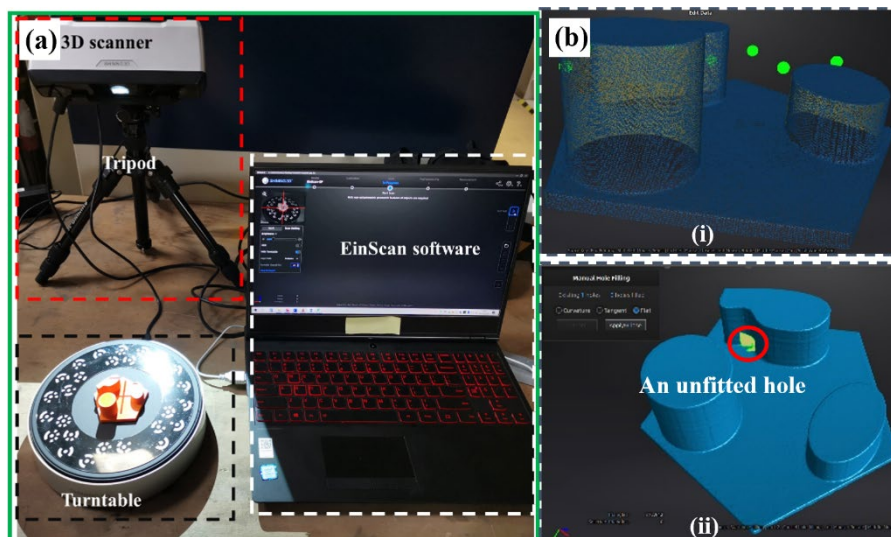


Fig. 2 Acquisition of the digital model of the workpiece to be manufactured: (a) Desktop 3D scanner; (b) Digital model acquisition

The 3D reconstruction process is shown in Fig. 2b. The collected point clouds, shown in Fig. 2b (i), can be used for surface fitting to get a 3D model in STL format, as shown in Fig. 2b (ii). It can be noticed that there is a “hole” due to a shadowing effect in some parts of the workpiece, which prevents them from being scanned. The hole can be filled with the software’s defect repair function. The efficiency and the accuracy of the surface reconstruction is satisfactory despite the deviation of the fitted model from the actual workpiece. We can also take measurements from two different angles

and stick them together using point cloud registration, like iterative closest points algorithm. Additionally, various methods, such as chord height deviation, homogenous filtering, and statistical outlier removal, can be utilized to reconstruct the 3D model for a better fitting effect (Ref 36,37).

Modelling and numerical simulation of material deposition

CS is a promising AM technology with high productivity, but it still faces challenges in achieving precise geometric control of deposit shape. To overcome this limitation, substantial developments in modelling and numerical simulation are still needed. The final deposit shape depends on kinematic spraying parameters such as SoD, spraying angle, and traverse speed of the gun. Moreover, the deposit often suffers from edge loss, which requires compensation (Ref 15). Determining these parameters by the conventional trial and error method can be inefficient and costly. Therefore, modelling and numerical simulation of powder deposition are essential to predict and control the deposit shape and geometry before spraying.

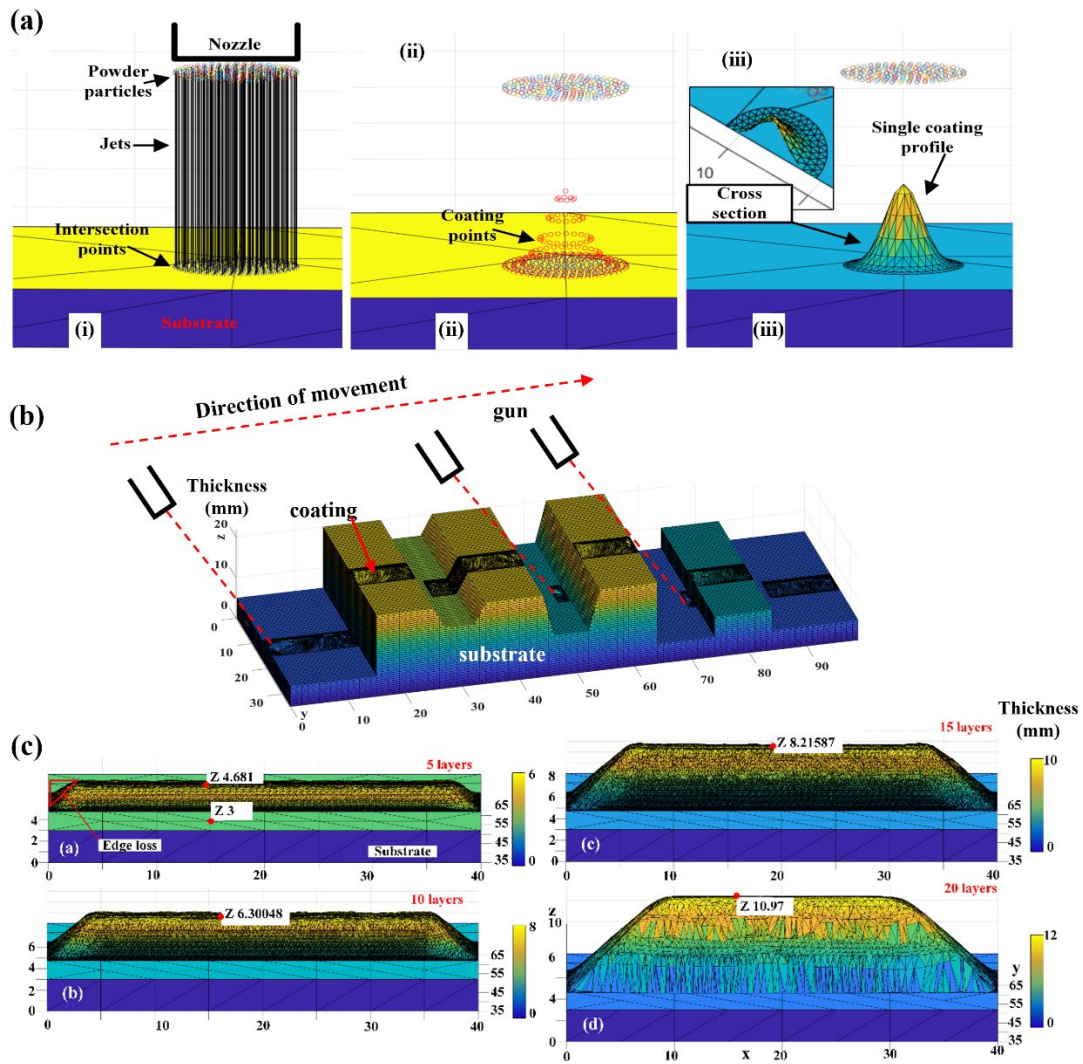


Fig. 3 Numerical deposition modelling methodology: (a) a single coating spot modelling process; (b) application of the model on substrate with shadow effect; (c) Topology geometry shape at different layers (mm) (Ref 38)

In our previous study (Ref 38), we proposed a general-purpose numerical deposition modelling methodology based on a mesh geometry reconstruction strategy implemented in MATLAB, as shown in Fig. 3. The model was developed from scratch in MATLAB and can predict the evolution of any shaped deposit, as well as determine the optimal process parameters. Fig. 3a shows the single coating spot modelling process. Specifically, a spray jet model based on the cylindrical distribution of the powder streams is proposed in Fig. 3a (i). The 3D coordinates of the coating points are obtained based on the intersection of the streams and substrate, as shown in Fig. 3a (ii). Finally, these coating points are connected by triangular facets, as shown in Fig. 3a (iii). Fig. 3b shows that the continuous deposit can be built on the substrate with shadow effect based on a superposition of coating spots. Fig. 3c

shows the evolution of the deposit layer-by-layer. The modeling methodology can predict the deposit evolution well enough to guide the actual spraying.

A general spray trajectory planning and generation

CSAM is an efficient method for achieving materials deposition by layer-by-layer stacking. Unlike other AM processes, such as SLM, which can quickly achieve trajectory planning using commercial software, there is currently no general methodology for spray trajectory planning in the CSAM process. This poses a challenge for the accurate and fast generation of trajectories for each layer of the manufactured workpiece. When a component with multiple features is manufactured, the spray paths between features cannot be created easily due to the “one-stroke” character. The powder feeding cannot be interrupted during the entire spraying process. This means that for the deposition of multi-featured components, planning the path of the nozzle transfer from one feature to another is a challenge. If the transfer path goes directly across the area of the as-deposited features, it can significantly change the deposit shape and cause unexpected results.

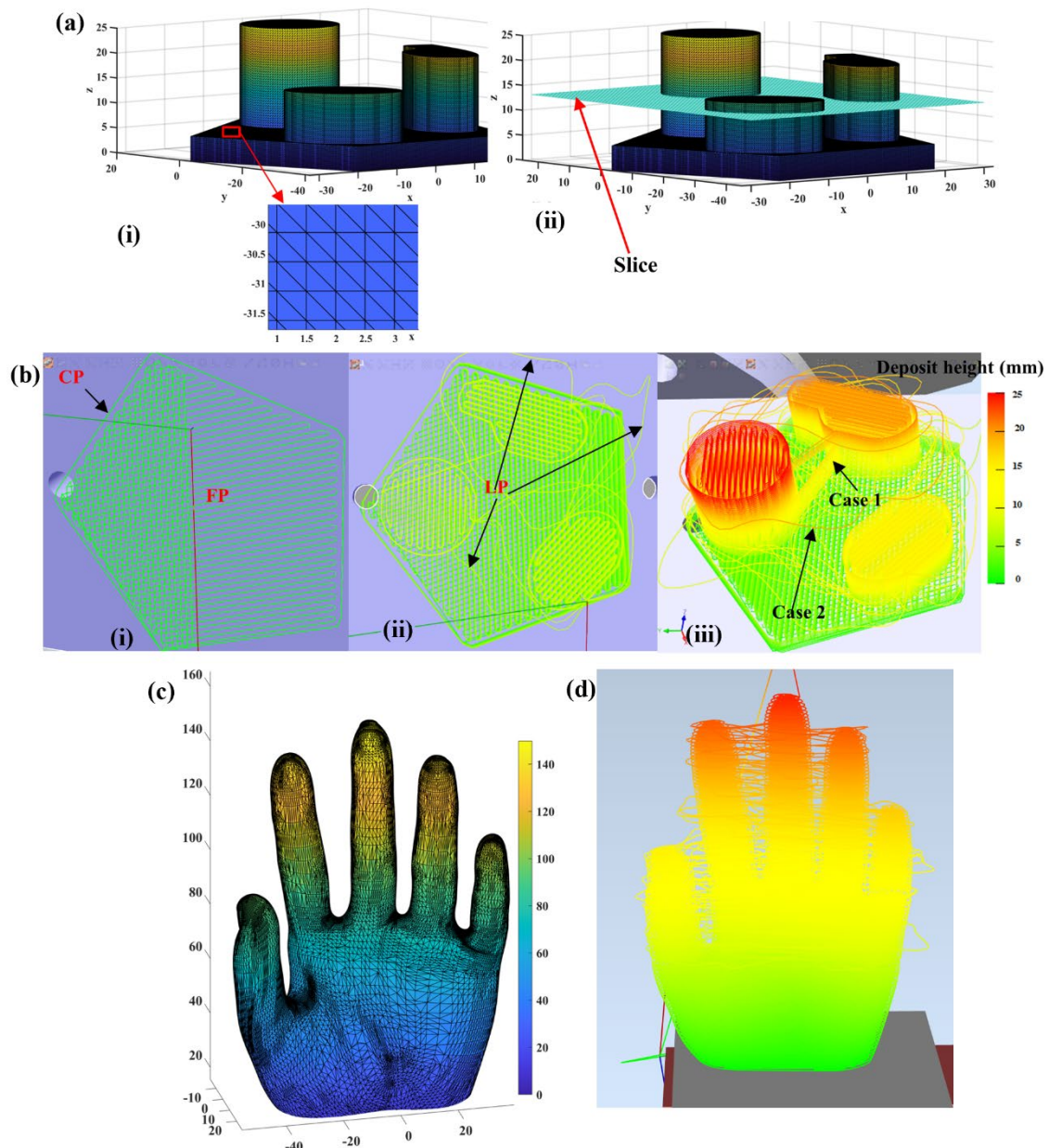


Fig. 4 Spray trajectory planning methodology: (a) a three-featured 3D model; (b) trajectory planning of the model; (c) a hand model; (d) trajectory planning of the hand model (Ref 25)

To address this challenge, our recent study (Ref 25) suggested a methodology of spraying trajectory planning for workpieces with complex structures, as shown in Fig. 4. As an example, we present the trajectory planning for a three-featured 3D model composed of a mass of triangular facets in Fig. 4a (i). The base of the model is a pentagonal prism with three features of unequal height on it: an elliptical cylinder, a cylinder, and an irregular-shaped component. Based on a uniform layer thickness, a slice perpendicular to the Z-axis is used to intersect with the model, as shown in Fig. 4a (ii). The intersecting points generated by the intersection of each triangular facet with the slice are the

basis for generating the paths for the layer. The slicing process is repeated from the bottom to the top of the 3D model to obtain the robot trajectory. Fig. 4b shows the trajectory simulation process in Robotstudio™ (developed by Asea Brown Boveri (ABB)). As seen in Fig. 4b (iii), there are two cases in the planning of transferred paths. For case 1, the path can be a straight line if the gun does not traverse any as-sprayed features. For case 2, the path has to bypass the as-sprayed features if the material is deposited on the as-sprayed features. More details can be referred in (Ref 25). In this way, a near-net-shape component can be fabricated. In addition, Fig. 4c and 4d show a hand model and corresponding spraying trajectory, respectively. Overall, these results have demonstrated that the strategy could provide a general spraying path planning scheme for complex structures in CSAM.

Artificial intelligence module

One of the challenges in CSAM is to optimize the process parameters that affect coating properties. The Taguchi design method is the most widely used method for estimating the effect of process parameters on coating properties (Ref 39). However, it is inefficient for determining the exact optimal parameters. Another approach is to use numerical modeling and simulation (Ref 40). Nevertheless, numerical simulation is limited due to the complex multi-physical phenomena involved in the CSAM process. Therefore, a more accurate method of analyzing, predicting and optimizing coatings is needed.

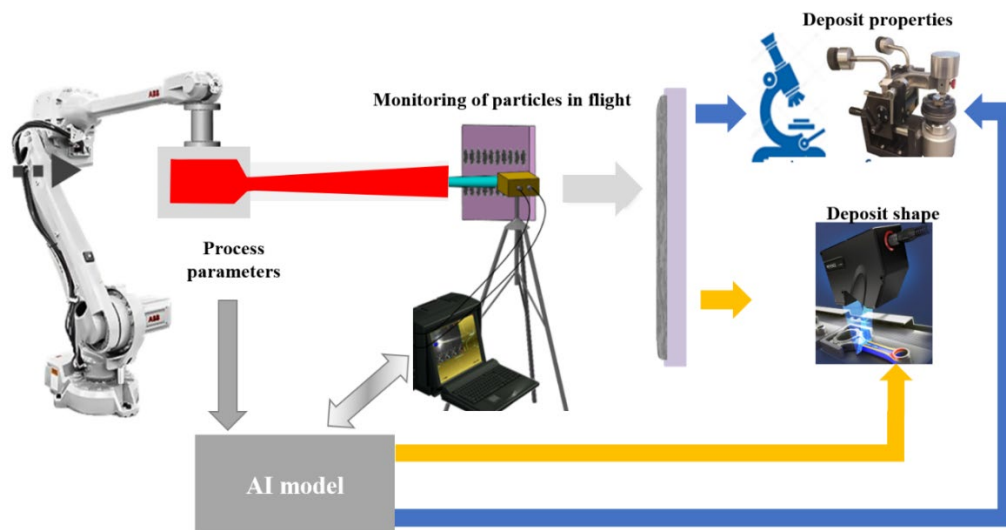


Fig. 5 Application of AI in the CSAM

Artificial intelligence (AI) offers a promising solution to this challenge. AI is a subfield of computational science dedicated to the creation of intelligent computer systems. It encompasses a wide range of techniques and technologies, including neural networks, deep learning and reinforcement learning, etc. (Ref 41). Today, the use of intelligent CSAM is made possible by promoting new and precise sensor technologies and computational methods at the cutting edge of intelligence. CSAM benefits from AI, which monitors, analyzes and makes the right decisions, complementing human operations (Ref 42). A convolution-based digital method for CSAM deposit shape prediction able to calculate the optimal process parameters to reduce surface waviness was developed (Ref 43). Additionally, the use of AI for studying mechanical properties of deposits has been explored. A machine learning model that could accurately predict the porosity of CSed deposits was developed (Ref 44). Another machine learning model was established to predict maximum residual stresses, encompassing both tensile and compressive states, in the CS process across various substrates (Ref 45). Therefore, we can integrate an AI model into the system to optimize the CSAM process, as shown in Fig. 5. The process parameters and collected velocity of the in-flight particles can be selected as inputs. The deposit shape and properties (e.g., porosity, hardness, roughness) are the targets. Conversely, the predicted results can be used to optimize the process parameters.

Data postprocessing

Data postprocessing is a crucial step in CSAM, as it enables acquisition of digital model of deposit and final workpiece (Ref 46). Industry 4.0 promotes the utilization of AM in responding to various manufacturing challenges. However, AM will not replace the traditional SM, as the SM can achieve higher surface finishes and tighter tolerances. Therefore, AM is increasingly combined with SM to benefit from the synergistic advantages of combining both technologies and overcoming their drawbacks. To achieve this combination, the data postprocessing of the deposit is essential.

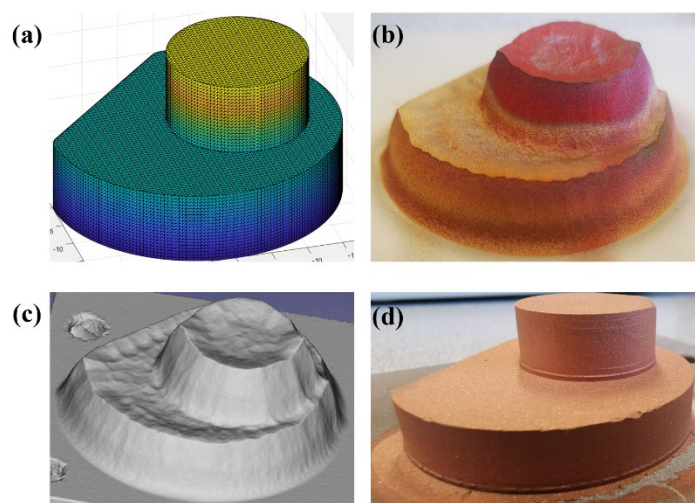


Fig. 6 Data postprocessing process: (a) 3D model of the workpiece to be manufactured; (b) the manufactured deposit; (c) 3D model of the deposit built by reverse engineering; (d) deposit after physical postprocessing

In CSAM, data postprocessing involves the acquisition and processing of the digital model of the deposit, which can be used for quality control and optimization (Ref 26,47). Fig. 6a and 6b represent the 3D model of the workpiece and the deposit, respectively. Since the inherent defects of CS itself result in a low resolution of the deposit, it is necessary to cooperate with SM to achieve the desired size of the workpiece. A digital model of the deposit is first obtained through RE before machining to remove redundant deposits. In this study, the model shown in Fig. 6c can be reconstructed by the EinScan SE Desktop 3D Scanner. Finally, a computer-aided manufacturing (CAM) based machining path is generated to make the deposit achieve the desired accuracy, as shown in Fig. 6d.

Hardware component

The hardware component is the physical system that implements the CSAM process. The component is designed and organized as an open framework, as shown in Fig. 7. It consists of the following four modules: the robot module, the spray module, the in-situ online monitoring module and the subtractive module. These modules work together to perform the hybrid CSAM deposition process.

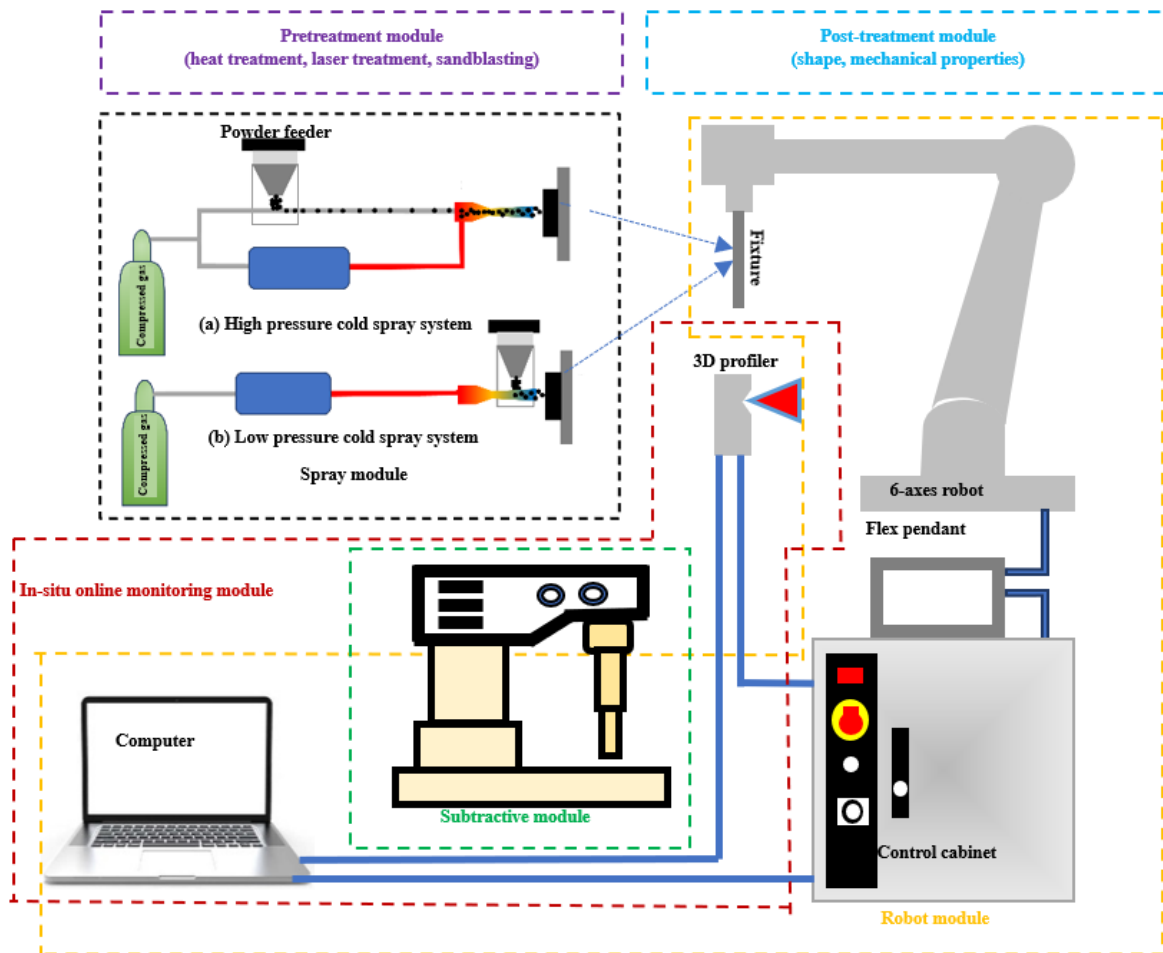


Fig. 7 Schematic diagram of the hardware component

Robot module

The robot module is the core component of the hardware system. In CSAM, industrial robots play a crucial role in several aspects of the process (Ref 48,49). They are used to precisely deposit powder onto a substrate. This involves controlling the movement of the robot arm to ensure accurate

positioning and deposition of the material. The robot's precision and repeatability are critical for achieving the desired part geometry.

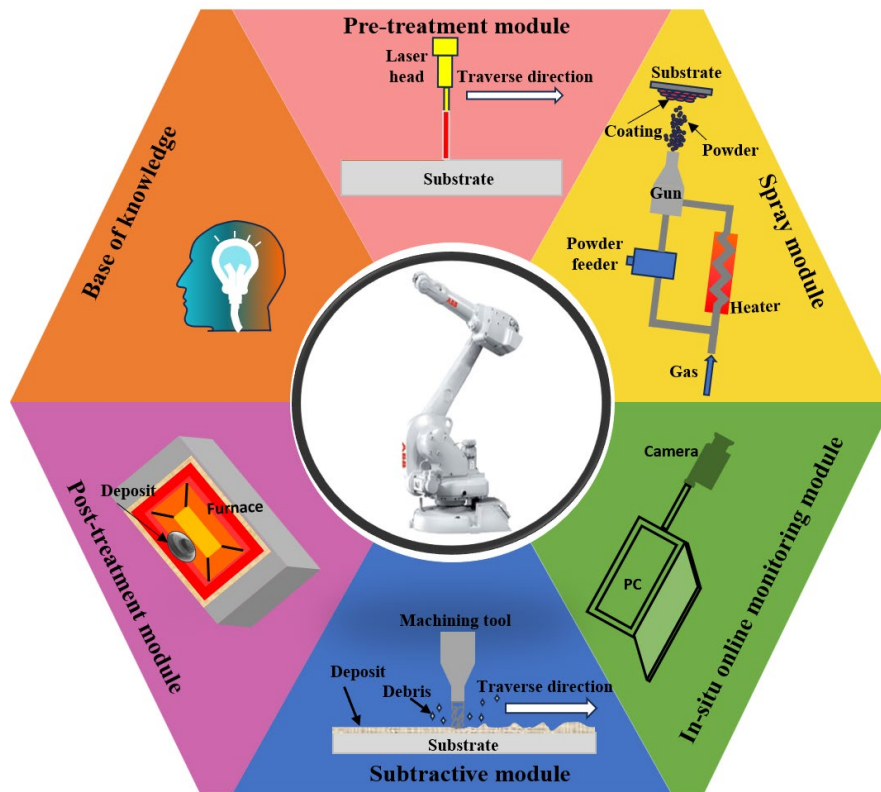


Fig. 8 Industrial robot, as a bridge between multiple processes

The robot module also enables the integration of CSAM with other techniques, such as pretreatment, online monitoring, and post-treatment to form a hybrid CSAM system. As shown in Fig. 8, the robot enables the substrate/workpiece to be transferred between multiple process modules. Before the deposition, the substrate surface often needs to be prepared to ensure proper adhesion of the powder. The robot moves the substrate to a position where it can accurately perform surface preparation tasks such as cleaning, roughening or masking, i.e., pre-treatment. During the deposition, it can also move the deposit to the online monitoring equipment to monitor the deposition process in real-time and perform quality control checks. In this way, the deposit shape, particle velocity, and temperature can be inspected and adjusted to ensure consistent deposit quality. In addition, at any time during or after the deposition process, the robot can transfer the deposit to the SM module for

machining to remove undesired deposits. Last, robot can move the substrate to a position where it can accurately perform post-treatment, such as heat treatment, shot peening, finishing and surface polishing. Therefore, the robot module can be considered as a bridge between multiple processes.

Pretreatment module

Pretreatment is a process that prepares the raw materials and substrate for the CSAM by modifying their surface properties and temperature. It is well known that the CS processing parameters affect the coating properties (e.g., DE, hardness, adhesive strength and porosity). Therefore, the optimization of the process parameters requires pretreatment of the raw material and substrate prior to deposition according to the user-specific requirements.

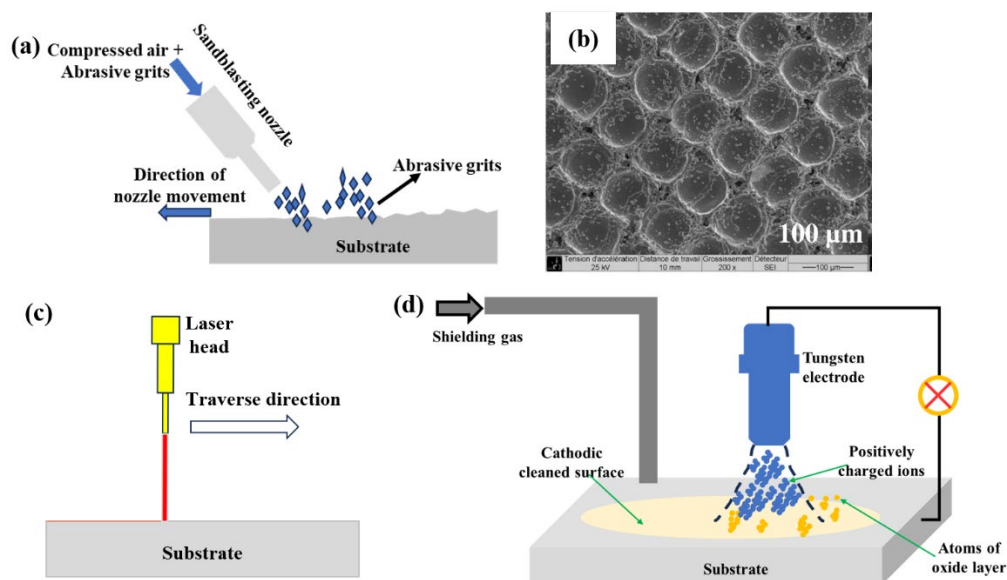


Fig. 9 Substrate pretreatment processes: (a) schematic view of sandblasting working process; (b) laser texturing of substrate surface (Ref 50); (c) laser-assisted preheat substrate; (d) schematic diagram of the cathode cleaning process

One of the main goals of pretreatment is to enhance the bonding strength between the powder and the substrate, which is crucial for the deposit quality and durability. Poor bonding strength at the beginning of the deposition process can even cause the deposit to fall off from the substrate (Ref 51). One of the most important aspects of obtaining permanent and strong adhesion is surface pretreatment. The purpose of this pretreatment is to clean the bonding surface and eliminate oxides and sticky

oils/greases from the surface, and to improve the surface roughness to increase the adhesion between the coating and the substrate. There are different methods of surface pretreatment, such as sandblasting, laser texturing, substrate preheating, and arc-dis-charge pretreatment. As a traditional pretreatment process, sandblasting is an operation where abrasive grits are sprayed on a surface under high-pressure gas to clean or modify its surface properties, as shown in Fig. 9a. Wojciech et al. (Ref 52) discovered that the bond strength of Ni coatings increased with greater substrate surface roughness at preheating temperatures of 700 to 800 °C, whereas no significant change was observed at temperatures of 500 to 600 °C. Laser texturing, shown in Fig. 9b, involves using a laser beam to create precise micropatterns on a substrate/coating surface through a laser ablation. This technique selectively removes materials with micrometer precision, resulting in repeatable patterns such as dimples, grooves, and free forms (Ref 50). Kromer et al. (Ref 53) employed laser surface texturing as a pretreatment to create a specific topography of the substrate. Experimental results indicated that the textured surface significantly improved the adhesion of the metal (Al, Cu, and Ti) coating to the ceramic (Al_2O_3 and SiC) substrate. Substrate preheating (e.g., using a laser) involves preheating the substrate without melting it before powder deposition to improve adhesion, as shown in Fig. 9c. In addition, arc-discharge pretreatment, also known as cathodic cleaning, can be used to pretreat the substrate surface. It is a process where a metallic surface acts as an electrode and is connected to an electrical current in an electrolytic cell to remove oxides or corrosion deposits. Any metal that has been cathodically cleaned is more susceptible to hydrogen embrittlement (Ref 54). Fig. 9d shows a schematic diagram of the cathode cleaning process.

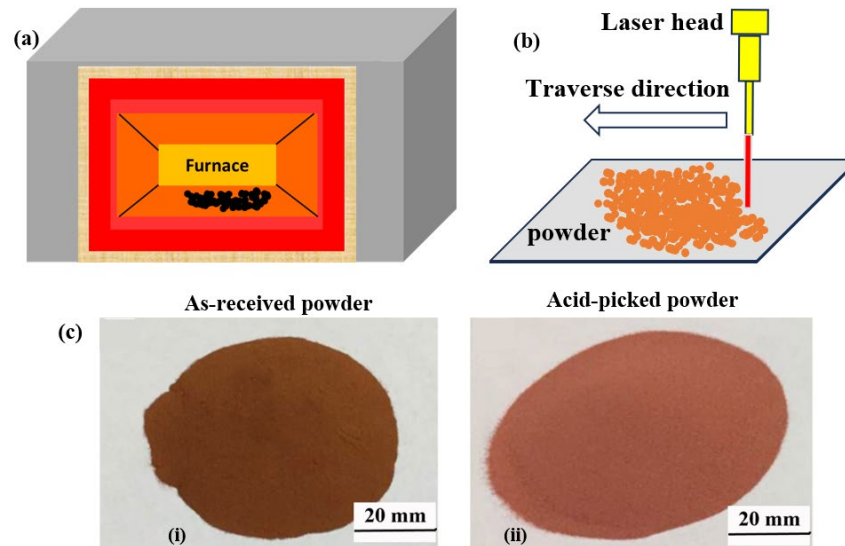


Fig. 10 Powder pretreatment processes: (a) powder preheating in furnace; (b) powder preheating using laser; (c) acid pickling method (Ref 55)

Another goal of pretreatment is to improve the powder depositability by increasing the particle temperature and removing oxides. The pre-treatment of the feedstock is usually the preheating of the powder before spraying. Li et al. (Ref 56) studied the influence of particle initial temperature on impact velocity. The simulation results showed that the critical velocity decreases with the increase of the initial temperature of powder. Particle temperature can be increased by several methods. The simplest way is to increase the propelling gas temperature. However, there can sometimes be physical limitations on the heater elements of the CS system. It is also possible to preheat the powder in a furnace before spraying, which removes any moisture present in the powder and softens it to help it deposit better, as shown in Fig. 10a. Fig. 10b shows the powder preheating using laser before CS. Li et al. (Ref 55) used acid pickling to remove the oxide scale on the surface of the copper powder, thereby improving the powder DE, as shown in Fig. 10c.

Spray module

The spray module performs the CS process, which can be classified into high-pressure cold spray (HPCS) and low-pressure cold spray (LPCS) based on propellant gas pressure. Generally, the pressure selected in HPCS is greater than 2 MPa, whereas in LPCS it is lower than 1 MPa. Fig. 11 shows the two sets of CS equipment we have in our laboratory. For HPCS, shown in Fig. 11a, the main elements

of CS setup are the spraying unit, consisting of a supersonic nozzle, powder feeder, gas heater and a compressed gas source. Due to the high pressure involved, HPCS system is less suitable for delicate substrates (composite materials, e.g., carbon fiber-reinforced polymer) that might be damaged by the high impact forces. In addition, the system requires more energy to maintain the high -pressure and -temperature. A LPCS system shown in Fig. 11b seems to provide an effective solution. The system consists of two portable units. One unit is used to control the system startup. The other unit (for spraying and monitoring) includes a system connected by an electric cable with electric heating elements, locking-control system (fed from the compressed gas source) connected by pneumatic pipelines with the gas heater, powder feeder, and manometers, gas-temperature indicator and a compact gun.

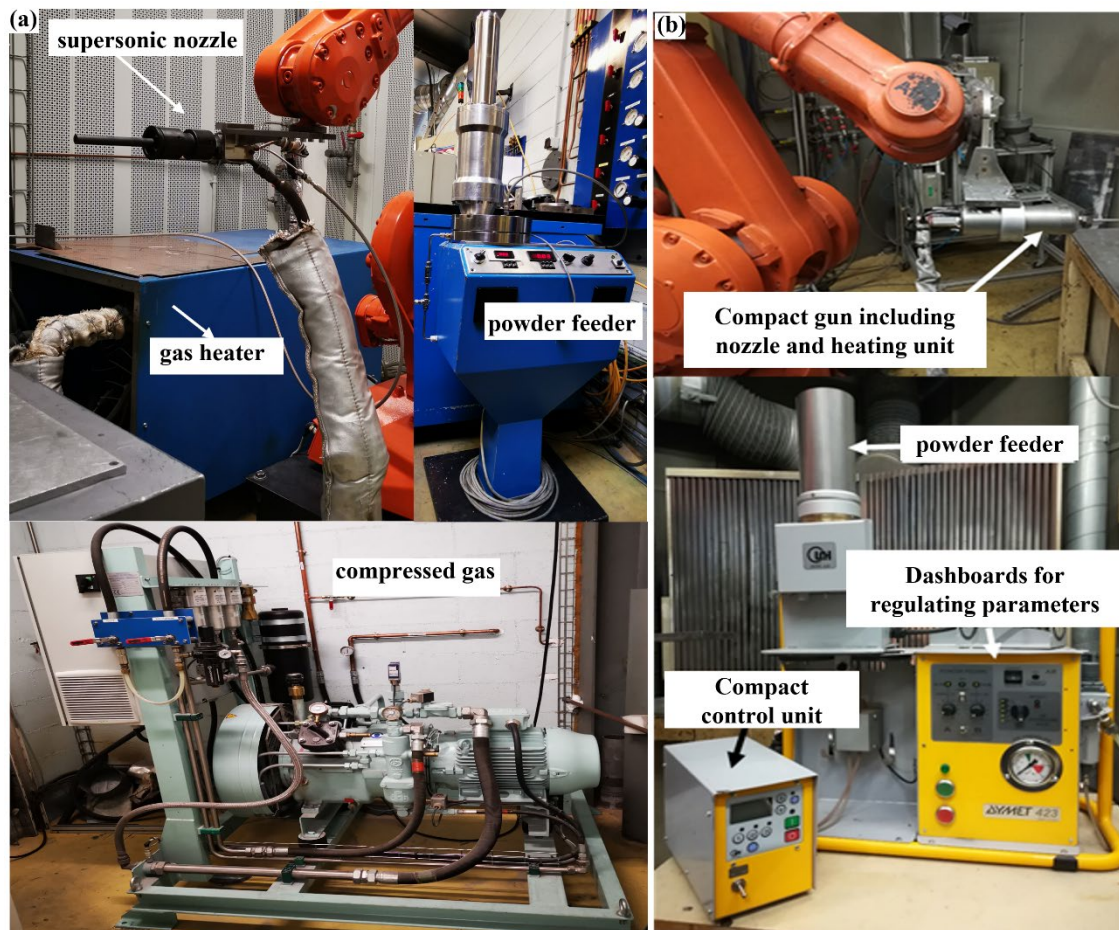


Fig. 11 The spraying systems: (a) HPCS; (b) LPCS

The spray module can produce deposits with different structures and geometries, depending on the process parameters and path planning. Fig. 12 presents deposits with structures of varying complexity. The copper deposit with a single feature, i.e., at most one feature per layer, shown in Fig. 12a consists of 2 parts: a partially truncated cylinder serving as a base, above which is a smaller

cylinder. It is obvious that the verticality of the upper cylinder is poor, which may be due to unsuitable process parameters (e.g., scanning step, compensation parameters on the edges). The base of the aluminum deposit shown in Fig. 12b is a pentagonal prism with three features of varying heights: an elliptical cylinder with a height of 10.8 mm, a cylinder with a height of 21.2 mm, and an irregularly shaped component with a height of 16.2 mm. It can be noted that there are no unexpected deposits between the features, greatly reducing the need for post-CSAM machining of the deposit, resulting in a more efficient process and workpieces that better meet design requirements. Fig. 12c shows a deposit sprayed using pure copper powder. Due to the high DE of the CS, it took 70 minutes to manufacture this 2.3kg copper hand. The dimensions of this hand are 145 mm in height and 95 mm in width. The features of the palm and back of the hand as well as five fingers are evident. It is also noticeable that the deposition of the fingertips is not as good as the rest of the hand. This is because the depositable areas of the fingertips are too small and the diameter of the nozzle outlet is in the millimeter range.

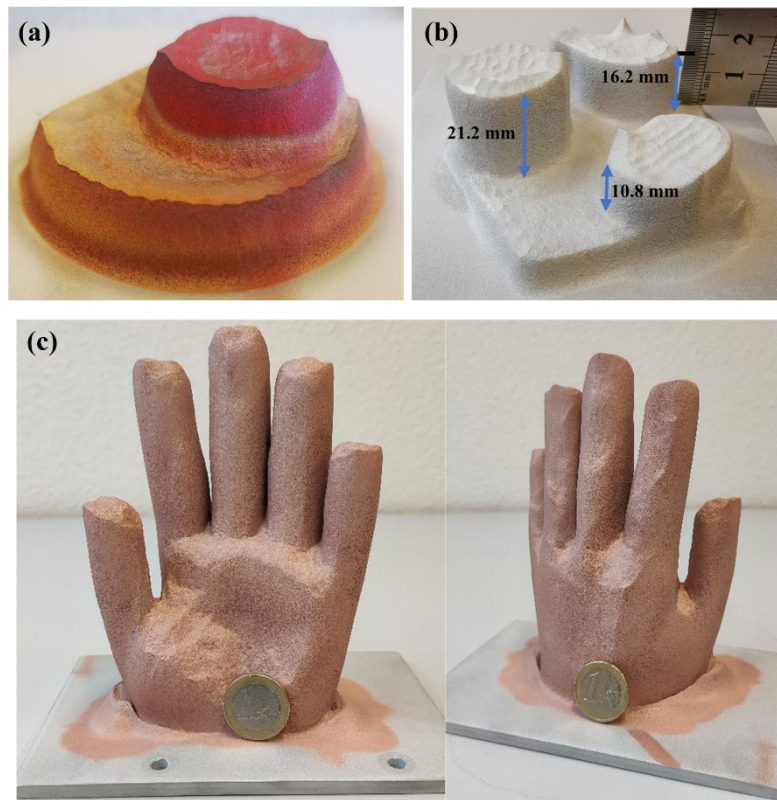


Fig. 12 The deposits: (a) with a single feature; (b) with multiple features; (c) a copper hand (Ref 25)

In-situ online monitoring module

In-situ online monitoring module enables real-time observation and control of the deposition, improving the quality and consistency of the deposit. In the CSAM process, the evolution of the deposit involves multiple process parameters, and the deposit shape may not be as expected. The lack of quality assurance is the key technological barrier hindering the CSAM process from being widely employed. Implementing in-situ online monitoring and adaptive feedback control appears to be a powerful strategy to address this problem. Fig. 13 shows the module (green square box), including a high-speed laser profiler (LJ-X8000, Keyence, Japan) and a PC.

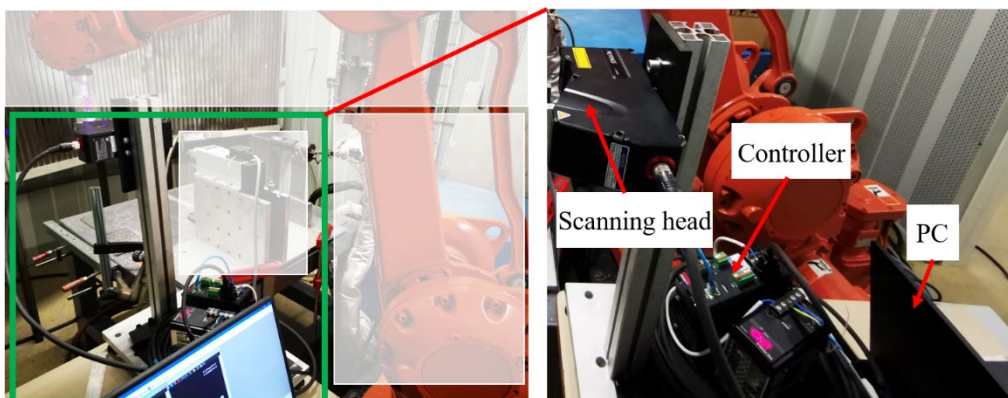


Fig. 13 In-situ online monitoring module

The in-situ online monitoring module has several functions, such as scanning the substrate surface, monitoring the deposit growth, controlling the deposition process, and optimizing the parameters and trajectory. The utilization of the in-situ online monitoring module is as follows: first, the substrate surface before spraying is scanned by the profiler to obtain its position and geometry information. Subsequently, the evolution of the deposit is monitored layer by layer. During the actual deposition, the deposit may not grow layer by layer in accordance with the predetermined spray trajectory. For instance, powder deposition might be too quick (e.g., heat accumulation) or too slow (e.g., nozzle clogging). These phenomena can make the final deposit shape very different from

expectations. The deposition can be controlled and adjusted in real time based on the module. In addition, the profiler can be used to measure, record and process data from the spraying process. This allows for the optimization of parameters and spraying trajectory.

Subtractive module

A subtractive module removes the excess or undesired material from the deposit by using machining methods. It is well known that the resolution of the workpiece fabricated by CSAM is usually low. Additionally, the traverse speed of the robot drastically decreases when changing the robot's motion direction, resulting in an excessive deposition in that location, further affects the subsequent deposit shape. Some spiky deposits can be found in Fig. 12b. Meanwhile, the deposit growth is also affected by heat accumulation. All of this can lead to large deviations in the quality and geometric accuracy of the deposits from expectation. Therefore, the application of subtractive module in the CSAM system is indispensable, as shown in Fig. 14. The milling cutter was used to finish the deposit surface shown in Fig. 14a and machine off the redundant coating after defect repair, as shown in Fig. 14b. It is worth mentioning that the traverse speed of the workpiece, the rotational speed of the milling cutter and the feeding distance of the workpiece for each milling are the key parameters in the process. Improper parameters can lead to deposit or the cutter damage. In addition, considering that the high-speed movement of the milling cutter generates a lot of heat during the milling process, a cooling device is necessary. In general, the subtractive module adds flexibility and fosters applications of the CSAM.

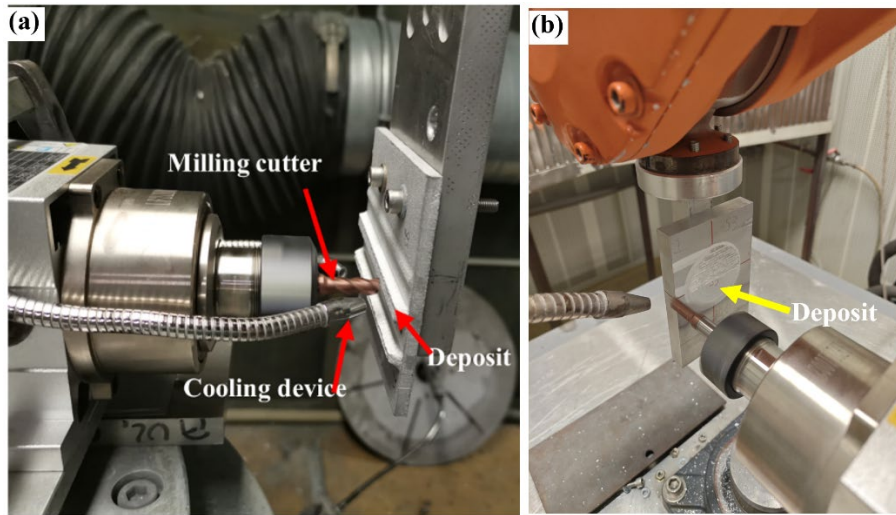


Fig. 14 Subtractive module: (a) machining of the wall in the AM; (b) machining of the coating for as-repaired defect

Post-treatment module

The post-treatment module modifies the shape and properties of the deposit after CSAM, improving its performance and functionality (Ref 57). Shape post-treatments, including turning, grinding, milling, polishing and lapping, are used to achieve the desired deposit shape and reduce surface roughness. These methods were discussed in the previous section. Additionally, post-process the deposit is crucial for ensuring good properties, such as consistent compressive stress, enhanced of cohesion between particles, improved adhesion between coating and substrate, and reduced coating anisotropy (Ref 58).

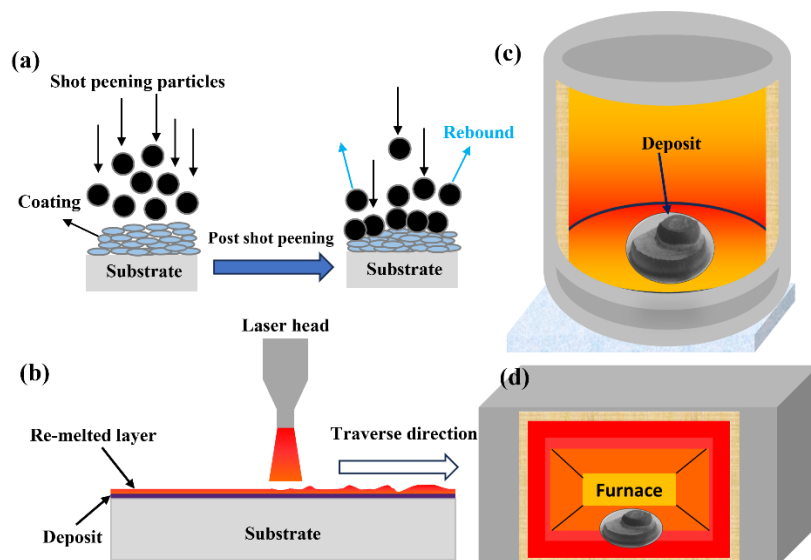


Fig. 15 Post-treatment processes: (a) shot peening process over the coating; (b) working operations of laser re-melting process; (c) hot isostatic pressing with parameters; (d) annealing process

There are different methods of property post-treatment, such as shot peening, heat treatment, laser remelting, and hot isostatic pressing. Shot peening is a cold work method, which can eliminate surface cracking, increase surface hardness, coating density and improve fatigue performance by applying residual compressive stress to the deposit surface, as shown in Fig. 15a (Ref 59). Ghelichi et al. (Ref 60) presented that shot peening can enhance the coating density by inducing additional deformation of the powder particles. The coating's surface becomes more uniform and smoother following the shot peening process. Heat treatment (e.g., annealing, tempering, quenching, precipitation strengthening) is a method of altering the microstructure of metals or alloys by heating them at a high temperature for a certain time. Laser remelting shown in Fig. 15b uses a laser beam to generate enough heat energy to melt the deposit surface, followed by a rapid cooling process to minimize surface roughness and porosity (Ref 61). This remelting technique can improve the wear and corrosion resistance of the deposit. Hot isostatic pressing (HIP) is a manufacturing process that uses high temperature and pressure to reduce the porosity, improve the mechanical properties and workability of the components, as shown in Fig. 15c. Petrovskiy et al. (Ref 62) discovered that HIP markedly decreased the porosity of CSed pure titanium coatings, from 4.3% to 2.2%, and significantly enhanced the ultimate tensile strength (UTS), elevating it from 110 to 480 MPa. Last but not least, annealing the deposit in a furnace shown in Fig. 15d is also a conventional post-processing method. Kumar et al. (Ref 63) found that the interlayer boundaries of the niobium coating were completely removed and the porosity was reduced to about 0.1% during heat treatment at 1500°C.

Information exchange

As market conditions continue to change, CSAM faces the challenge of ever-shorter product life cycle and an increasing demand for customized products. This requires enterprises to be able to adapt

to changes and increases the demand for flexible manufacturing systems. The ability to react to changes related to products and production processes is a core requirement for flexible CSAM system.

With the advent of the digital age, information has become an important production factor.

Information exchange refers to the process of sharing, transmitting, or transferring data between system modules. This information exchange can occur within each component or between two components of the system, depending on the stage of the fabrication process. Efficient and effective information exchange within the integrated intelligent CSAM system is a key aspect for deposits fabrication. Fig. 16 shows the integrated module hybrid CSAM system we developed. A spray path is firstly generated in the software component (computer) based on the 3D model of the object to be manufactured, which is then fed into the robot module in the hardware component, and the deposit is fabricated in the spray module. The in-situ online monitoring module (laser profiler) can be used to monitor and record the evolution of the deposit, which helps in the subsequent optimization of the process parameters and spray paths. The deposit is then digitally modeled by means of reverse engineering and fed into the software component for data postprocessing to generate machining toolpaths. Finally, redundant deposits are removed by machining (milling cutter).

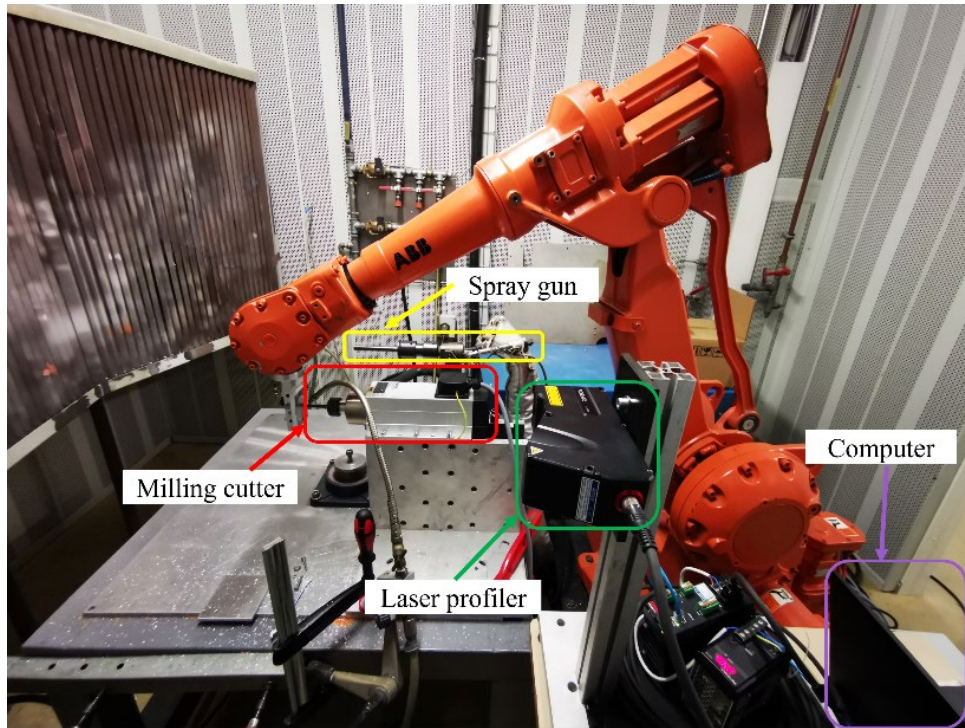


Fig. 16 Integrated module hybrid CSAM system

Conclusions and prospects

This paper introduces an innovative integrated modular CSAM system. The system consists of two components: the software that performs modeling and simulation, and the hardware that performs precise fabrication. The software component that performs modelling and simulation, and the hardware component that performs precise fabrication. The software component here is mainly used to simulate and predict the deposit shape evolution as well as provide the required spray trajectory for the industry robot. Of course, data preprocessing of the object to be manufactured and data postprocessing of the deposit are also inseparable from its support. As for the hardware component, it is used to implement the manufacturing required for conforming workpieces. It integrated 4 modules of robot, spray, in-situ online monitoring and subtractive. These modules work together to perform the CSAM and the necessary modifications of the deposit shape. It should be noted that manufacturing is inseparable from the support of data and information from the software component. That's why the modular concept of components is proposed in this paper to execute the information

exchange between the components and modules within components. This information exchange enables real-time feedback and adjustment of the fabrication process, which can improve the flexibility and consistency of the system.

However, there are still some limitations to the current developed system. CSAM can leverage AI in several advantages, e.g., process control and optimization, material selection and design as well as properties prediction and assurance. Pre-treatment of substrates and powders and post-treatment of deposits to improve mechanical properties are also necessary in CSAM. These modules are still not integrated into the system. In addition, how to realize the interaction of information among all the modules needs to be refined.

Overall, the developed integrated modular CSAM system automates multiple manufacturing phases, enhancing fabrication efficiency and paving the way for broader commercialization of CSAM.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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