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Cold Spray Additive Manufacturing of Leading Edges Robotics Requirements

by Isaac Nault and Michael Nicholas

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14. ABSTRACT

This report documents the design requirements for a robotic manufacturing cell capable of fabricating leading edges up to 10 ft in length using the cold spray process. The report also covers the requirements for software to be used in running the system. The design requirements were influenced by the authors' prior experience and subject matter expertise in the area of cold spray additive manufacturing (CSAM). The report will be used to define the requirements for a prototype manufacturing cell that is being built as a deliverable to the Army Manufacturing Technology Program. The design principles can be used by the Army and other Department of Defense agencies to define the requirements for other similar CSAM cells.

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1. Introduction

The US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) is leading an Army Manufacturing Technology program titled “Cold Spray Additive Manufacturing (CSAM) of Leading Edges for Extreme Environments”. The overall objective of the program is to develop mature technology for additively manufacturing leading-edge erosion protection using cold spray (CS). ARL has previously manufactured prototype leading edges ranging from 4 to 72 inches long using in-house robotic capabilities, but the results have revealed critical shortcomings in the current equipment that must be addressed. Therefore, one of the deliverables of the program is to build a new prototype robotic cell specifically designed for CSAM of leading edges. The purpose of this document is to outline the requirements of such a system for prospective robotics integrators. The CSAM prototype system is expected to be a collaborative effort among ARL, a CS system provider, and a robotics integrator.

2. Technology Description

CS is a kinetic energy-driven, metallic powder consolidation process in which metallic particles are heated and accelerated to high speed (>1000 m/s) and impacted onto a metallic substrate on which a deposit is gradually built. Typically, CS is used as a coating or repair technique, but in this case, CS is being used as an additive manufacturing (AM) technique to manufacture a new part. The CSAM process for a leading-edge part is illustrated in Fig. 1. First, CS is applied to a mandrel bearing the inner shape of the part. The first layer of CS is intentionally applied at lower velocity to promote debonding after the build is complete. Before debonding, surface finishing would be done to bring the part to final dimension. After debonding, the part is heat treated and then attached to a structure using adhesive bonding. The prototype CSAM system for this program will be required to, at minimum, perform the CS deposition onto the mandrel (step 2) and potentially the surface finishing (step 3). The manufacturing of the mandrel (step 1), release of the deposit from the mandrel (step 4), heat treatment (step 5), and adhesion to the composite (step 6) will be performed by other systems and/or processes. Figure 2 shows an image of a released 4-inch long CSAM leading-edge specimen.

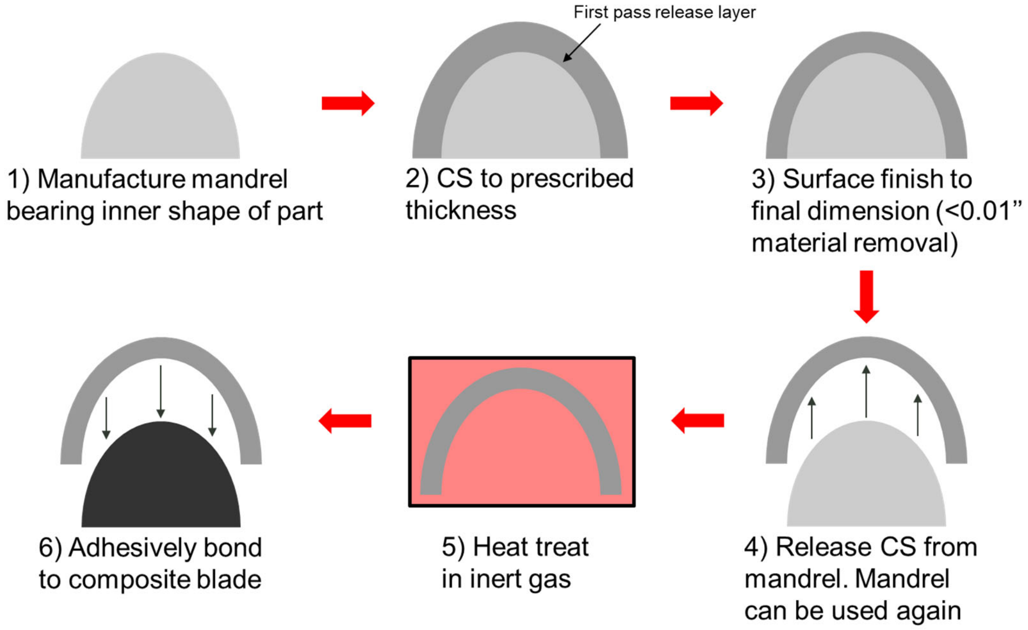

Fig. 1 **CSAM leading-edge process**

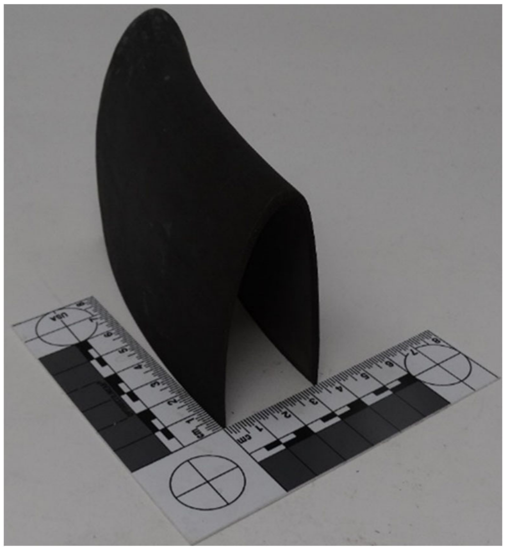

Fig. 2 **Example of a CSAM leading edge**

2.1 Deposition Strategy

CS has a “bell-shaped” or “Gaussian” deposit profile as illustrated in Fig. 3. Therefore, a smooth layer can be deposited by overlapping consecutive lines of CS. Using this approach, CS can be used in AM of objects in a manner similar to other AM technologies, by building up one layer at a time.

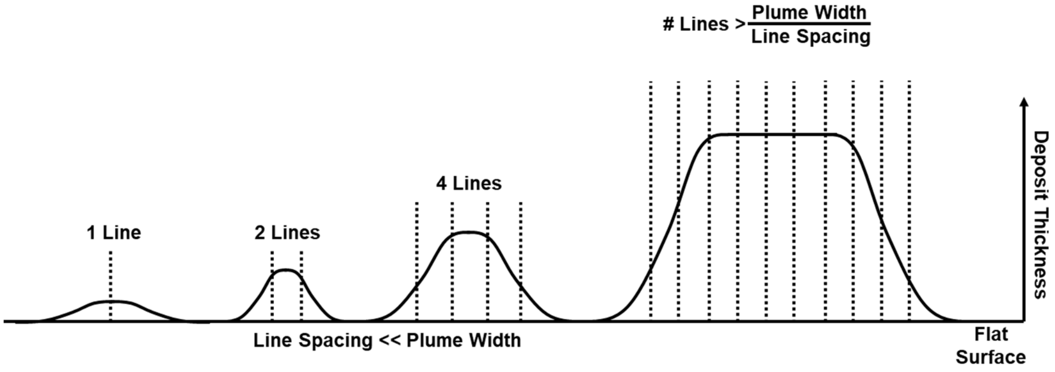

Fig. 3 Effect of number of lines on CSAM deposit

On each layer, a tool path must be generated that fully covers the surface. The local thickness of a CS layer will be sensitive to two factors as illustrated in Fig. 4: the tool path velocity and the effective line spacing. Increasing the tool path velocity or line spacing has the effect of decreasing the effective layer thickness. Furthermore, increasing the line spacing too much can lead to a “ripple” effect on the outer surface. Unlike some other AM processes, in CSAM it is not practical to reliably stop or vary the feed rate of the powder in real time. The powder feed rate is effectively held constant throughout the build, and local variations in the thickness are achieved through variations in the path velocity or line spacing. For these reasons, the prototype CSAM system must maintain tight tolerances on the path velocity and accuracy.

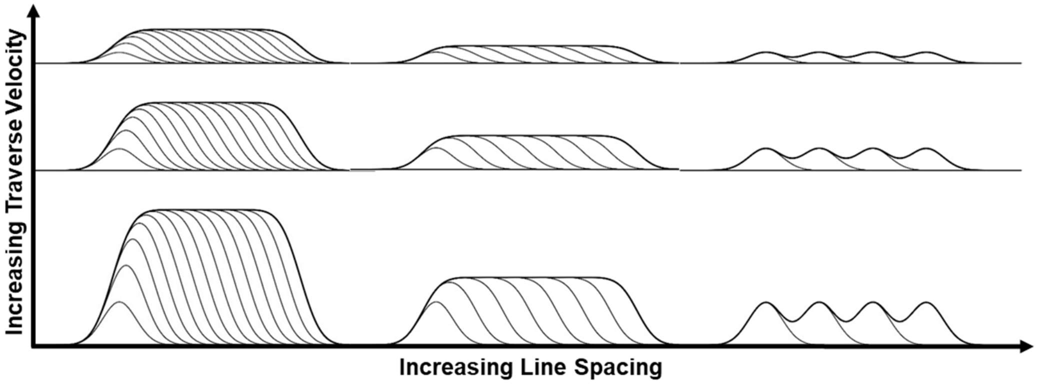

Fig. 4 Effect of line spacing and traverse velocity on CSAM depost

The tool path for CSAM of a leading edge is described in US Patent Application US20210402478A1[1] and illustrated in Fig. 5. In the figure, the line spacing is greatly exaggerated for illustration purposes. The tool path makes smooth sweeps along the spanwise direction of the leading edge. At the ends, the tool path makes an abrupt turn in the opposite direction before sweeping back. Because the powder feed cannot be turned off mid-build, the tool path extends beyond the edge of the mandrel to avoid excess material from building up when the robot slows down to execute the turn.

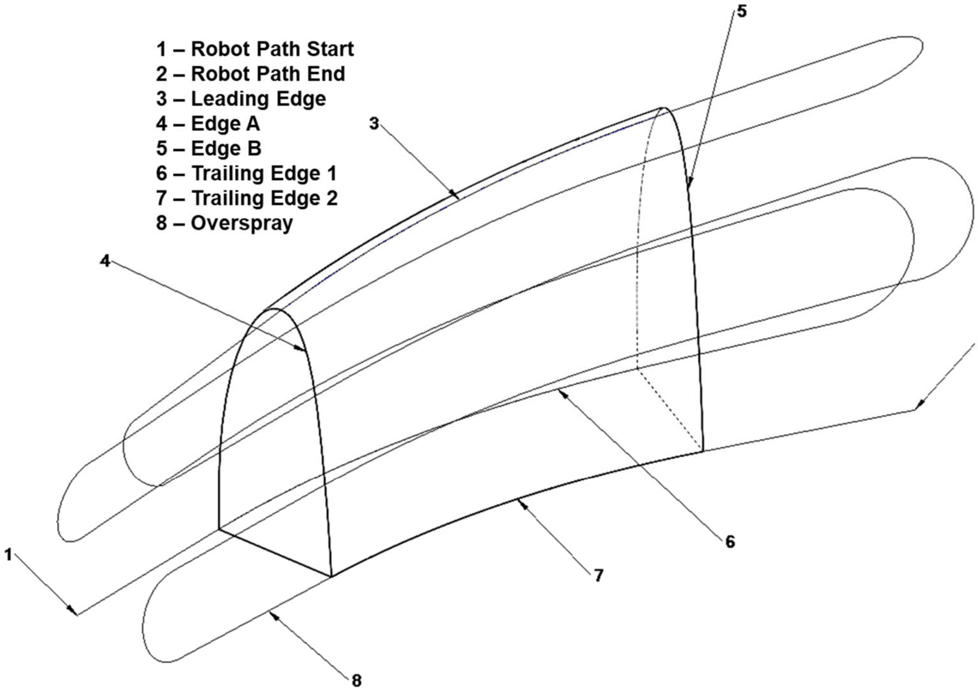

Fig. 5 Conceptual illustration of CSAM tool path on leading edge

The tool path can be described as the projection of a 2D raster pattern (illustrated in Fig. 6) onto the 3D surface of the leading edge. The 3D surface of the leading edge generally will not have a 2D projection that is perfectly rectangular and may likely be trapezoidal. Therefore, the effective line spacing may be locally "stretched" to fit the surface of the leading edge. Without changing anything else, a varying line spacing would result in a varying layer thickness. To achieve a uniform layer thickness, a dynamic velocity correction is applied in which the tool motion accelerates or decelerates during each sweep to account for local deviation in effective line spacing.

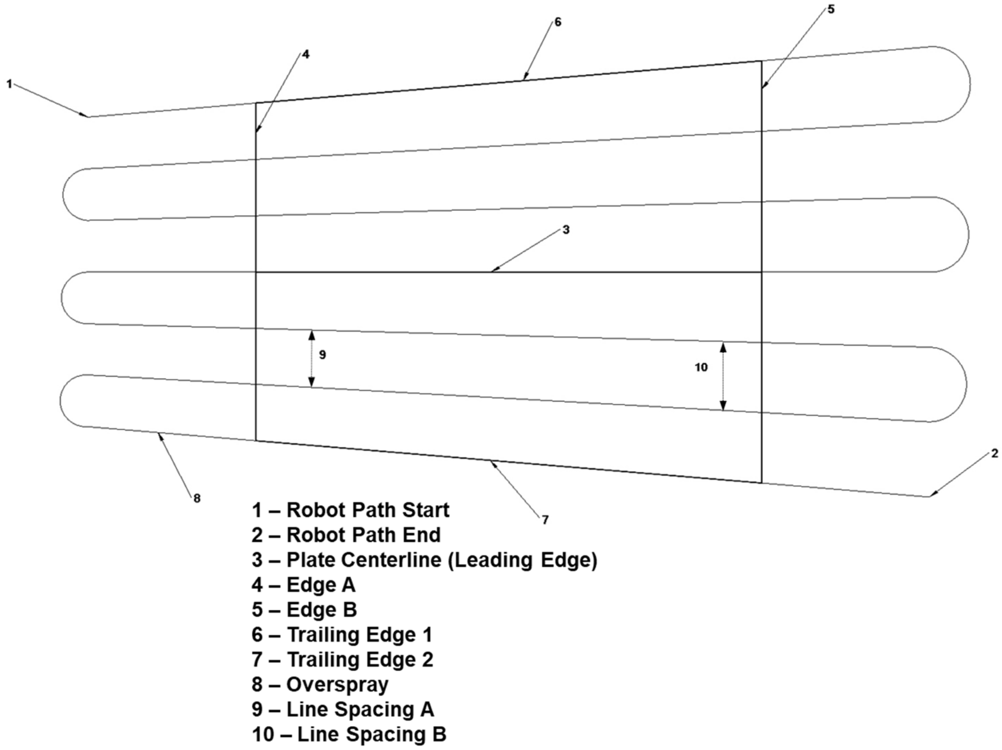

Fig. 6 2D projection of CSAM leading-edge tool path

2.2 Tool Path Generation

ARL has developed an algorithm to apply a dynamic velocity correction to a tool path to achieve a target layer thickness.[2] As illustrated in Fig. 7, the algorithm receives a tool path and target layer surfaces as input and applies a correction to the tool path velocity so that the CS layer will match the target layer surface. This algorithm can be used as part of a layer-by-layer process to accurately build larger objects such as a leading edge. This method requires a CAD/CAM software environment in which target layer surfaces can be defined and robotic tool paths can be generated on each respective surface. To utilize the method in practice, the CSAM prototype system must be fully compatible with the CAD/CAM software so that robot programs generated in the software can be repeated on the hardware with minimal human intervention and with the highest possible accuracy.

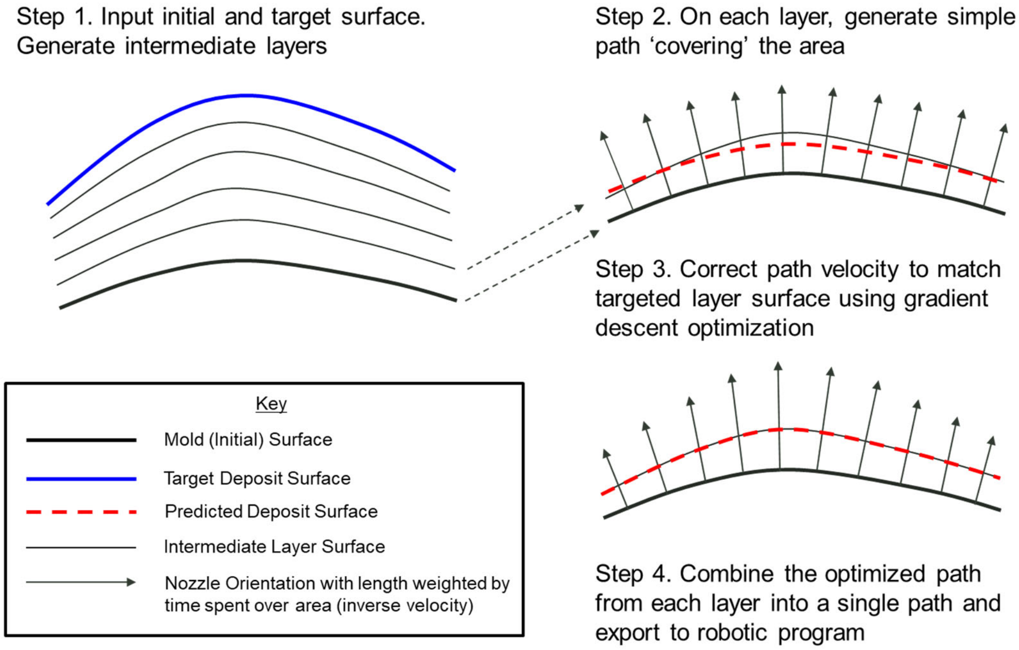

Fig. 7 CSAM dynamic velocity correction

2.3 Effects of Path Inaccuracy

ARL has observed detrimental effects to deposit quality due to path inaccuracy. The effects are most pronounced near regions of high curvature such as the tip of the leading edge as illustrated in Fig. 8. Small misalignments along the tool path can result in a substantial portion of the CS plume missing the substrate, leading to a local decrease in thickness. In addition, elevated levels of high-angle impacts can lead to increased porosity defects in the deposit.

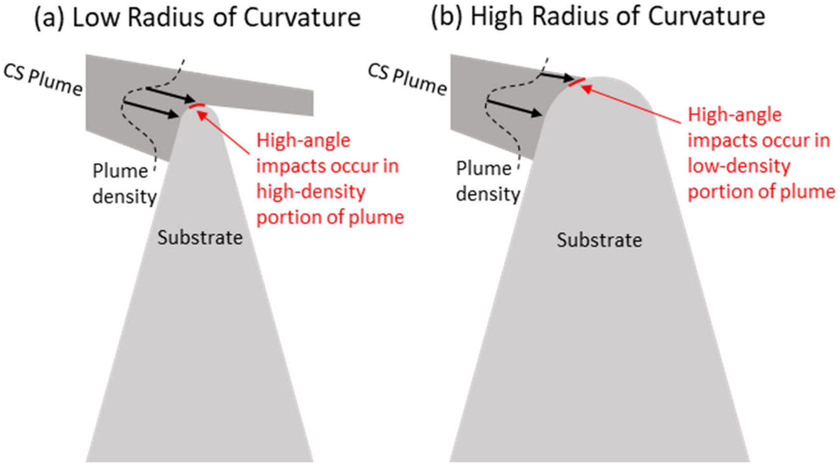

Fig. 8 Effect of high curvature

The effects of path misalignment, in particular the decrease in expected thickness near the tip, have been seen in virtually every sample produced by ARL to date. A representative example is shown in Fig. 9. A polished cross section of a leading edge is shown with a red curve overlaid showing the target leading-edge shape. This outcome—a lower thickness at the tip with two "mounds" of slightly higher thickness on either side of the tip—is indicative of path misalignment.

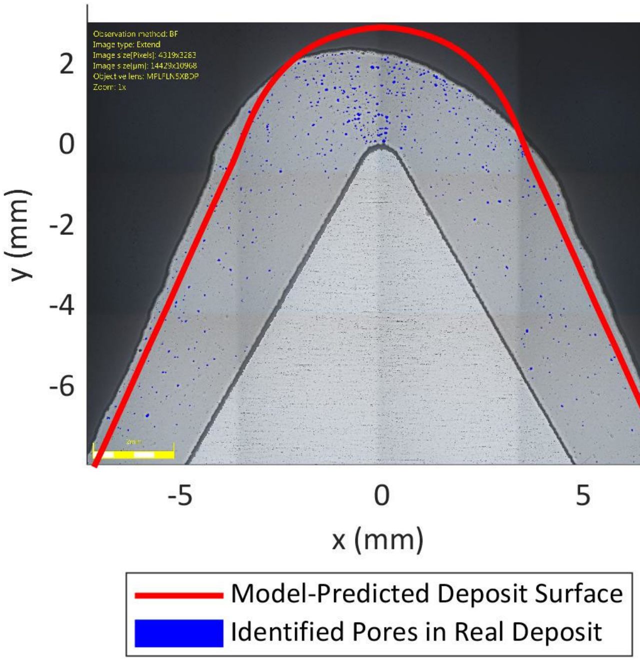

Fig. 9 Example of leading-edge defects due to high curvature

ARL deposition modeling has shown that path deviations (on the order of 1 mm) can have substantial effects on the shape and deposit quality as shown in Fig. 10. The top row of images represents leading edges of various corner angles simulated with an ideal tool path with no misalignment. The bottom row is simulated using the same tool paths but with realistic misalignments that can occur due to tool calibration and work object locating. These misalignments were simulated on the order of 1 mm, and the misalignments were chosen such that the final deposit shapes matched actual observed leading-edge samples produced by ARL. The results show that path misalignment contributes to more than just geometric defects, but they may also lead to higher local porosity near the tip. This is important because geometric defects can be addressed by applying additional layers, but material defects cannot be fixed. Therefore, mitigating path misalignment may be the only way to address material defects near the tip.

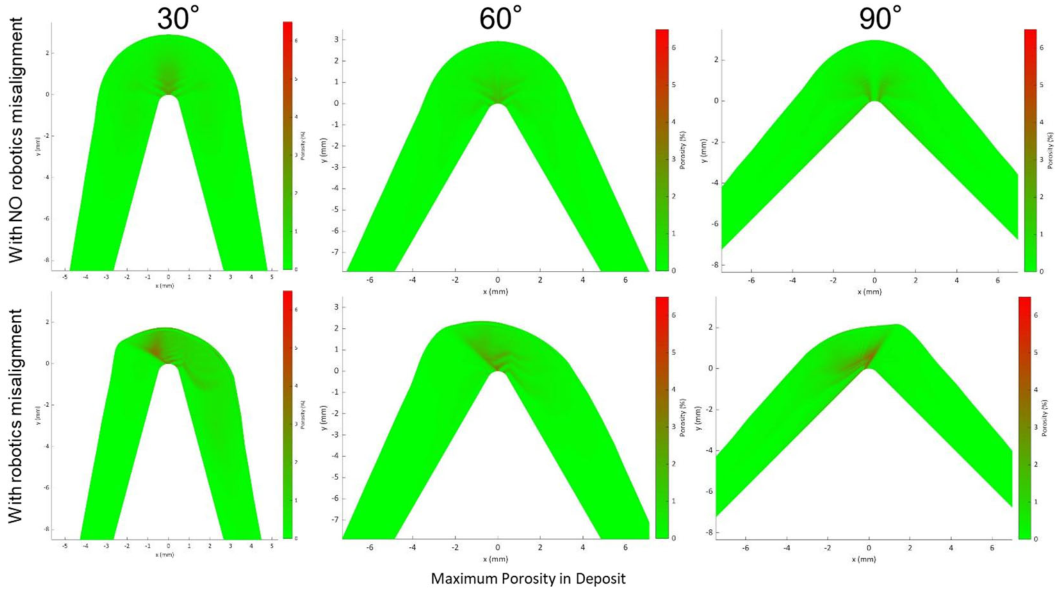

Fig. 10 Effect of robotics misalignment

2.4 Mandrel and Release Process

The CSAM deposit release process requires a hardened steel mandrel. Due to the requirement for hardened steel, the mandrel will be very heavy. Therefore, the CSAM prototype system requires hardware capable of supporting the mandrel, and, if necessary, moving the mandrel as part of the deposition process. Due to the hot gas and powder-carrying hose connected to the CS applicator, ARL has found it is not practical to CS a full-length, leading-edge mandrel without some movement of the mandrel during the process. The current practice is to use a 6-axis robot arm to carry the CS applicator and a 1-axis horizontal positioner to rotate the mandrel to allow the CS applicator to access all surfaces of the mandrel without the hoses contacting the mandrel.

2.5 Helium Recovery

In some cases, ARL uses helium gas as the process gas to manufacture leading edges. To offset the costs of using helium gas, ARL has previously developed helium recovery systems to recover and repurify helium that can be reused for CS. In a helium recovery process, the CS is performed inside of a gas-tight booth. The gas within the booth is collected and processed through a series of membranes and pressure swing adsorption to separate helium from other gasses collected from the booth. This process is repeated until the purity of the helium reaches a set level, and then the purified helium is moved to a separate storage. In longer sprays, the system can eventually reach a closed loop in which the system draws on the purified helium that was recovered earlier in the process. Eventually, the gas-tight booth reaches an equilibrium where almost all the gas in the booth is helium, at which point the process becomes the most efficient. Therefore, the overall efficiency of the process, and consequently the ability of the system to reach a closed loop, is highly dependent on the volume of the gas-tight chamber. The smaller the chamber, the less contaminant gas is collected initially and the sooner the chamber fills with helium. The CSAM prototype system must contain a working volume that is gas tight and small enough to facilitate an efficient helium recovery process.

3. Minimum System Requirements

3.1 CS Enclosure and Environment

Some of the system (robot, positioner, CS applicator, and lines connecting to the applicator, etc.) will need to be installed in an enclosure that is completely contained to collect small powder particles that do not adhere to the work object and to contain helium that is used in the process. The enclosure will have continuous air flow while in operation, but any systems in the enclosure will experience interactions with powder particles and helium gas. The ambient temperature in the enclosure may rise to as high as 180 °F while in operation.

The enclosure must accommodate install and/or removal of the strong-back and mandrel as well as the CS applicator, hot gas hose, and powder feed lines. The enclosure should have a door or resealable opening that would accommodate a full-length helicopter rotor blade to be inserted through the opening and positioned along the same axis as the mandrel in an ordinary build. The purpose of this feature is to accommodate future repair work on blades. The robotics integrator is not responsible for any hardware to hold the blade in place. The integrator is only responsible to ensure an opening is built into the enclosure to allow this in the future. The opening can coincide with an otherwise planned door into the enclosure. The enclosure does not need to be helium gas-tight while the door is open.

The enclosure must be leakproof and sound dampening, and it should have a false floor. The ARL has learned from previous experience that enclosures bolted to concrete floors are not sufficient to retain helium for recovery purposes. The enclosure should have space for a video or thermal camera to be mounted inside where it will be safe from collision with the robot. The robotics integrator is not required to supply the camera.

The robotics integrator will be responsible for the design and construction of the enclosure to ensure the robotic system can safely operate inside the enclosure without colliding with walls or other objects inside the enclosure. The CS system provider will provide the CS hardware and helium recovery system. The CS system provider will provide the specific ducting requirements for the enclosure to be compatible with the CS, helium recovery system (HeRS), and dust collector (DC). Figure 11 depicts a conceptual rendering of a CS helium recovery enclosure showing the ducting in and out of the enclosure. A total of four, 4-inch-diameter ducts are required: 1 on top and 3 on bottom. The enclosure shall contain a false floor to mitigate leaking. Ideally, a trough-shaped collection bin will be designed under the rotor blade mandrel to aid in the collection of powder. In addition to the ducts, a gas-tight conduit for gas and electrical lines related to the CS system to pass into the enclosure will be required. The lines associated with the CS system include the following: two cold gas lines (main gas and powder-carrying gas), thermocouple wire, heater power cable, and two water lines for optional nozzle cooling (water in and water out). All of the CS lines can be bundled and are flexible. The CS system provider will provide all CS lines and ducting to the helium recovery system. The robotics integrator must ensure the booth is compatible with these requirements.

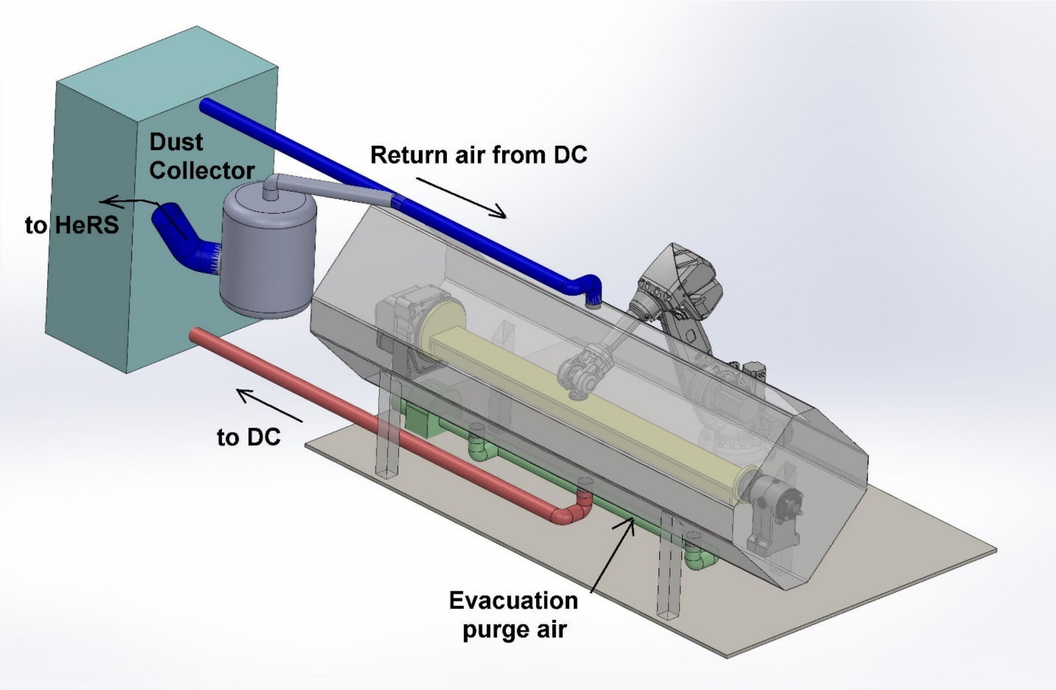

Fig. 11 Conceptual helium recovery booth

3.2 Work Volume

To accommodate effective helium recovery, the work volume of the enclosure must be helium-gas-tight and no larger than 800 cu ft. The work volume is defined as the volume of space in which helium from the CS applicator may freely enter during the spray process. There are no other requirements on the shape of this volume. It does not need to be rectangular. Furthermore, the robotics system does not need to be completely contained within the work volume. For example, one proposed idea is to use flexible gas-tight plastic bags that enclose the mandrel and fit tightly around an axis of a robot arm. The ARL is open to any proposed solution to keep the work volume under 800 cu ft.

3.3 Path Accuracy

The path accuracy is defined as the maximum distance between the actual tool path and the prescribed tool path. The line spacing on a CSAM leading edge build can range between approximately 0.5 and 1 mm. Furthermore, ARL plans to build leading edges with radius of curvature as small as 0.5 mm. Therefore, ARL is targeting a path accuracy of 0.1 mm or better for the CSAM prototype system. The calculation of path accuracy must include the stack-up of all other types of misalignments such as tool control point (TCP) or work object misalignment.

3.4 Velocity Accuracy

As described previously, ARL uses a dynamic velocity in which the tool motion accelerates or decelerates within a single sweep to achieve a uniform layer thickness. Within a single sweep, the velocity is projected to accelerate (or decelerate) as much as 2× (or 0.5×). Expected velocity ranges are 100 to 800 mm/s. ARL aims to achieve total deposit thickness within 10% of the prescribed value. To meet this requirement, the tool velocity must stay within 10% of its prescribed value at any point along the sweep.

3.5 Automated Tool Calibration

In CSAM, the “tool” is the CS nozzle, and the TCP is the point on the central nozzle axis that is 1 inch from the end of the nozzle (to account for the 1-inch standoff between the nozzle and substrate). ARL currently uses a manual TCP calibration process in which a pointer is placed on the end of the nozzle (with the point designed to sit exactly 1 inch from the end), and the pointer is aligned to another fixed point in space in several different poses. However, it is believed that this manual process leads to TCP misalignment well exceeding the target value of 0.1 mm. Furthermore, the calibration process is carried out while the system is cold, and the CS applicator may warp slightly when running at a high temperature, leading to a TCP misalignment. For all of these reasons, the prototype CSAM system must include a means to automatically calibrate the TCP location while the system is running and hot gas is flowing out of the nozzle. ARL is open to considering any automated TCP calibration method that ultimately leads to the required path accuracy of 0.1 mm or better.

3.6 Work Object Calibration

The CSAM prototype system must include a means to locate the work object or mandrel in space. Previously, ARL located the work object using robot user coordinate frames and teaching points of the work object that can easily be identified in both the physical space and the CAD model. The robot path is then exported in that user coordinate frame. It is suspected that this manual process leads to work object misalignment that well exceeds the target value of 0.1 mm. Although solutions such as 3D scanning have been proposed, ARL is open to considering any work object locating technology that ultimately leads to the required path accuracy of 0.1 mm or better.

3.7 Mandrel Size and Weight

The prototype CSAM system must accommodate leading edges up to 10 ft in length. Leading edges may have twist and curve, but the entire component can be contained inside a cylindrical volume of 24-inch diameter. In previous work, ARL has used a two-part fixture to hold the mandrel. One part of the fixture is the mandrel itself, made of a hardened steel, which bears the inner shape of the leading edge. The second part is a strong-back, made of steel, designed to support the mandrel and bridge the gap between the head stock and tail stock of a 1-axis horizontal positioner. The mandrel is designed to be detachable from the strong-back to facilitate release of the deposit from the mandrel. The strong-back is also designed to have an additional length of 12 inches on either side of the leading edge to allow space for the robot to turn around off the part. Therefore, the CSAM prototype system must accommodate up to a 12-ft long strong-back. In ARL's previous design with an 8-ft long strong-back, the total weight of the strong-back and mandrel was 350 kg. Projecting that to a 120-ft strong-back, the system must accommodate a weight of 600 kg (rounding up). The strong-back and mandrel combined should fit inside a cylindrical volume of 30-inch diameter. The design and manufacture of the strong-back and mandrel are not requirements of the CSAM prototype system, but the system must be able to accommodate the weight and size of the fixture.

3.8 CS Applicator Size, Weight, and Hose Attachments

The CSAM system must accommodate the CS applicator depicted in Fig. 12. A CAD model of the applicator will be provided to the robotics integrator upon request. There are six lines that connect to the applicator: one cold gas line (the main gas line) that connects to the heater, one cold gas line (the carrier gas line) that connects to the back of the nozzle, one thermocouple wire, two water lines that connect to the nozzle cooler (in and out), and one heater power cable. All lines are flexible and can be produced in sufficient length as requested by the robotics integrator. The CS system provider will be responsible for providing the applicator and all connecting lines. The weight of the applicator and all connecting lines will not exceed 15 kg. The CSAM system must be able to move the applicator such that the nozzle can follow the prescribed tool path without the applicator or connecting lines colliding with any other objects in the booth.

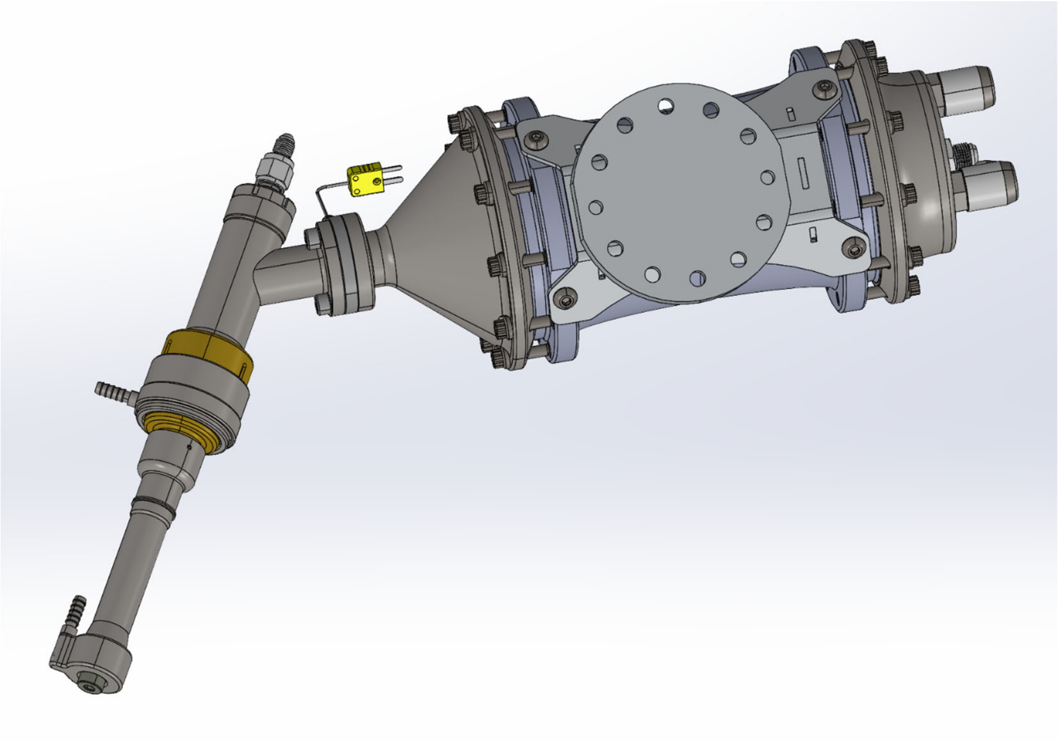

Fig. 12 CS applicator

3.9 Robotic Configuration

Previously ARL has used a 6-axis robot arm and 1-axis horizontal positioner to manufacture prototype leading edges. The CS applicator is fixed to the end of the robot arm and the mandrel is rotated by the 1-axis positioner. However, due to the new work volume requirement for helium recovery, a 6+1 axis configuration may not be the best solution. ARL does not require a 6+1 axis configuration for the CSAM prototype system. The only requirement is the robot system must be able to position the CS nozzle at a normal angle to any and all points on the build surface of the mandrel, and the nozzle must be able to move through these points (as part of a path described previously) without crashing into the work volume enclosure or any other solid objects in the space.

An alternative configuration that has been explored by CSAM system producers is one in which the CS applicator is held fixed and the work object is moved by a 6-axis robot arm. The advantage of this configuration is that one does not need to consider the motion of the hoses or the applicator crashing into another object during build. However, this configuration has been used exclusively for lightweight builds. In the case of the CSAM prototype system, the work object will weigh hundreds of kilograms. ARL is not opposed to such a configuration, but the system must be able to move the mandrel at the positional accuracy and velocity required.

3.10 CAD/CAM Compatibility

The CSAM prototype system must be compatible with a commercial CAD/CAM software, and a digital twin of the cell must be produced in the software. A user should be able to generate a tool path on the software and reproduce that tool path on the actual system with minimal intervention and to the required degree of path accuracy. The robotics integrator will supply a computer with the CAD/CAM software and digital twin of the cell installed. The robotics integrator will include a license for at least one seat to use any software required to run the system for at least 3 years.

3.11 Scanning Capability

The CSAM system must include a capability to scan the work object before and after CS deposition to assess the thickness of the build and ensure an adequate thickness has been built up.

4. Additional System Features

The below features are not minimum requirements, but ARL is interested in implementing them if the budget allows. The system will function without these features, but their inclusion will increase the efficiency and utility of the system.

4.1 CAD to Part Software

ARL is interested in accelerating the tool path planning because it is extremely resource intensive. Tool paths can take up to 1 week to generate with numerous iterations required.

4.2 3D Scanning

ARL is interested in a 3D scanner that could be used to scan the work object at the beginning and end of the build, or even between layers to monitor progress in situ. The 3D scanner could also be used to locate the work object at the beginning.

4.3 In-Process Build Geometry

ARL is interested in integrating a monitoring system that will evaluate the build periodically throughout the process. If precise enough, this system could also be used to create a feedback loop to modify the build geometry based on previous layers.

5. Requirements Summary

The minimum system requirements described in previous sections are summarized in Table 1.

Table 1 Summary of system requirements

Feature	Requirement
Enclosure	Helium gas-tight, equipped with four 4-inch ducts
Environment	Operating up to 180 °F
Path Error	<0.1 mm
Velocity	100–800 mm/s
Velocity Error	<10%
Tool Calibration	Automated and while system is running
Work Object Calibration	Automated
Mandrel + Strong-back Length	12 ft
Mandrel + Strong-back Diameter	30 inches
Mandrel + Strong-back Weight	Up to 600 kg
Work Volume	No greater than 800 cu ft
CS Applicator	Provided CAD model is compatible with work cell
Robot Configuration	Nozzle can be positioned at a normal angle over any point of the mandrel surface; nozzle can move through target points without crashing
Scanning	Ability to assess thickness of build
CAD/CAM	License included and installed on computer

6. Acceptance Criteria

Acceptance of the prototype system will be done in two phases: (1) at the robotics integrator's site and (2) at the final destination.

6.1 Acceptance at Robotics Integrator's Site

The first phase of acceptance will occur after the system build is complete at the integrator's facility. ARL will send the robotics integrator: a prototype mandrel and strong-back, a CS applicator, and all lines that connect to the applicator. ARL will visit the robotics integrator's site for at least one day during the demonstration. During the visit, the robotics integrator will perform a demonstration of the workflow to operate the system. The demonstration shall include the following: generation of a tool path in the CAD/CAM software, automatic locating of the mandrel (work object calibration), automatic calibration of the CS nozzle, scanning of the work object, and dry run of the robotic tool path. During the dry run, the integrator will use appropriate metrology equipment to capture the path of the CS nozzle during the program and compare this to the prescribed path. The path error will be calculated as the maximum deviation between the measured and prescribed path. The velocity of the CS nozzle will also be calculated and compared to the prescribed velocity. Acceptance will be contingent on the calculated path error and velocity error meeting the requirements outlined previously. During this phase, running of the CS system during the demonstration is optional. If the robotics integrator chooses to run the CS system, the facility must be appropriately prepared for CS operation. The robotics integrator will notify ARL if a full CS system is required. The onsite demonstration shall be conducted using nitrogen process gas. ARL will not be able to supply helium during this phase.

6.2 Acceptance at the Final Destination

The second and final phase of acceptance will occur at the final destination after installation has been completed. ARL will provide the following: a prototype mandrel and strong-back and an operational CS system. At the final destination, the robotics integrator will perform a demonstration of the workflow to operate the system. The demonstration shall include the following: generation of a tool path in the CAD/CAM software, automatic locating of the mandrel (work object calibration), automatic calibration of the CS nozzle, scanning of the work object before and after build, a dry run of the robot program (with the CS system off), and execution of the spray program with the CS system running. During the dry run, the integrator will use appropriate metrology equipment to capture the path of the CS nozzle during the program and compare this to the prescribed path. The path error will be calculated as the maximum deviation between the measured and prescribed path. The velocity of the CS nozzle will also be calculated and compared to the prescribed velocity. Acceptance will be contingent on the calculated path error and velocity error meeting the requirements outlined previously. After the “wet” run with the CS system on, the build up of material will be assessed by scanning and compared to the prescribed build up.

6.3 Contingency Plan for Nonconformance

If, during either phase, the system is found to be out of compliance with requirements, the integrator will develop an action plan to correct performance. The plan shall include a root-cause analysis and actions to correct the nonconformance. The action plan will be due to ARL 30 days after discovery of nonconformance. After corrections are made, acceptance testing will be redone.

7. Other Requirements

During the design stage of the project, the robotics integrator is expected to participate in meetings (no more frequent than biweekly) with ARL and the CS system provider. ARL will have final approval authority on the design. ARL has attempted to anticipate all major requirements of the system in this document. The robotics integrator is expected to stay within an agreed-upon budget during the design phase. Increases to budget will not be approved by ARL for minor design changes (i.e., change of the diameter of inlet or outlet duct in the enclosure).

The robotics integrator will be required to deliver the CSAM prototype system to a final destination determined by ARL. Currently, the final destination is expected to be at the following location: 22 Town Forest Rd., Webster, MA 01570.

After delivery, the robotics integrator will be required to install the prototype system at the final destination and perform final prove-out as described in the Acceptance Criteria above. The robotics integrator will send personnel to the destination as necessary to complete this task. The robotics integrator will provide ARL with a list of facility requirements and requested installation support at least 12 months before the planned installation date. This list should include minimum electrical and other utility drops and foundation requirements.

The robotics integrator will provide a training session for users of the equipment. The training session will be conducted at the final destination after installation has been completed and last at least 3 full days.

8. References

1. Nault IM, Young KW, Ferguson GD, Nardi AT, inventors; Army Research Laboratory (US), assignee. Motion technique for deposition processes to manufacture leading edge protective sheaths. United States patent US 20210402478A1. 2021 Dec 30.

2. Nault IM, Ferguson GD, Nardi AT. Multi-axis tool path optimization and deposition modeling for cold spray additive manufacturing. Addit Manuf. 2021;38:101779.

List of Symbols, Abbreviations, and Acronyms

2D	2-dimensional
3D	3-dimensional
AM	additive manufacturing
ARL	Army Research Laboratory
CAD	computer-aided design
CAM	computer-aided machining
CS	cold spray
CSAM	cold spray additive manufacturing
DC	dust collector
DEVCOM	US Army Combat Capabilities Development Command
HeRS	helium recovery system
TCP	tool control point

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