COSMOS: COld Spray Manufacturing fOr Space

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Dept. of Aeronautics, Imperial College London

Outline

- Project objectives and WPs
- Overarching progress update
- Milestones, Schedule and Risks
- Update on WP2 (specifically, D2.2)
  - Nozzle, Items identified / purchased, Health and Safety
- Update on WP3: CSAM in high vacuum
- Next Steps

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Project Objectives and Work Packages

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Objectives and Corresponding Success Criterion (CSC)

1. Develop and experimentally test a CSAM system to evaluate the feasibility of this technology in free space applications.
   CSC: Operational CSAM test rig demonstrated in a high vacuum environment.

2. Objective: Characterize the parametric sensitivity of the CSAM system.
   CSC: Optimised processing window identified, material samples produced and characterized to assess their quality.

3. Objective: Implementation of an optimisation framework for deposition trajectories to result in high-quality parts.
   CSC: Sample parts produced with reduced error/discrepancy from CAD models.

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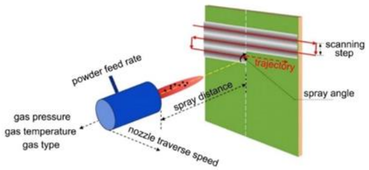
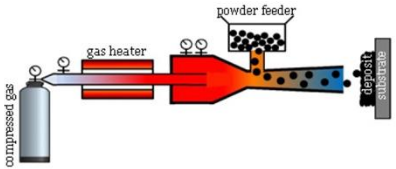
Work to be undertaken





WP1: Project management and exploitation strategy

Overall management and financial tracking of the project. Report on regular progress.

WP2: System requirements for the CSAM hardware platform

We will be building a CSAM platform that can be operated in our high vacuum facility.

WP3: Experimental testing of CSAM in high vacuum conditions

Several parameters will be swept to identify the optimal processing window

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Work to be undertaken

WP4: Microstructural characterisation of parts

As deposited parts will be inspected for porosities. Archimedes' principle will be utilised for the porosity calculations whilst metallographic analysis will be performed for a microstructural assessment by TWI.

WP5: Trajectory optimisation framework

A framework based on trajectory/tool-path optimization to result in superior prints will be developed. Where appropriate, image-based ML techniques will be deployed to reduce error.

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Overarching Progress Update

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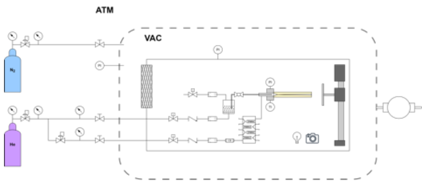
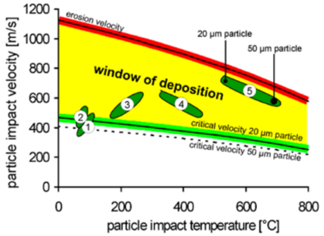
Progress made (Technical)



- Overall set-up and CSAM configuration revised/finalised.
  - Chamber and pump systems to be utilised will be covered later
- Input/output parameters identified (e.g. mass fraction, deposition rate etc.)
- Feasibility of the design space evaluated and confirmed.
- Nozzle sizing has been finalised and design sent for manufacture.
- We aim to test with Ti64 to demonstrate the feasibility.



Progress made (Operational)

- Identified more suitable facility for experimental work (Hypersonic Tunnel).
- Dept. H&S discussions have resulted in the “go-ahead”, liaising at College level now.
- Majority of components have been purchased and others have been identified for purchase (e.g., powder, diagnostics).
- Outstanding component purchase, manufacture costs, and timelines estimated.

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Milestones, Schedule, & Risks

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Test Readiness Review (TRR)

- **Milestone event:** Test Readiness Review
- **Expected Outcome:**
  - Detailing the proposed experimental test plan
  - <u>Demonstration of a successful print</u>
- **Unforeseen issues**:
  - Health and Safety iterations took much longer than anticipated but all okay to proceed
  - Spec'ing everything for vacuum rating has meant an entirely bespoke set-up
  - Custom designed Nozzles were needed to be appropriate for the operating pressures

Gantt Chart (last meeting)

Today

		Year 1												Year 2			
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Des.
WP	**Details**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
1	**Project management and exploitation strategy**	M0															KO
1.1	Project management and administrtation	1.1															
1.2	Exploitation strategy (TWI)														1.2		
2	**System req. for the CSAM hardware platform**			M1													SRR
2.1	System specification and Health & Safety (TWI)			2.1													
2.2	Procurement and assembly of hardware							2.2									
3	**Exp. testing of CSAM in high vacuum conditions**								M2								TRR
3.1	Demonstration of successful printing								3.1								
3.2	Operating window and parameter sensitivities est.												3.2				
4	**Microstructural characterisation of parts**																
4.1	Porosity and quality assessment											4.1					
4.2	Metallographic analysis (TWI)													4.2			
5	**Trajectory optimisation framework**															M3	FR
5.1	Calibration of Guassian and CNN models											5.1					
5.2	Optimised trajectories for intended topography															5.2	

Deliverable Milestone

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Milestones

Mile-stone number	Milestone description	Work Package Number	Deliverables	weeks ([] in Months)	Date due
MS0	Kick-off (KO) meeting	WP1	Meeting Minutes	T+[0]	17/4/23
MS1	System Requirement Review (SRR)	WP2	Systems Requirement Report	T+[3]	21/7/23
MS2	Test Readiness Review (TRR)	WP3	Experimental test plan	T+[8-10]	27/11/23 to 31/01/24
MS3	Final Review (FR)	WP5	Final project report and presentation	T+[15]	10/6/24 to 30/6/24

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Low
Medium
High

Risk Identifier	Risk Description	Impact H/M/L	Likelihood H/M/L	Owner	Mitigation
R1	Issues recruiting a suitable postdoc for the project	H	L	ICL	The advertisement for the postdoc position will be posted on job sites and sign-posted on LinkedIn as soon as the project contract is signed, ahead of the kick-off date of the activity. The skills needed are quite broad and match well with those completing PhDs in our Dept., so there should be a large pool of skilled candidates available.
R2	Requirements analysis is not complete, resulting in impractical design	M	L	ICL	The requirements analysis will consider all aspects of the technology, taking into account available literature into cold spray systems for industrial applications as well as spacecraft compliance and the high vacuum environmental aspects. The requirements analysis will be informed by a similar state-of-the-art analysis and current market assessment already performed by ICL during a MEng research project.
R3	Materials do not withstand the heat and pressure of the gas heater and injector system	H	L	ICL	Materials and components will be designed and chosen with a safety factor >2 given the low technical maturity of the system.
R4	System requirements definition cannot be satisfied with feasible design.	H	L	ICL	Ongoing development of similar devices indicates feasible requirements. Formalised requirements definition process will ensure identification of any conflicting requirements. Importantly, TWI's involvement/support in the project helps de-risk this.
R5	Low adherence of powder to the substrate during experimental testing	L	M	ICL	Since this technology has never been tested in a high vacuum environment, there is an inherent risk that the system will not work as expected and the powder will not adhere to the deposited material. However, the main aim of this project is to establish the concept feasibility for future in-space applications, so this finding itself would be a useful, albeit undesirable, outcome of the activity.
R6	Optimisation framework unable to reveal desired topography	L	L	ICL	As Gaussian distribution for the deposition profile has never been considered for predicting topography when dealing with multiple curved tracks, the inclusion of machine learning based (i.e. CNN) model to predict such a scenario may help overcome any shortcomings.

Risks and Impact

i) R2 - Requirements analysis is not complete, resulting in impractical design

ii) R4 - System req. definition cannot be satisfied with feasible design

Impact:

Unable to meet this milestone in a timely fashion effect delivering on D2.2 (procurement and assembly of hardware) and D3.1 (demonstration of successful printing).

Gantt Chart (updated)

MS2 completed

		Year 1												Year 2			
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Des.
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Deliverable Milestone

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Deliverables

- D1.1: Meeting minutes from KO meeting [M1]
- D1.2: Exploitation Strategy [M14]
- D2.1: System Requirement Review (SRR) [M3]
- D2.2: Hardware assembled and operations [M10]
- D3.1: Experimental Test Plan [M09-10]
- D3.2: Optimised printing window identified [M13]
- D4.1: Porosity and quality assessment done [M12]
- D4.2: Metallographic analysis undertaken [M14]
- D5.1: Calibration of Gaussian models [M12]
- D5.2: Final [M15]

D2.2: Procurement and Assembly of Hardware

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System Overview

- Experimental work will be carried out at the ICL Hypersonic Laboratory
- The Hypersonic Tunnel has a robust pumping system that is suitable for use with metal powders
- No additional filtration is required beyond the enclosure
- The CSAM device, powder hopper, and X-Y translation stage will be positioned inside of an enclosure, within the vacuum chamber
- The system will be primarily controlled and operated using LabVIEW, with secondary manual shut-offs available in case of system failure
- The CSAM device and enclosure will be fitted with diagnostics to monitor temperature and pressure to trigger auto shut-off in case of thermal/chemical reaction, or blockages of the nozzle or enclosure filter

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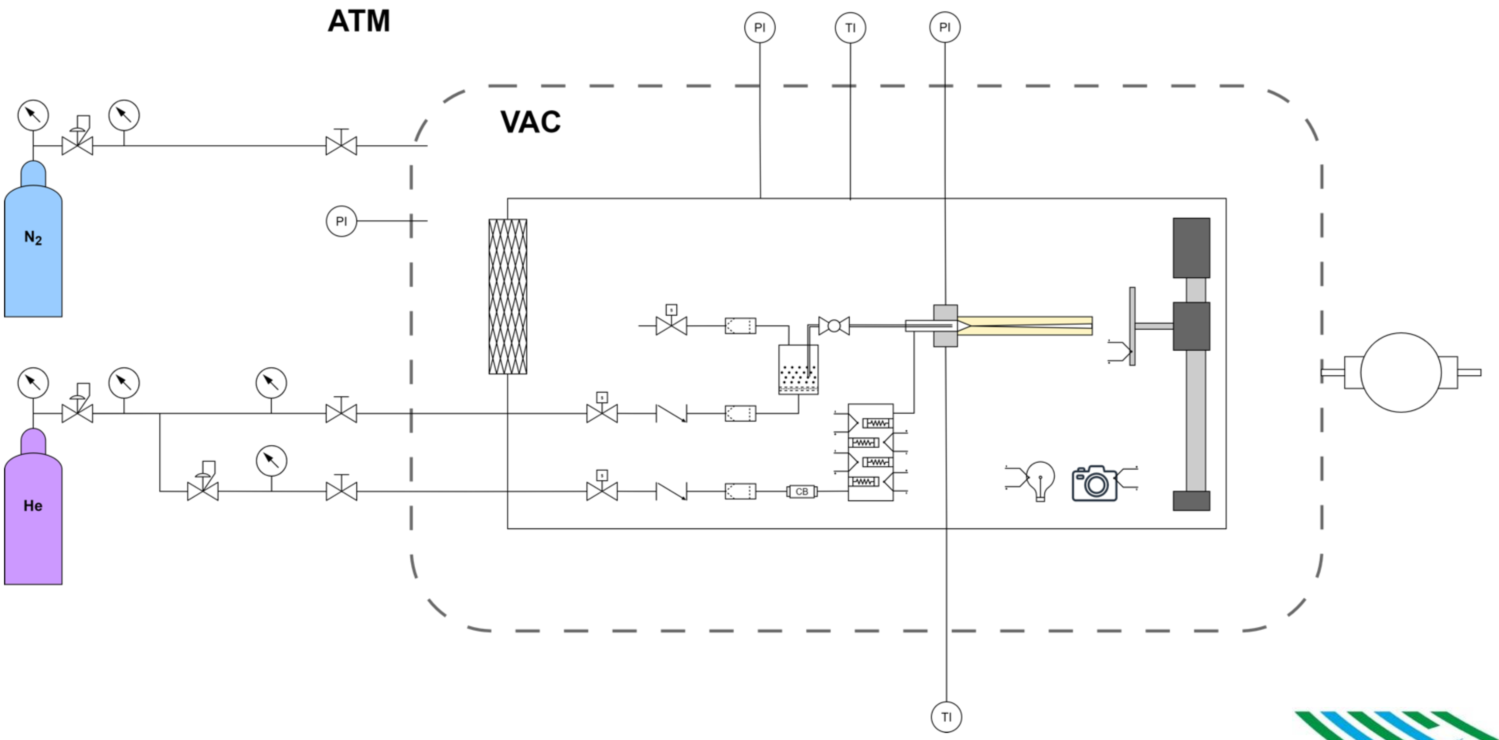
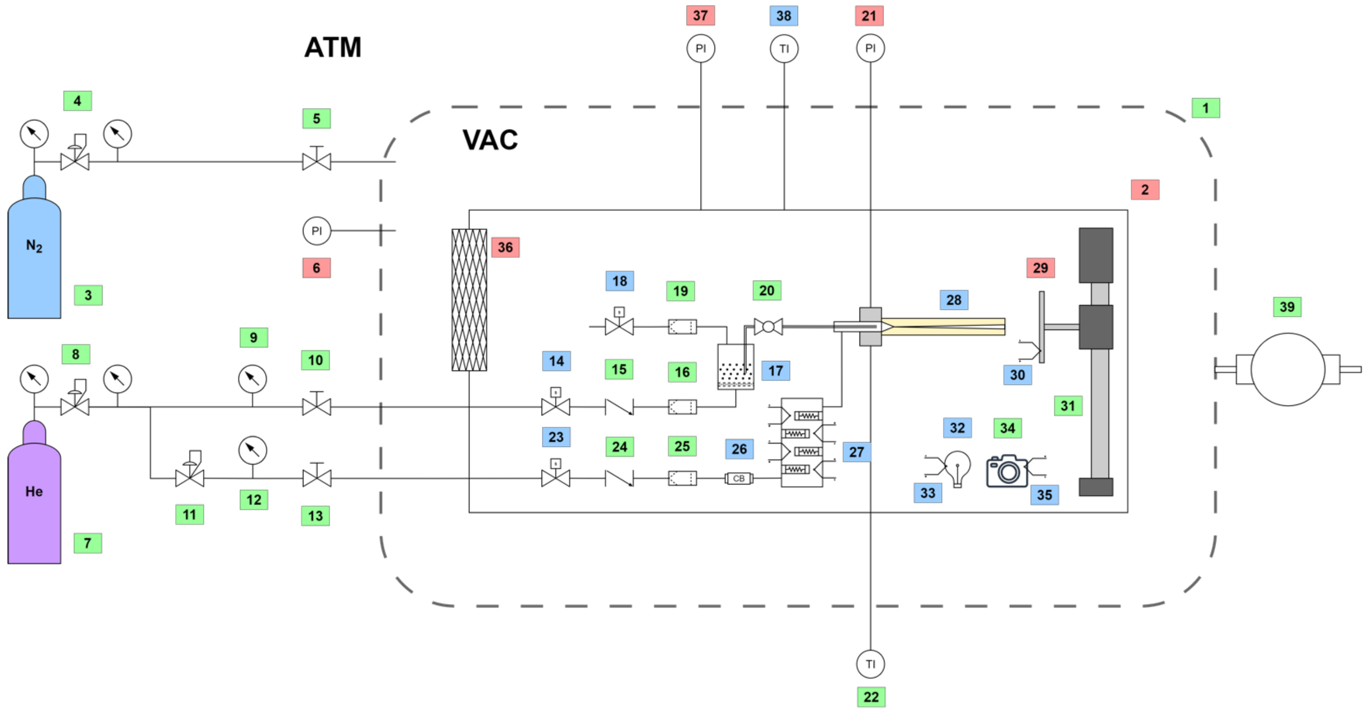
System Piping and Instrumentation Diagram



System Status



List of Components

1 - Vacuum Chamber
2 - Cold Spray System Enclosure
3 - Nitrogen Cylinder
4 - Nitrogen Regulator
5 - Manual Valve
6 - Pressure Transducer (Chamber)
7 - Helium Cylinder
8 - Helium Regulator
9 - Analogue Pressure Gauge
10 - Manual Valve
11 - Pressure Reducing Pressure Regulator
12 - Analogue Pressure Gauge
13 - Manual Valve
14 - Solenoid Valve
15 - Check Valve
16 - Particulate Filter
17 - Powder Hopper
18 - Solenoid Valve
19 - Particulate Filter
20 - Servo Ball Valve
21 - Pressure Transducer (Device)
22 - Thermocouple (Device)
23 - Solenoid Valve
24 - Check Valve
25 - Particulate Filter
26 - Ceramic Break
27 - Heater Block (4x Cartridge Heater, 4x Thermocouple)
28 - Cold Spray Device / Nozzle
29 - Substrate
30 - Thermocouple (Substrate)
31 - X-Y Translation Stage Assembly
32 - Lighting
33 - Thermocouple (Lighting)
34 - Camera
35 - Thermocouple (Camera)
36 - HEPA 14 Box Filter
37 - Pressure Transducer (Enclosure)
38 - Thermocouple (Enclosure)
39 - Rotary Vane Vacuum Pump

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Nozzle Design

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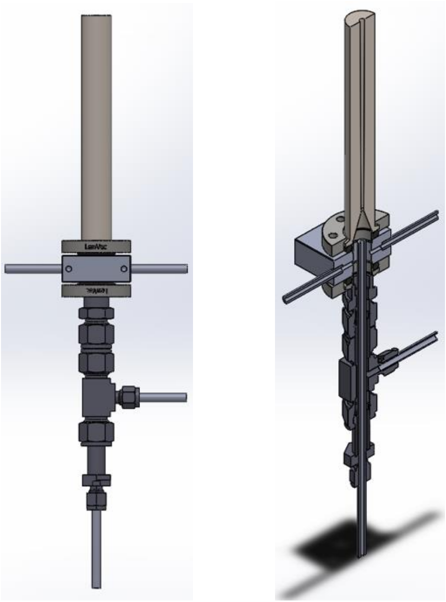
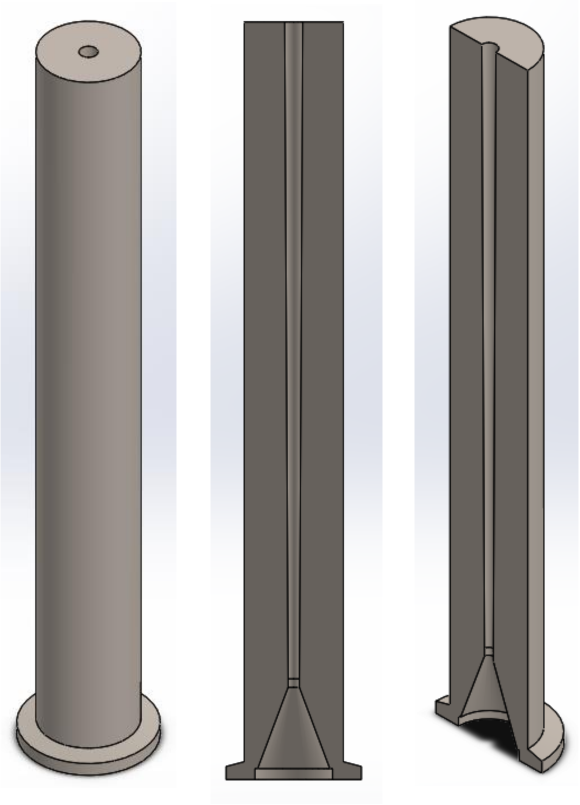
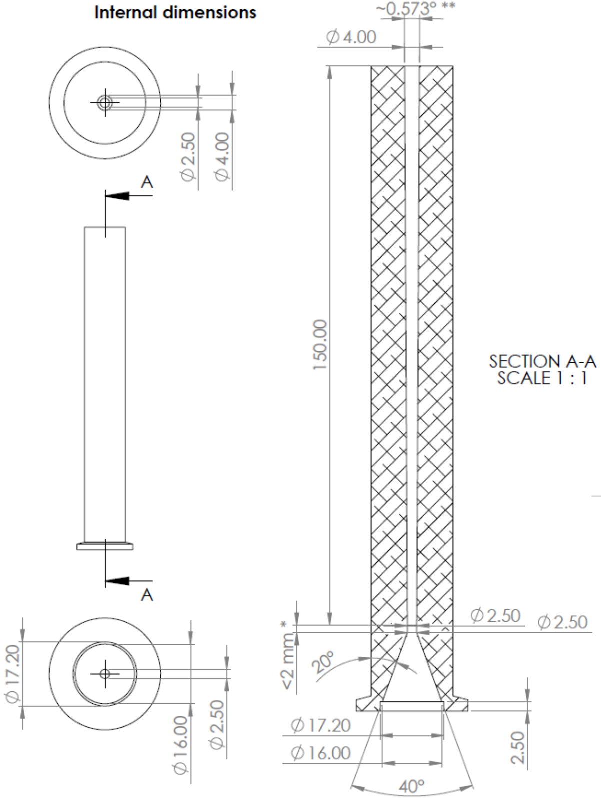
Nozzle Design

(Due by mid-January)







Preliminary Parameters

- Gas: Helium (He) or Nitrogen (N_2)
- Gas Temperature: 0 - 400°C
- Powder: Titanium
- Particle Size: 45 – 106 μm
- Vacuum pressure: ~3 x 10^{-5} mbar
- Print sample size: 50 x 50 x 5 mm
  - Assume 50% print density, 50% waste
  - ~20 min print duration
- Mach Number: 2.77
- Total Pressure: 0.5 bar

1 Table 1 Values of critical and erosion velocities for different materials (Ref 13, 20)

Material	Vcr (m/s)	Vero (m/s)	T_m (°C)
Aluminum	600	1250	660
Titanium	700	1350	1680
Zirconium	500	1000	1855
Fe	650	1300	1400
SS 316	700	1350	1400

2 **Table 1 Values of critical velocity for bonding assuming a particle size of 20 μm**

Material	Melting point, °C	Critical velocity, m/s
Aluminium	660	620-660
Titanium	1670	700-890
Tin	232	160-180
Zinc	420	360-380
Stainless steel (316L)	1400	700-750

[1] *2019, Kamaraj et. Al., "Cold Spray Coating Diagram: Bonding Properties and Construction Methodology"*

[2] *2009, Schmidt et. Al., "From Particle Acceleration to Impact and Bonding in Cold Spraying"*

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Device, Apparatus, and System Update

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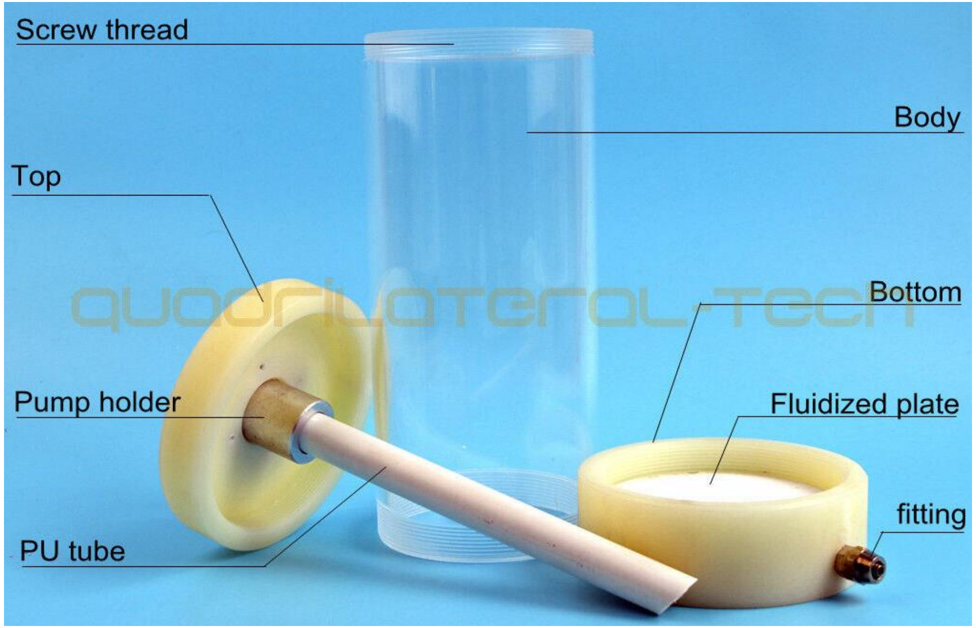
Outline

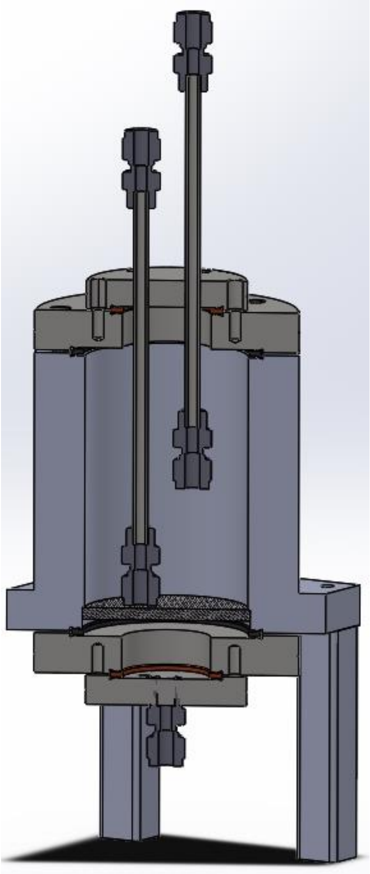
1. Fluidised Powder Hopper
2. Servo Actuated Ball Valve
3. Cold Spray Device
4. Gas Heater
5. X-Y Translation Stage
6. Print Monitoring
7. Device Enclosure
8. Gas Supply and Regulation
9. Vacuum Facilities
10. Vacuum Feedthroughs
11. System Controls / Electronics
12. Powder Transfer and Cleanup
13. Vacuum Cleaner

1. Fluidised Powder Hopper

- Design based on COTS fluidising powder hopper used with powder coating machines
- COTS vacuum components (CF-type)
- 1/4" stainless-steel fluidics
  - Gas inlet with solenoid valve, check valve, and 0.5 µm particulate filter
  - Pump-down / vent line with 0.5 µm particulate filter and solenoid valve
  - Powder feed line with in-house designed servo actuated ball valve (ICLR)
- 10 µm stainless-steel mesh fluidising plate
- Custom hopper body manufactured in-house
- COTS support structure

1. Fluidised Powder Hopper





1. Fluidised Powder Hopper

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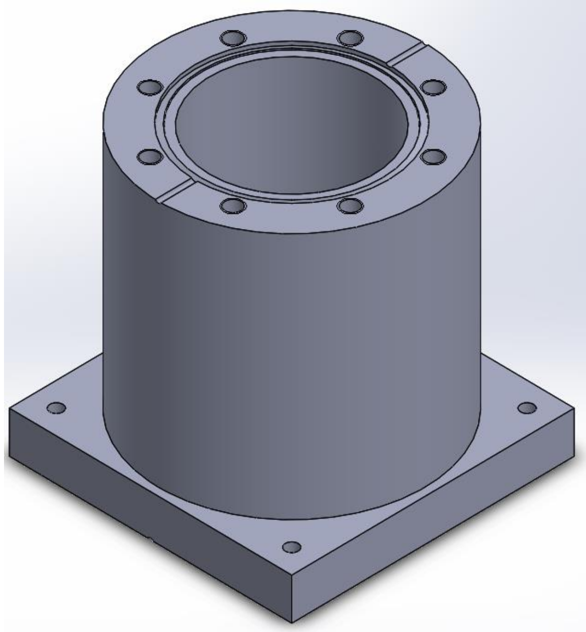
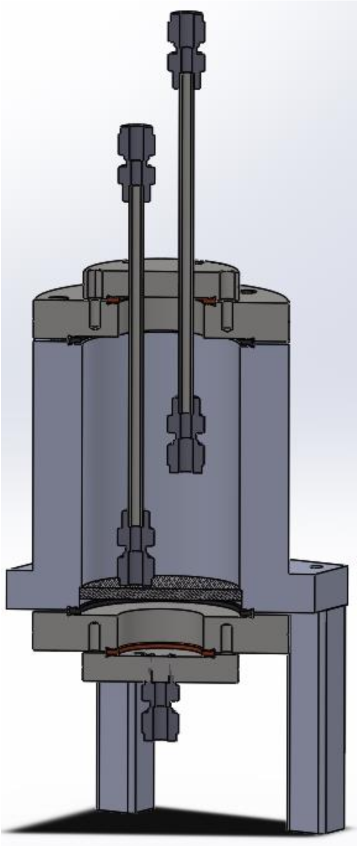
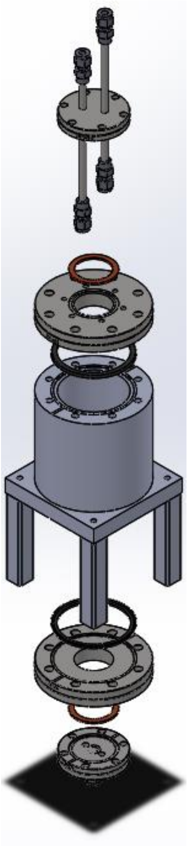
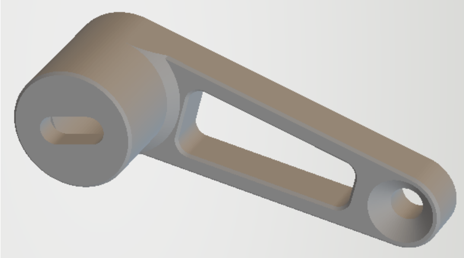
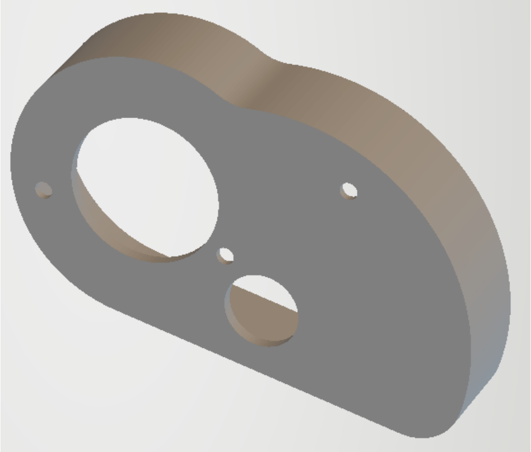


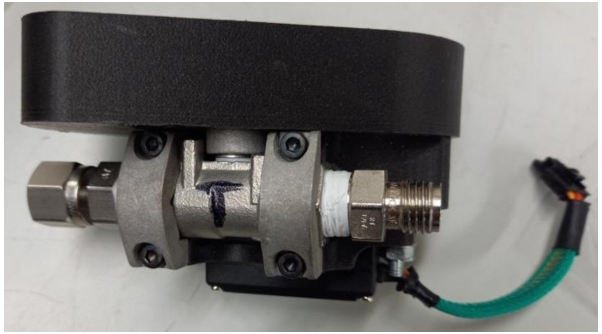


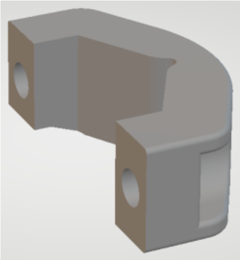


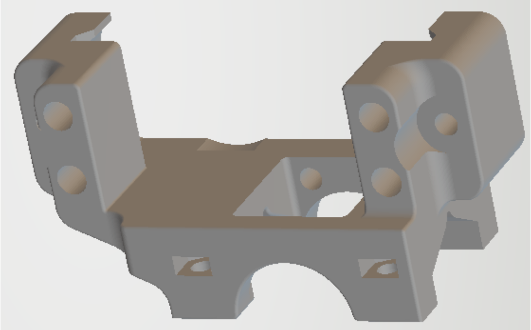
2. Servo Actuated Ball Valve







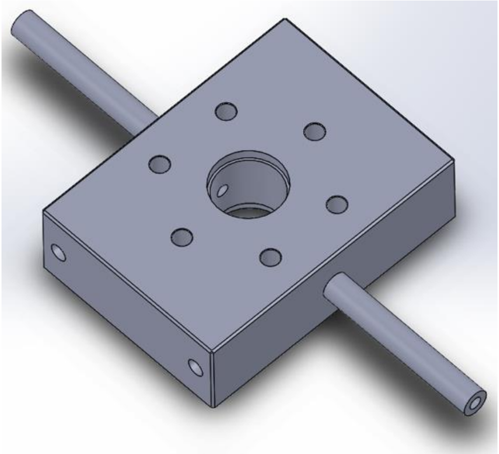


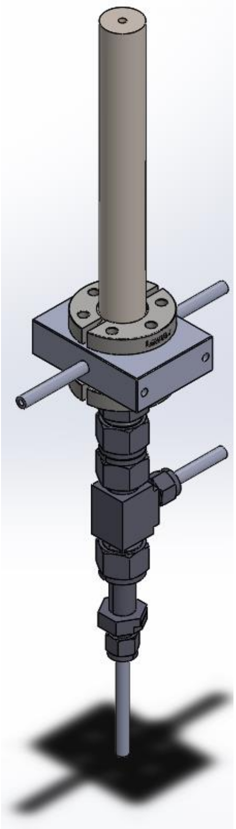


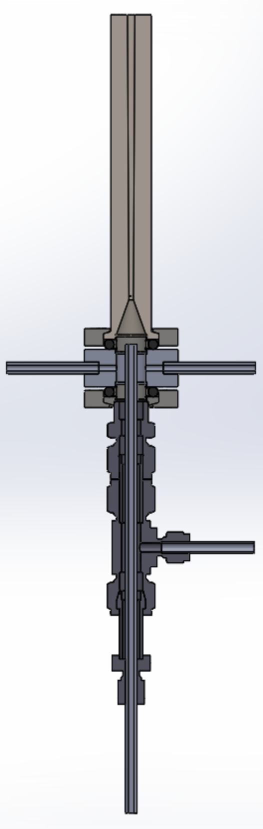
3. Cold Spray Device

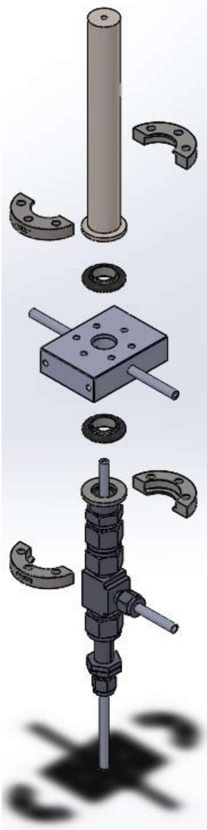
- COTS vacuum components (KF-type)
- 1/2" and 1/4" stainless-steel fluidics
  - Gas feed line with solenoid valve, check valve, and 0.5 µm particulate filter
  - Concentric gas and powder injector
- Custom alumina nozzle (due by mid-January)
- Custom device chamber with diagnostics
  - Thermocouple
  - Pressure transducer

3. Cold Spray Device





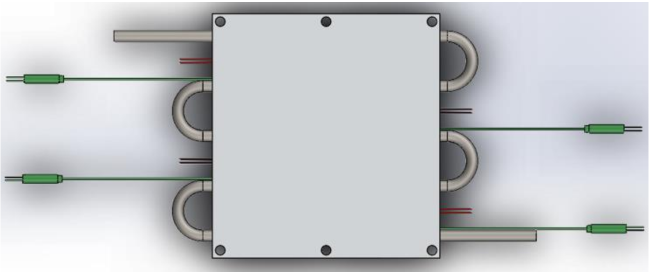


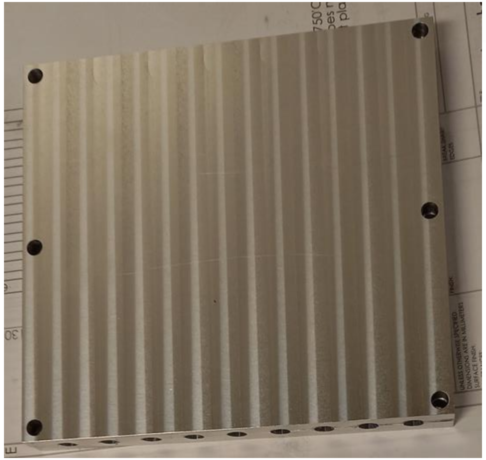


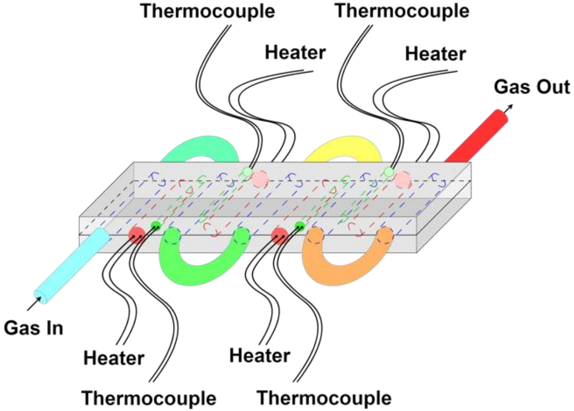
4. Gas Heater

- Gas heater block manufactured in-house
- 4 x 5" cartridge heaters (20 – 400°C)
- 4 x thermocouples
- 1/4" stainless-steel tubing to connect directly to device gas feed line
- (To be operated with PID control via LabVIEW)

4. Gas Heater






Thermocouple
Thermocouple
Heater
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Gas Out
Gas In
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Heater
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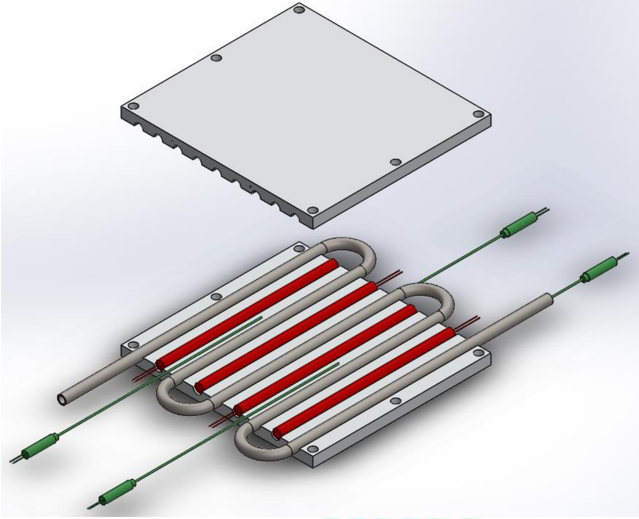
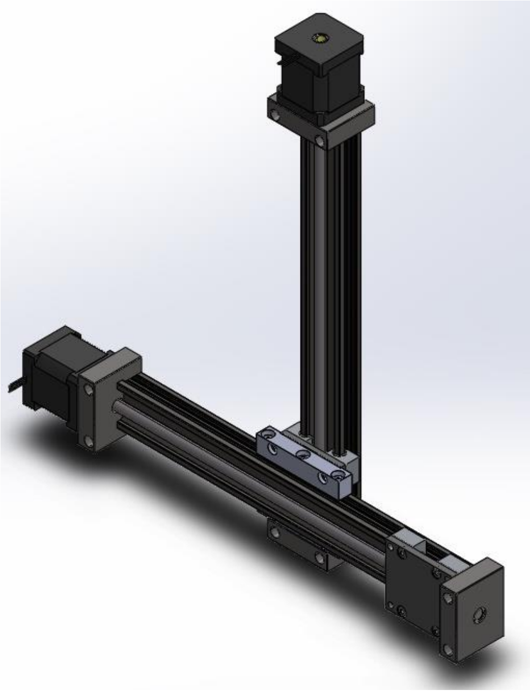
Thermocouple

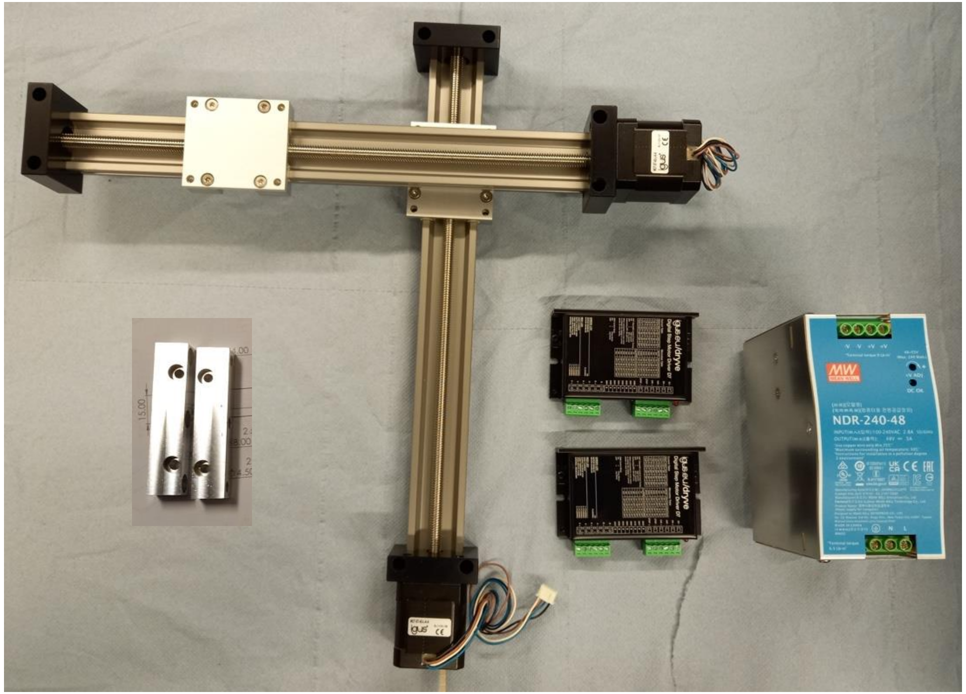


5. X-Y Translation Stage

- 2 x lubricant free linear translation stages and stepper motors
  - 1.5 mm thread, 500 RPM (~1/3 speed expected for X-Y config. and substrate)
- 2 x stepper motor drivers
- 48 V PSU
- Custom X-Y mounting adapter built in-house
- Arduino (or other) controller to operate drivers and relevant code
- Substrates
- Support and mount for attaching substrate to linear stage carriage

5. X-Y Translation Stage





6. Print Monitoring

- USB camera
  - 1MP 720P
  - 120 FPS
  - Glass slides to protect lens
  - Thermocouple to monitor operating temperature
  - (Operated via PC using python code)
- Lighting
  - LED strip lights – to be tested in vacuum
  - (Gas-filled filament bulbs if LEDs fail)
  - Thermocouple to monitor operating temperature

7. Device Enclosure

Design/items to be finalised once device components are complete

- Clear polycarbonate walls and lid with aluminium base plate
  - Can be bolted onto base of vacuum chamber for stability
  - Handles for ease of handling/loading
- Soft failure design – thin nylon screws, vacuum sealant, and O-ring seal on lid
- Extruded aluminium internal support structure for device/hopper/heater
  - Can be bolted onto base of enclosure for stability
  - Angle brackets and T-Slot nuts to allow for reconfiguration
- HEPA 14 high flow box filter
- Physical barrier between device and linear stage (e.g., curtained PTFE sheet)
- Vacuum rated feedthroughs

8. Gas Supply and Regulation

- Helium cylinders with pressure regulator
  - ~4 prints per XL-CP Grade (13 m^3) cylinder at low MFR
  - £415 per refill
- Helium supply split between device and hopper
  - Hopper gas supply direct from gas cylinder regulator
  - Device gas supply regulated to with in-line pressure reducing pressure regulator
  - Both lines fitted with analogue pressure readouts, manual shut-off valves, solenoid valves, check valves, and 0.5 µm particulate filters
- Nitrogen purge gas cylinders with pressure regulator
  - Quantity dependent on purging requirements
  - £12 per refill for W-44 (9 m^3) cylinder

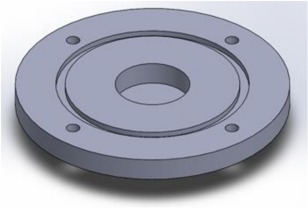
8. Gas Supply and Regulation (Helium)

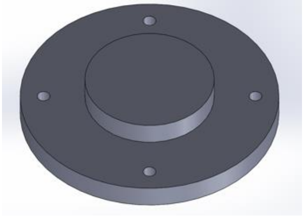
Device

Hopper

9. Vacuum Facilities – Hypersonic Tunnel

- Robust, oil-based pumping system suitable for use with powders
- Base pressure: ~10^{-5} mbar
- Quick pump-down: ~1 hour
- Useable volume: 620 x 570 x 970 mm
- Large volume dump-tank easily accessible for decontamination
- Built-in rail to bolt down system enclosure for increased stability
- 12 x vacuum feedthrough points available
- Feedthrough flanges manufactured in-house





9. Vacuum Facilities

10. Vacuum Feedthroughs

- Vacuum feedthroughs (TBC)
  - For both vacuum chamber and device enclosure
  - COTS KF-type vacuum feedthroughs to fit Hypersonic Tunnel flanges will reduce workload on workshop
  - Awaiting purchase of remaining outstanding components and wiring diagram for final feedthrough requirements, estimating:
    - (4 x) 2 x 1/4" Fluidics – Pressure transducers and gas feed lines
    - (4 x) 15-Pin D-Sub – Wiring for solenoid valves, servo valve, thermocouples, camera, linear stages, and pressure transducers
    - (2 x) 10 Power Pins – Mains power for heaters and lighting
  - Broad estimate of cost: ~ £2,600

11. System Controls / Electronics

- LabVIEW
  - National Instruments DAQ chassis and modules (6-months' FOC loan)
    - Solenoid valves
    - Pressure transducers
    - Thermocouples
    - Heaters
  - Arduino Mega
    - Translation stage
  - Arduino Uno
    - Servo actuated ball valve (ICLR)
- Python
  - Camera

12. Powder Transfer and Cleanup

- Powder storage, transfer, and cleanup within Hypersonic lab
  - Workbench
  - Lockable cupboard – (Titanium powder will be purchased once storage is in place)
  - Acrylic partitions/barriers to contain powder
- PPE
  - Respirator power packs and hoods
  - ESD-safe floor and bench mats
  - Grounding wrist straps
  - Ear defenders
  - Coveralls

13. Vacuum Cleaner

- Vacuum cleaner
  - KEVA 20H 230V
  - ATEX Rated
  - Anti-static chassis and castors
  - HEPA 14 filtration
  - Disposable microfibre bags
  - 20 litre capacity
  - £2,800
  - Due by mid-December

Experimental testing of CSAM in high vacuum conditions— WP3

Cletus John Akisin

Qualifications

- PhD (thesis submitted) in Mechanical Eng., University of Nottingham, 2024
- MSc in Mechanical Engineering, University of Nottingham, 2019
- BEng in Mechanical Engineering, FUTA, Nigeria, 2016

Current Position

- Research Assistant on COSMOS project, Dept of Aeronautics, Imperial College

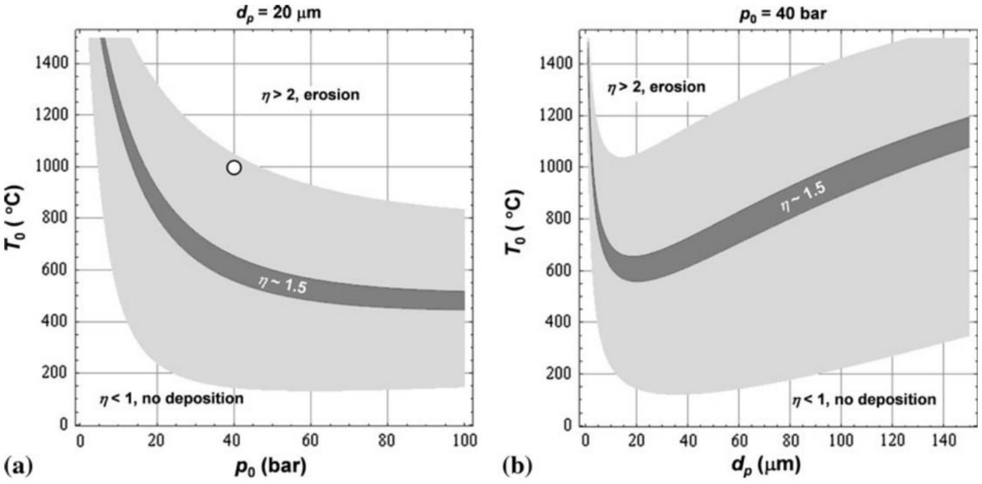
Previous Experience

- Research Assistant, Reusable Rocket Materials, University of Nottingham, May—Sept 2023.
- Materials Testing Engineer, 3D Xaar (now Stratasys), 2021-2022
- R&D, Miniaturisation of thermal spray for in-situ repair, Rolls Royce UTC, 2020-2021

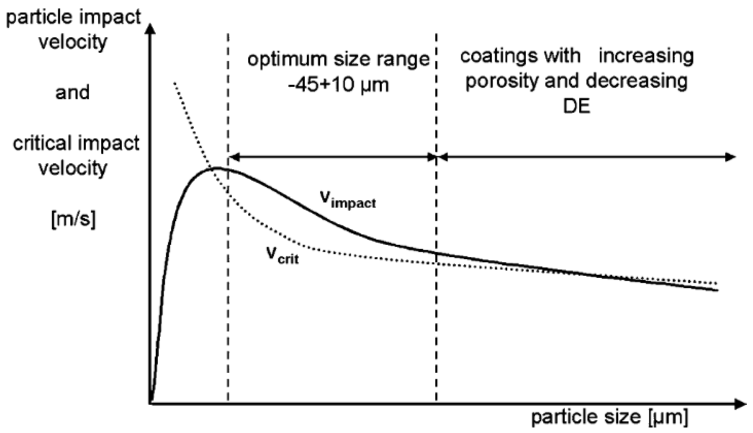
Publications (3 original research articles, 1 conference, 2 review articles, and 2 under review)

https://scholar.google.com/citations?hl=en&user=SxTmHXYAAAAJ

Window of deposition in cold spraying



Ref [1]



Ref [2]

Deposition in CSAM is determined mainly by the gas pressure, temp and particle characteristics

[1] Assadi, H., Schmidt, T., Richter, H., Kliemann, J.O., Binder, K., Gärtner, F., Klassen, T. and Kreye, H., 2011. On parameter selection in cold spraying. *Journal of thermal spray technology*, *20*, pp.1161-1176. [2] Schmidt, T., Gärtner, F., Assadi, H. and Kreye, H., 2006. Development of a generalized parameter window for cold spray deposition. *Acta materialia*, *54*(3), pp.729-742.

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D3.1 & 3.2: Experimental test plan to demonstrate successful printing and to select optimal spray parameters

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Proposed Experimental Spray Runs—Spraying Parameters

Spraying Parameters	Selected range	Spray runs				
		Run 1	Run 2	Run 3	Run 4	Run 5
Gas pressure (bar)	0.5-1.0	0.5	0.5	1.0	1.0	1.0
Gas temperature (°C)	20-400	20	200	200	200	400
Gas flow rate (m3/hr)	0.01-0.03	0.01	0.02	0.02	0.03	0.03
Powder flow rate (g/min)	1-5	3	5	5	3	5
Standoff distance (mm)	5-50	10	10	20	20	30
Transverse speed (mm/s)	4-10	5	10	10	10	4

Evaluation of optimal spray conditions

- $$\text{Density of deposit} = \frac{\text{Weight of sprayed sample} - \text{weight of substrate}}{\text{Volume of deposit}}$$

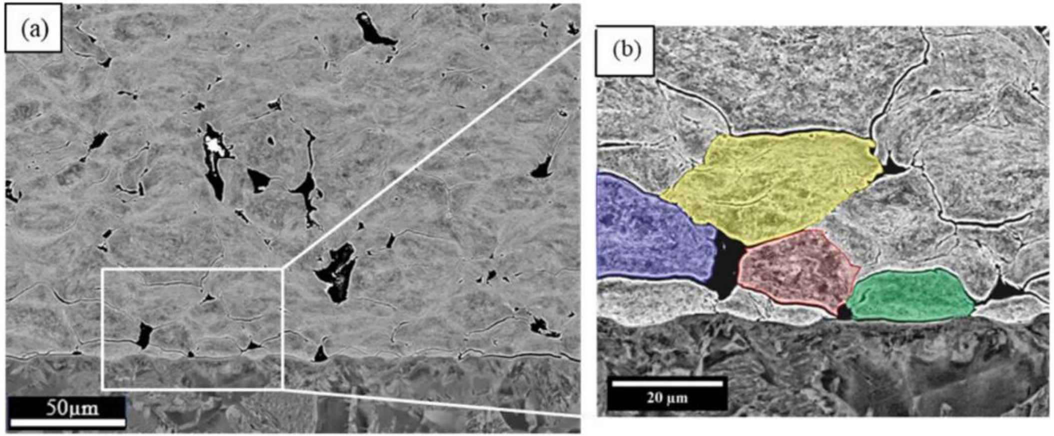
- $$\text{Volume of deposit} = \text{cross sectional area of deposit} \times \text{thickness of deposit}$$

- Weight of samples will be measured using a digital weighing balance of high accuracy

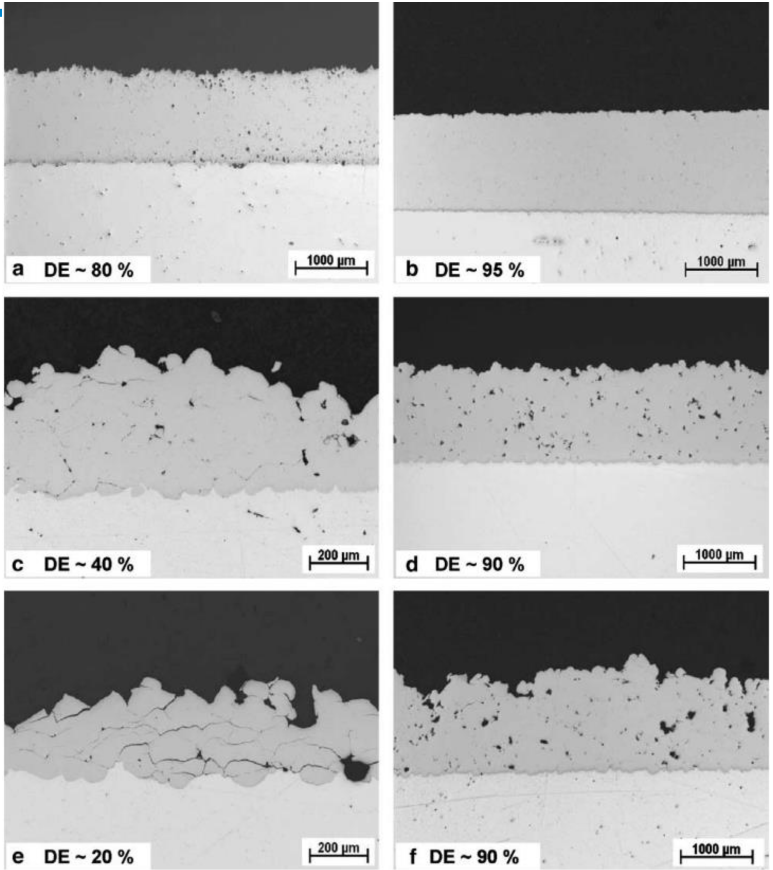
- Deposit thickness will be measured using micrometre screw gauge

- Area cross-section can be measured using vernier calliper.

Example microstructures of cold-sprayed deposits



Ref [1]



Ref [2]

Microstructural assessment of the high-vacuum CSAM deposit would be performed in collaboration with TWI

[1] Akisin, C.J., Dovgyy, B., Bennett, C.J., Pham, M.S., Venturi, F. and Hussain, T., 2023. Microstructural Study of Cold-Sprayed CoCrFeNiMn High Entropy Alloy. *Journal of Thermal Spray Technology*, pp.1-24.[2] Schmidt, T., Gärtner, F., Assadi, H. and Kreye, H., 2006. Development of a generalized parameter window for cold spray deposition. *Acta materialia*, 54(3), pp.729-742.

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Health and Safety

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Health and Safety

Approved Items:

- Use of Hypersonic Lab and Tunnel
- Dedicated workspace
- Design of device components and system enclosure
- Target operating pressures
- Wiring / cabling for remote pump operation
- System decontamination procedures

Outstanding Items:

- Workbench setup (powder storage, transfer, and waste storage)
- Waste disposal arrangements
- Documentation (FMEA, HAZOP, RA, SOP)
- Final review and discussion with Health and Safety team for final sign-off

Next Steps

Next Steps

- Outstanding Health and Safety items **(early-Dec)**
- Finalise enclosure design and provide drawings to Workshop for manufacture **(early-Dec)**
- Purchase/manufacture remaining items **(mid-Dec)**
- Design and build electronics control unit **(early-Jan)**
- Coding for LabVIEW and Arduinos **(early-/mid-Jan)**
- Assemble device, powder hopper, and gas feed system as components become available **(mid-Jan)**
- Assemble and install enclosure **(mid-Jan)**
- Run preliminary tests with N2, He, and Al-oxide **(end-Jan)**
- Print with Ti powder **(end-Jan/early-Feb)**

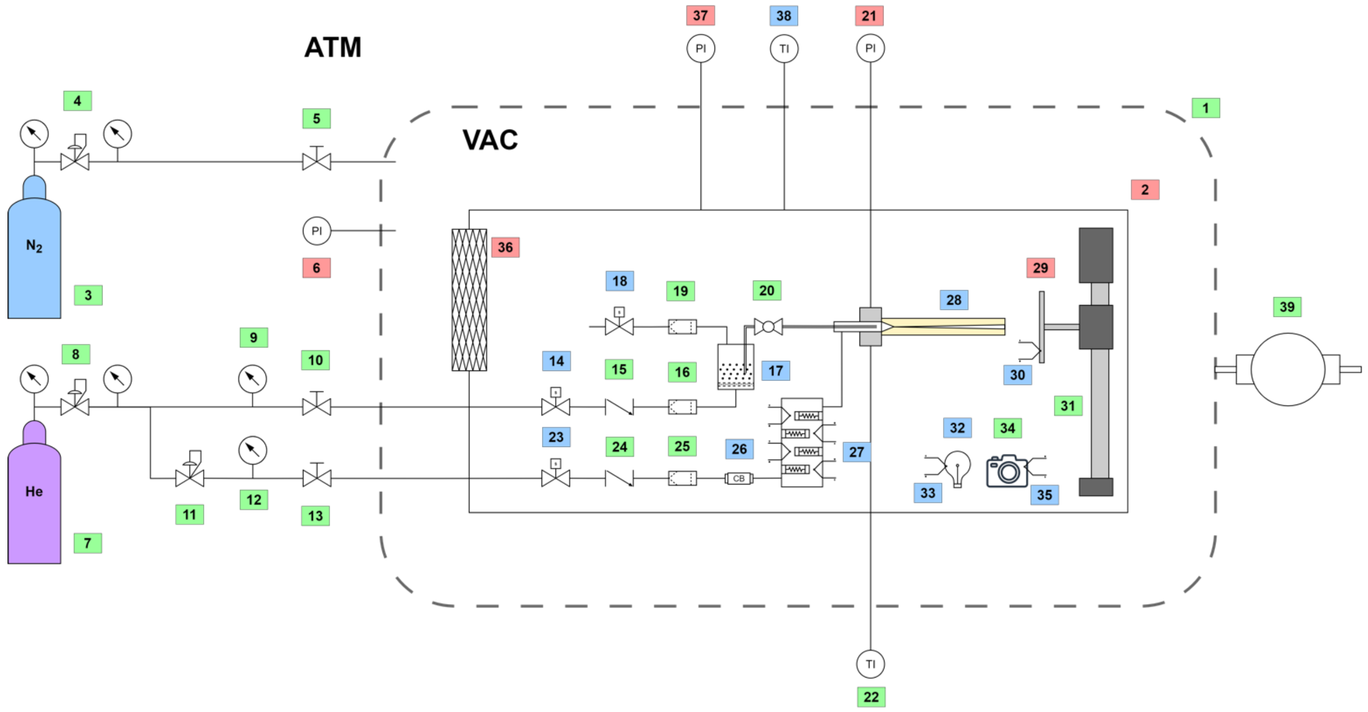
		Year 1												Year 2			
WP	Details	Apr 1	May 2	Jun 3	Jul 4	Aug 5	Sep 6	Oct 7	Nov 8	Dec 9	Jan 10	Feb 11	Mar 12	Apr 13	May 14	Jun 15	Des.
1	**Project management and exploitation strategy**	M0															KO
1.1	Project management and administrtation	1.1															
1.2	Exploitation strategy (TWI)														1.2		
2	**System req. for the CSAM hardware platform**			M1													SRR
2.1	System specification and Health & Safety (TWI)			2.1													
2.2	Procurement and assembly of hardware										2.2						
3	**Exp. testing of CSAM in high vacuum conditions**										M2						TRR
3.1	Demonstration of successful printing										3.1						
3.2	Operating window and parameter sensitivities est.													3.2			
4	**Microstructural characterisation of parts**																
4.1	Porosity and quality assessment												4.1				
4.2	Metallographic analysis (TWI)														4.2		
5	**Trajectory optimisation framework**															M3	FR
5.1	Calibration of Guassian and CNN models												5.1				
5.2	Optimised trajectories for intended topography															5.2	

Thank You!

☺

Appendix – Detailed List of Items Identified/Purchased

System Status



List of Components

1 - Vacuum Chamber
2 - Cold Spray System Enclosure
3 - Nitrogen Cylinder
4 - Nitrogen Regulator
5 - Manual Valve
6 - Pressure Transducer (Chamber)
7 - Helium Cylinder
8 - Helium Regulator
9 - Analogue Pressure Gauge
10 - Manual Valve
11 - Pressure Reducing Pressure Regulator
12 - Analogue Pressure Gauge
13 - Manual Valve
14 - Solenoid Valve
15 - Check Valve
16 - Particulate Filter
17 - Powder Hopper
18 - Solenoid Valve
19 - Particulate Filter
20 - Servo Ball Valve
21 - Pressure Transducer (Device)
22 - Thermocouple (Device)
23 - Solenoid Valve
24 - Check Valve
25 - Particulate Filter
26 - Ceramic Break
27 - Heater Block (4x Cartridge Heater, 4x Thermocouple)
28 - Cold Spray Device / Nozzle
29 - Substrate
30 - Thermocouple (Substrate)
31 - X-Y Translation Stage Assembly
32 - Lighting
33 - Thermocouple (Lighting)
34 - Camera
35 - Thermocouple (Camera)
36 - HEPA 14 Box Filter
37 - Pressure Transducer (Enclosure)
38 - Thermocouple (Enclosure)
39 - Rotary Vane Vacuum Pump

Sample Test Equipment

- Small fluidised powder hopper (£40) – received (100%)
- Test powders (£45) – received (100%)
  - Fine powder coating powder
  - 50 µm aluminium oxide powder
- Handheld airbrush sandblaster (£22) – received (100%)

Translation Stage Assembly

- Translation stage (£1800) – Received (90%)
  - 2 x lubricant-free linear stage with 300 mm stroke length in X and Y direction
  - 2 x stepper motor with drivers
  - Mounting bracket
  - PSU
  - Arduino
- USB Camera (£50) – Received (90%)
  - Python code to be verified
- Substrate and substrate support for mounting onto translation stage – In-house manufacturing – Need to generate drawings (0%)

Filters, Powders, Hopper

- HEPA 14 filters (~£200 each – multiples required) – Stock items – Awaiting confirmation of sizing requirements, College supplier (50%)
- Titanium powders (£340 /5 kg)– Stock items – Awaiting confirmation of storage before placing order, supplier identified (40%)
- Powder hopper – COTS items received, customs parts in progress (90%)
  - In-house manufactured hopper body – In progress (80%)
  - Fluidisation plate – Received (100%)
  - COTS CF-type vacuum fittings – Received (100%)
  - Support structure – Supplier identified, item to be purchased (50%)

Nozzle and Device Enclosure

- Nozzle – In progress (50%)
  - Custom alumina nozzle ordered from supplier – Due mid-Jan (50%)
- Device – COTS items received, customs parts in progress (90%)
  - In-house manufactured device chamber – In progress (80%)
  - COTS KF-type vacuum fittings – Received (100%)
- Device enclosure – awaiting final dimensions (20%)
  - In-house manufacture
  - Support structure – Supplier identified, item to be purchased (50%)
  - Materials TBC based on final dimensions
- LED lighting for inside of enclosure – Received but requires testing (80%)

Measurement and Thermal Control

- Pressure transducers x 3 (~£600 each) – possible stock items – Requirements defined, new supplier to be sourced (20%)
- Thermocouples x 5 (~£20 each) – Partially received (80%)
  - Device and heater block thermocouples – Received (100%)
  - Enclosure and diagnostics thermocouples – stock items – Supplier identified, to be ordered (80%)
- Gas heater (90%)
  - Heaters – Received (100%)
  - Thermocouples – Received (100%)
  - Heater block – Manufactured in-house, in progress (80%)

Vacuum Feedthrough and Valves

- Vacuum feedthroughs for vacuum chamber and device enclosure (TBC, ~£2600) – stock items – quotation to be requested (80%)
- Solenoid valves for gas feedlines – stock items – quotation requested (80%)
- Servo ball valve for powder feedline (£150) – In-house designed / stock items – awaiting 3D parts, all other items received (90%)

Gas Supply, Regulation, and Feed System

- Helium (£415 per refill as required) – stock item – on-site supplier (100%)
  - Pressure regulator – Already available (100%)
- Nitrogen for system purging and alternative to helium (~£10 per refill as required) – stock item – on-site supplier (100%)
  - Pressure regulator – Already available (100%)
- Feedline tubing, fittings, etc. – stock items – supplier identified – Majority of items purchased and received (90%)

Powder Handling and PPE

- Hood for powered respirator (~£80 each) – Received (100%)
- ESD-safe floor and bench mats – stock items – Supplier identified, to be ordered (80%)
- Grounding wrist straps (~£20 each) – stock items – Supplier identified, to be ordered (80%)
- Coveralls (~£5 each) – stock items – Supplier identified, to be ordered (80%)
- Ear defenders (~£55 each) – stock items – Supplier identified, to be ordered (80%)
- ATEX rated vacuum cleaner (£2800) – Ordered, due for delivery mid-Dec (100%)