BEYOND THE BUILD VOLUME: COLD SPRAY ADDITIVE MANUFACTURE FOR BIMETALLIC COMBUSTION CHAMBERS

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Iain Waugh$^{(1,3)}$**, Jan Kondas**$^{(2)}$**, Reeti Singh**$^{(2)}$**, Max Meinicke**$^{(2)}$**, and Leonhard Holzgaßner**$^{(2)}$

$^{(1)}$*Airborne Engineering Ltd., Westcott Venture Park, Aylesbury, HP18 0XB, UK*
$^{(2)}$*Impact Innovations GmbH, Bürgermeister-Steinberger-Ring 1, 84431 Rattenkirchen, Germany*
$^{(3)}$*Corresponding author: iain@ael.co.uk*

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ABSTRACT:

Cold Spray Additive Manufacture (CSAM) uses an inert gas carrier to accelerate metal powder to supersonic speeds and spray it towards a target object, where the powder particles subsequently deform and adhere to the substrate material with solid-state bonding. By changing between powders, the technique can be used to create multi-material (or graded material) parts. High performance liquid rocket engine (LRE) chambers are typically bimetallic, combining a high thermal conductivity copper alloy liner with a high strength nickel alloy structural jacket. As such, the CSAM process has many advantages for liquid rocket engine combustion chamber manufacture. This paper discusses the advantages and disadvantages of using CSAM for LRE manufacture, then describes the design of a demonstrator bimetallic combustion chamber to be made using the CSAM technique, and shows results of the manufacturing trials.

1. INTRODUCTION

Additive manufacture has the potential to revolutionise the production of liquid rocket engine (LRE) combustion chambers, which have complex geometries and internal coolant channels. Most efforts to date have focused on powder bed fusion (PBF) methods with several engines successfully in production. In the literature combustion chambers have been successfully demonstrated from copper alloys such as GRCop-42/84 and CuCrZr [1, 2, 3, 4, 5, 6], nickel based alloys such as IN718/625 [7] and ABD®-900AM [8] and aluminium alloys with protective coatings [9, 10].

PBF has the advantage over conventional manufacturing methods of being able to create closed internal cooling channels without any fixed tooling and within a single operation, but PBF does also have significant disadvantages:

1. The maximum part size is defined by the build volume of the machine, which limits the maximum thrust level of a one-piece combustion chamber.
2. Parts are limited to a single material.
3. The build volume must be completely filled with powder even though only a small fraction is used. The unused powder can degrade during each cycle, so powder re-certification procedures may be necessary for critical parts.
4. Parts have higher surface roughness (dependent on build angle) and more variance in geometry than traditional machining methods.
5. Depowdering requires great attention for parts with small channels and/or integral manifolds.
6. Certification of the process is difficult, because subtle changes in process parameters affect the part: e.g. powder quality, laser parameters or part temperature.

Regeneratively cooled combustion chamber designs are typically limited by the thermal stresses generated in the firewall by the extreme heat flux. Typical lift engines may have peak heat fluxes from $20 MW/m^2$ for lower performance or film cooled engines, up to $160 MW/m^2$ for high-performance engines such as the Space Shuttle Main Engine (SSME). The thermal stresses in the firewall are proportional to the heat flux and wall thickness, but inversely proportional to thermal conductivity.

High-performance lift engines therefore typically use copper alloy liners, due to the combination of copper's extremely high thermal conductivity - which reduces the firewall thermal stress - and good mechanical performance at elevated temperature. Copper alloys have low strength-to-weight ratio, however, so would result in a heavy engine if used to contain the engine pressure stresses. High performance combustion chambers are therefore typically bi-metallic, with a copper alloy liner and a structural jacket made of a higher strength-to-weight ratio material such as a Nickel alloy. A traditional manufacturing route for the structural jacket is to machine coolant channels into a copper alloy billet/forging, before filling the channels with wax, conductivising the outside of the channels by burnishing in silver powder, then growing the outer jacket via electroforming and post-machining to finish.

Current state-of-the-art PBF methods have demonstrated the advantages of additive manufacture for rapid development of single-material, single-piece combustion chambers with thrust ranges <30kN for standard build height machines and <100kN for extended height machines [6]. PBF methods are uneconomic for larger parts, however, such as high thrust combustion chambers or nozzle extensions, and fundamentally infeasible for producing of bimetallic parts.

Several additive manufacturing techniques have been investigated in the literature as candidates for bimetallic LRE chamber manufacture without build volume limitations. Foremost among these is Direct Energy Deposition (DED), also known as Laser Metal Deposition (LMD) or blown-powder deposition. DED works by blowing powder into a melt pool created by a laser, which builds up the surface, and this nozzle/laser head is moved across the part. DED typically uses larger powder feedstock (50-150µm) than PBF (15-45µm) and typically uses higher laser powers [11]. DED has been successfully used to deposit IN625 jackets onto PBF liners made of GRCop-42/84 [12], and has been used to manufacture nozzle extensions directly onto copper liners [12, 13] or as standalone objects [11, 13]. The DED process does have some disadvantages for LRE structural jackets. First, the liner closeout cannot be too thin or the DED melt pool penetrates through into the coolant channel, which means that the bimetallic chamber will be heavier than optimal. Second, there is a significant amount of part shrinkage through distortion in the axial and radial directions, of the order of several percent [13]. Third, the optimal heat treatments for the superalloy jacket require a higher temperature than the copper alloy liner is capable of, so a compromise must be made and material properties will not be optimal [13].

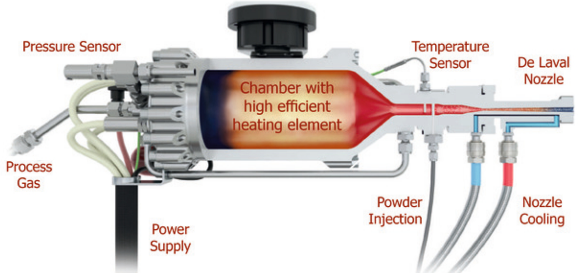


Figure 1: Schematic of an Impact Innovations GmbH cold spray gun. An inert carrier gas is electrically heated at pressure and then expanded slowly through a water-cooled nozzle with a shallow taper. Metal powder is seeded into the flow and accelerated to supersonic speeds where it then deforms plastically against a target material.

2. COLD SPRAY ADDITIVE MANUFACTURE

Cold Spray Additive Manufacture (CSAM) involves seeding metal powder into a stream of inert gas that is heated at pressure and then accelerated to supersonic speeds through a nozzle (Figure 1). The powder is sprayed at a target using a robot where it deforms plastically and solid-state bonds to form deposited material, which is then post-machined. Minimal thermal stresses are generated because the process remains near room temperature. The deposited material has a very fine grain structure with lots of dislocations and vacancies, due to the fine grained powder feedstock and the subsequent plastic deformation. The deposited material can therefore be heat treated at relatively high temperatures without undue grain growth reducing the mechanical properties [16].

CSAM has several key advantages over PBF for manufacturing LREs:

1. No inherent build volume limit with no fixed tooling
2. Joining of dissimilar materials (including dissolvable fillers), and ability to form graded materials
3. No thermal stress or heat-affected-zones (unlike welding processes)
4. It deposits powder quickly with very little loss. Deposition rates are ~20 times higher than the fastest PBF machines.
5. The resulting part has machining quality geometry and surface roughness.
6. Access for inspection between production steps
7. Ability to join additional parts without welding (e.g. injector head, actuator mounts)
8. Ability to re-work/repair areas
9. CSAM can use a wide range of alloys and does not require an inert atmosphere or vacuum

CSAM does has several disadvantages for LRE combustion chamber manufacture, however, notably:

1. Requiring several intermediate steps of machining to form closed channels, as per traditional electroforming manufacturing routes.
2. The as-deposited material has residual stresses and low ductility, so a heat treatment is required. For multi-material parts, this heat treatment is common to all materials and a compromise must be made, whereby the heat treatment temperature/timings are best for the combined part but not optimal for the individual materials.
3. Some materials might require helium as the driver gas (rather than nitrogen), which is expensive and needs to be recycled to make the process cost effective.

Whilst several machining operations leads to more process steps that PBF for creating closed channels, CNC machining is standard industry practice at a wide variety of scales, and easier to make reproducible than PBF. The machining of the channels also gives the opportunity for internal inspections or to introduce other high-accuracy features into the firewall, such as film cooling or injector holes. New methods of cutting coolant channels have been investigated for being faster than conventional machining, such as abrasive waterjet milling [18].

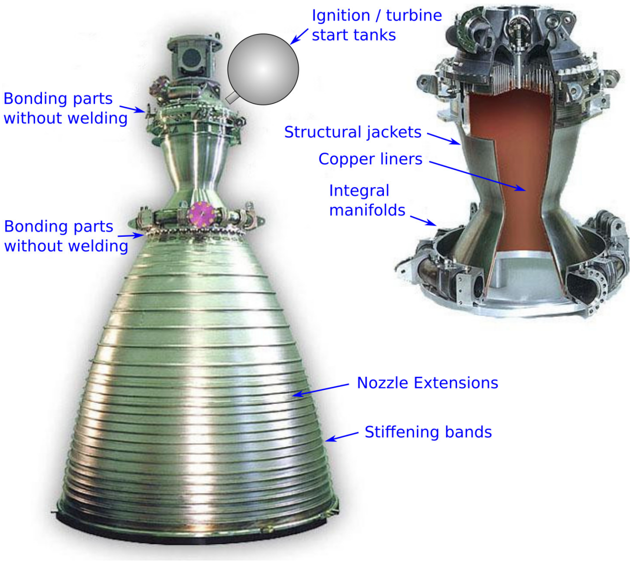


Figure 2: Potential areas for cold spray additive manufacture in liquid rocket engines (background image from [20]).

3. CSAM FOR LIQUID ROCKET ENGINES

CSAM has several potential application areas for LRE manufacture, as shown in Figure 2.

First, for adding structural jackets to copper alloy liners to create bimetallic combustion chambers. CSAM requires a thinner channel closeout than melt-pool based methods such as DED, leading to a lighter end product. This process has been demonstrated recently by NASA [13] with the ALPACA engine [12] and separately by ArianeGroup [19], using copper liners produced by PBF.

Second, for manufacturing the copper liners themselves, using a multi-step process similar to the traditional electroforming manufacturing routes. CSAM is used to form the copper liner, then the coolant channels are machined and a filler material sprayed into the channels. The channels are then closed out using a layer of copper alloy (optional) and/or a bonding layer, before a high-strength alloy (typically nickel based) jacket is then deposited. For bimetallic copper/nickel based parts, aluminium based fillers are generally used, because the material is cheap, easily machinable and readily dissolved using chemical etching without affecting the copper and nickel alloys. Water soluble fillers are also available.

The copper liner can be formed in two ways: either by spraying in a mostly radial direction onto an aluminium mandrel (usually not-exactly radial, but perpendicular to the profile), or alternatively without a mandrel by spraying in a mostly axial direction, although some radial component is necessary to maintain the thickness of the liner. The edges of the part are harder to control with the axial method, however, leading to more post-machining and material waste.

Third, for adding parts onto the structural jackets, such as manifolds, actuator mounts or injector heads. These parts can be created entirely by CSAM, using dissolvable fillers (such as for the manifold) followed by overspray, or pre-machined parts can be bonded on without welding.

Fourth, for creating other LRE components such as high pressure tanks (e.g. for ignition or turbine starting) or nozzle extension cones. Both of these cases use thin-wall, high-strength material and are typically formed by processes such as spinning, where process control and skill is required to achieve the correct wall thicknesses. For thin wall parts, CSAM has the advantage that the outer surface of the part can be machined to give the right wall thickness whilst the deposited material is still intimately bonded to the mandrel, which prevents tearing or distortion of the thin wall. Stiffening bands, bosses or attachment points

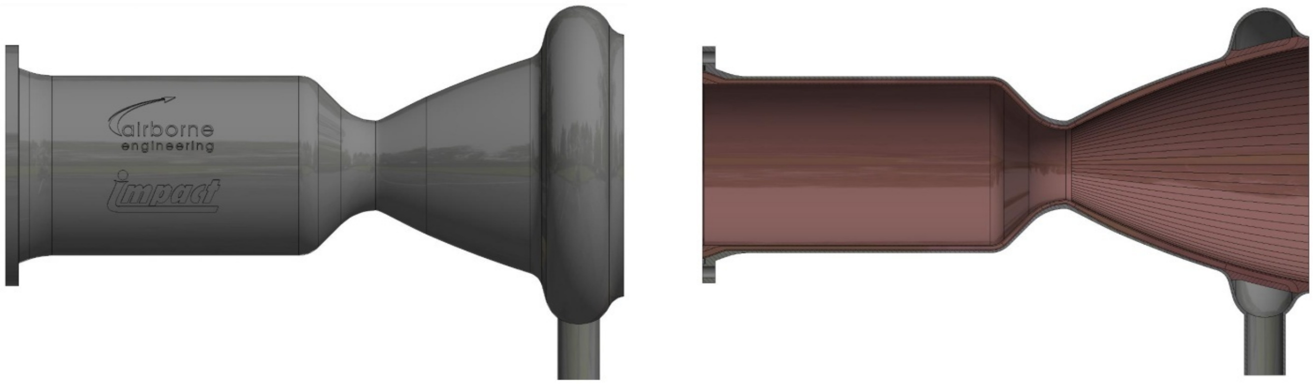


Figure 3: Combustion chamber demonstrator design for cold spray additive manufacture, using CuCrZr for the liner, and IN625 for structural and integral manifold.

can also be added with another spraying operation. CSAM of titanium alloy tanks has been demonstrated in the literature [21], as has cold spraying niobium alloy C103 [22], which together with titanium alloys can be used for nozzle extensions.

4. CHAMBER DEMONSTRATOR DESIGN

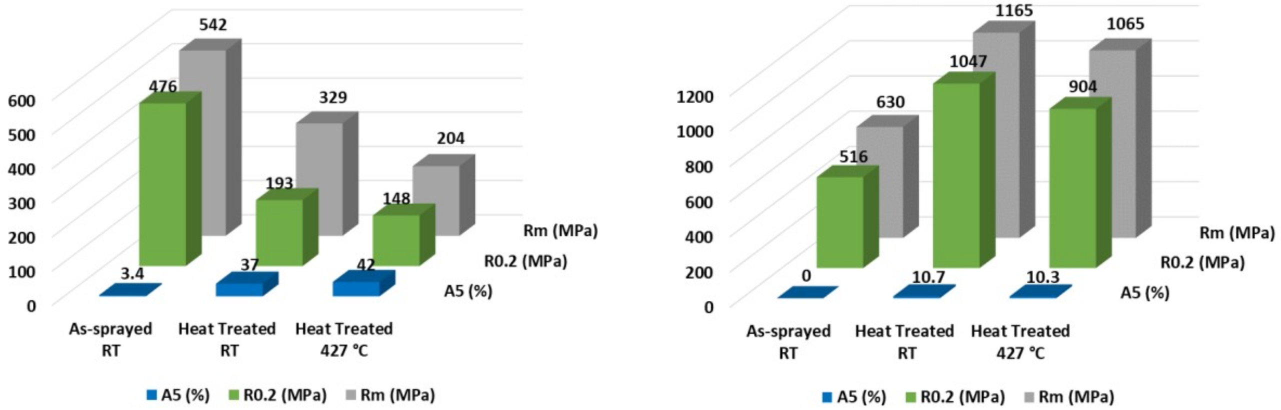
A collaboration was set up between Airborne Engineering (AEL) and Impact Innovations GmbH to investigate the possibilities of CSAM for combustion chambers. Impact Innovations GmbH are a manufacturer of CSAM machines, and have a research lab where the demonstrator samples were produced using an Impact Spray System 5/11 on a robot arm, with the parts mounted on a lathe capable of up to 1.5m diameter and 2m long parts.

Using CSAM process knowledge from Impact Innovations, a demonstrator was designed by AEL for an all-CSAM combustion chamber, where cold spray was used for the copper liner, jacket and manifold. A nominal 20kN thrust range was chosen, with liquid oxygen and methane as baseline propellants. Figure 3 shows the mechanical design of the combustion chamber demonstrator. The throat diameter is 65mm, with an 80% length fraction Rao nozzle. An integral flange attaches onto the injector head, and the coolant channels divert outwards slightly to allow for a face-seal onto the injector head.

Based on Impact Innovations' prior experience with the materials, CuCrZr was chosen for the liner and IN625 for the structural jacket. Material properties are shown in Figure 4 in both the as-sprayed condition and after a joint heat treatment. Both materials show good yield strength (R0.2) and elongation (A5) at room temperature (RT) and when tested at 427℃.

The demonstrator has all the key components of a regeneratively cooled LRE combustion chamber, however due to the low TRL there are several compromises in the mechanical design which would be changed for a flight-like engine:

1. The manifold is axisymmetric rather than variable-area, which will cause non-uniform massflow distribution of coolant in the channels. This was chosen to simplify spray toolpaths and the manifold mandrel for the first demonstrator.
2. The copper closeout thickness is high next to the manifold, in order to allow extra material in case several attempts were needed to add the manifold (they were not).
3. The nozzle contraction angle is higher (45°) than would typically be used (with a small radius to the combustion chamber), which results in a compact nozzle but would reduce nozzle thrust coefficient. High contraction ratios are sometimes used for PBF engines in order to maximise chamber volume but fit into the build height - the geometry used for the demonstrator should validate that CSAM can add the jacket successfully at the extreme of 45°.
4. The coolant channels are designed to be machined mostly with slitting saws, with a low number of tool changes. As such, towards the end of the nozzle expansion area (where the heat flux is low) the channel width becomes constant, whilst the copper thickness between the channels grows. This is not the most mass efficient, but reduces the machining cost for the demonstrator.
5. The combustion chamber volume is large, with both long length and high contraction ratio (5.3). This decision was nothing to do with the CSAM process, but was due to the desire to use this



(a) CuCrZr (deposition rate 10kg/h)

(b) Inconel 625 (deposition rate 6.7kg/h)

Figure 4: Materials properties for cold sprayed CuCrZr and IN625 in as-sprayed and heat treated states.

combustion chamber with an interchangeable injector head, where the injector face is recessed into the chamber to allow tunable resonator and film cooling rings. One of the injectors to be evaluated was a pintle, which would benefit from a wider diameter, high-contraction ratio chamber.

6. The thickness of the structural jacket (2-3mm depending on location) is conservatively high for the design chamber pressure and diameter of the demonstrator, and is therefore not flight weight. This thickness may be representative for higher-performance engines, however, with larger diameter and operating pressure.

The coolant channel geometry was designed using AEL's in-house heat transfer code, which couples an empirical hot-gas heat transfer model with a 3D finite-element conduction solver and a 1D coolant model, which uses empirical heat transfer correlations for the methane coolant [23]. Figure 5 shows example metal temperature results from the heat transfer analysis. The firewall temperatures peak locally at the throat, where the heat flux is highest, and also peaks towards the injector face where the heat flux rises, the methane temperature rises and its density drops, and the coolant side heat transfer therefore deteriorates. Wall temperatures near the injector face can be reduced using small amounts of fuel film cooling.

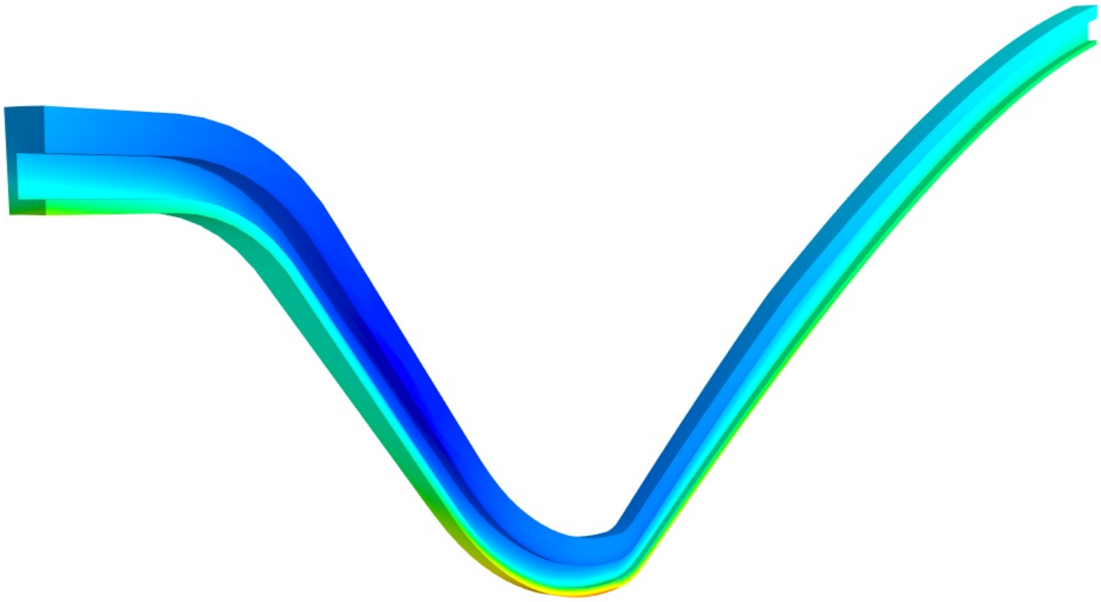


Figure 5: Example nozzle metal temperature results from the conjugate heat transfer simulations.

5. MANUFACTURING TRIALS

The first set of manufacturing trials aimed to verify the channel machining and filling operations. Two parts were produced with outer diameter 280mm and firewall thickness 1mm; one part with 5.0x1.0mm high aspect ratio coolant channels (Figure 7), and the other part with several different coolant channel sizes, representative of the channels in different locations on the demonstrator chamber. In all cases the dissolvable filler adequately filled the channels leaving behind a clean, machined finish after being dissolved. These parts proved that the CSAM technique should be able to produce the channels in all areas of the demonstrator design.

The second set of manufacturing trials aimed to verify the ability to form the manifold. The nozzle exit and manifold area of the demonstrator were manufactured as a standalone part, then welded onto a dummy inlet tube also made using cold spray, and then sectioned using EDM. Figure 8 shows the completed test piece and Figure 6 shows the manufacturing steps. A pre-machined aluminium mandrel was used to fill the manifold void, aligning on a shoulder machined into the copper closeout, as shown in Figure 8f. As discussed previously, the copper closeout in this area was very thick and conservative, allowing for several attempts to get the manifold overspray correct (by re-machining back into the copper and using a new mandrel). The manifold was produced correctly at the first attempt, however, so the closeout thickness could easily be reduced here for future designs.

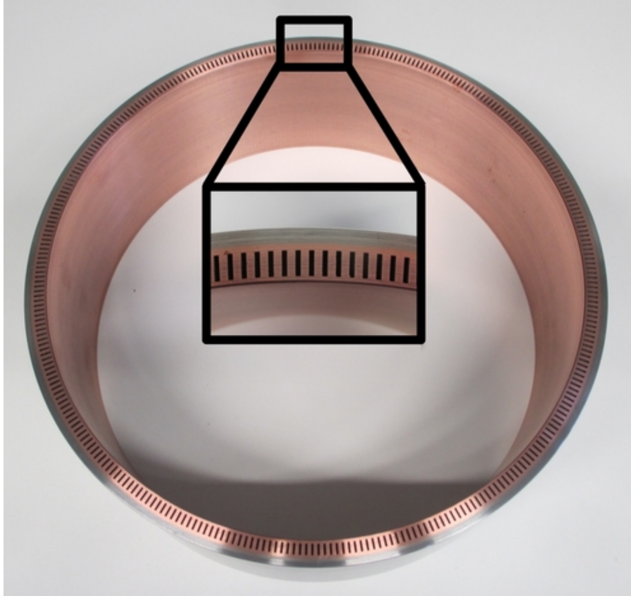


Figure 7: High aspect ratio coolant channel demonstrator piece, with rectangular coolant channels 5x1mm on a part with diameter 280mm.

The sectioned manifold showed that the internal structure of the part had a good surface finish. The dissolution of the aluminium mandrel was complete except for one very small location (Figure 9). This area of the part was vertically upwards in the chemical etching bath and there was likely a small gas bubble where the aluminium was not dissolved. The part should therefore be turned several times in the chemical etching bath to ensure complete dissolution.

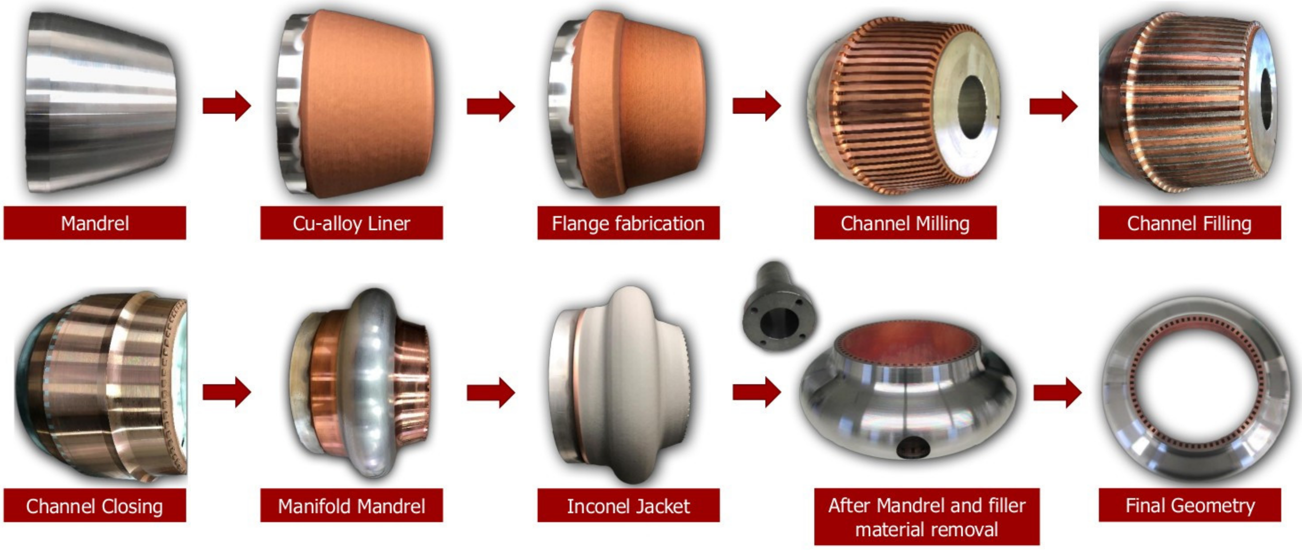


Figure 6: Manufacturing steps for the CSAM manifold demonstrator: liner fabrication, channel machining, filling and overspray.

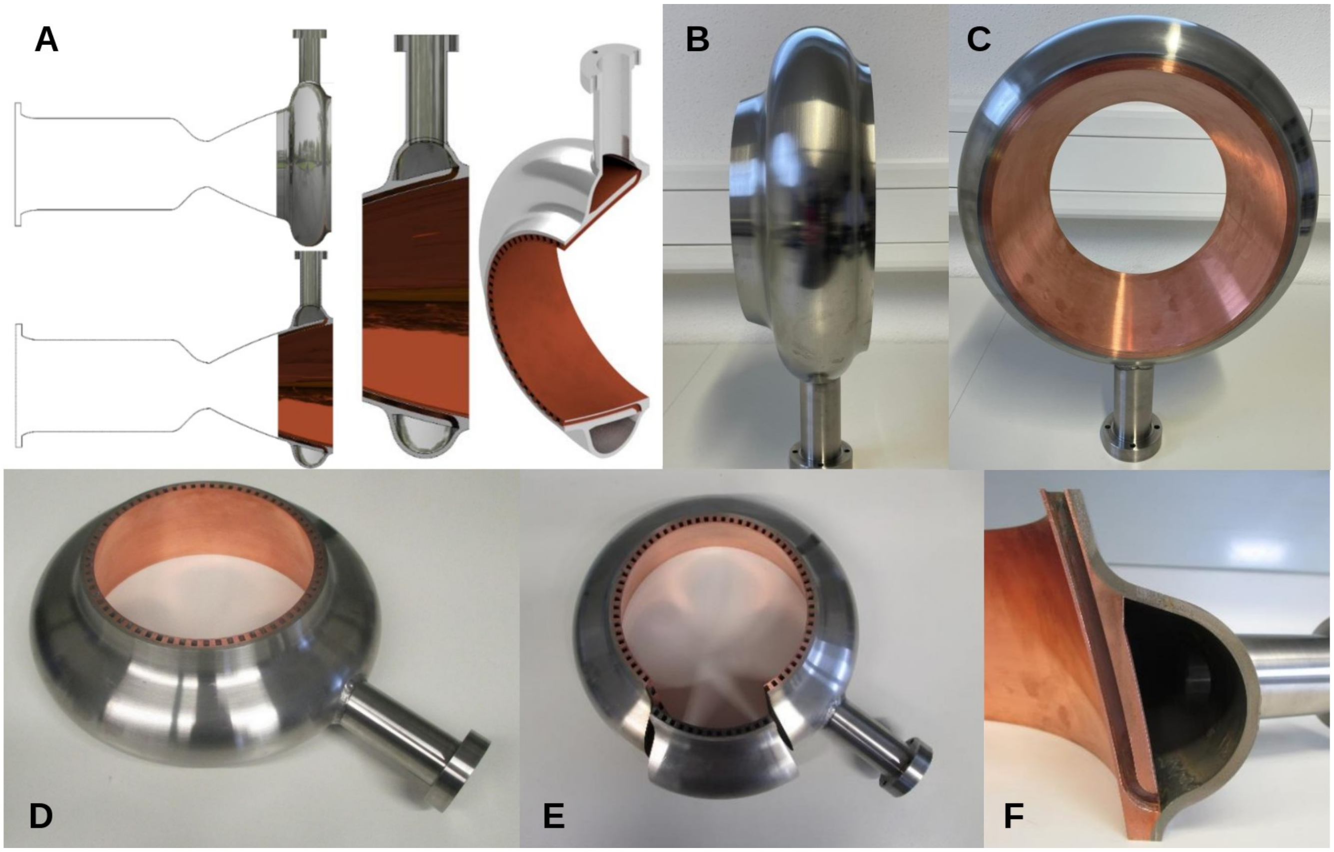


Figure 8: Manifold demonstrator test piece, where the liner, jacket and manifold are all produced by CSAM.

These manufacturing trials were successful enough to verify that the demonstrator engine can be manufactured by CSAM if further research budget allows. Given the conservative nature of the demonstrator design, and the quality of the trial parts, the material thickness can be reduced for the structural jacket and copper closeout in the manifold area. An intermediate cleaning step would be added after dissolving the filler, and an argon atmosphere would be used for heat treatment to avoid surface discolouration (Figure 9).

Further work should also focus on the creation of manifolds with variable-area profiles, which are required to distribute coolant massflow evenly amongst the coolant channels. To keep the distance constant between the cold spray gun and workpiece, and keep the spray direction perpendicular to it, manifolds with variable-area would require the robot to move the gun in-and-out as the workpiece rotates, which complicates the toolpath generation but is technically feasible if the rotary axis has a known angle.

Further work could also investigate the production of thin-wall nozzle extensions with integral stiffening bands, made of alloys such as C103 and/or titanium.

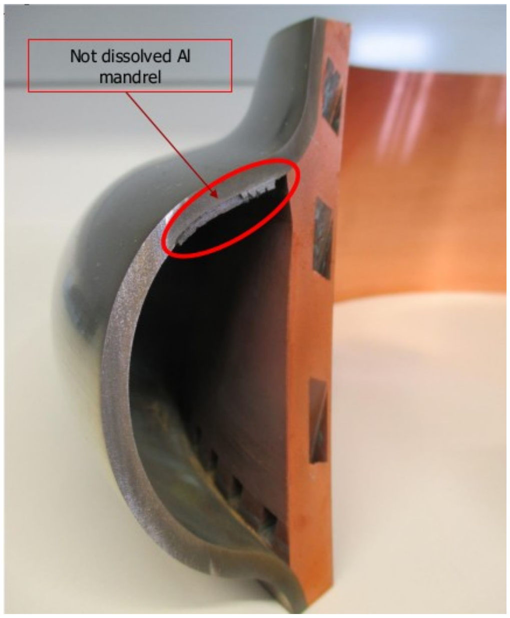
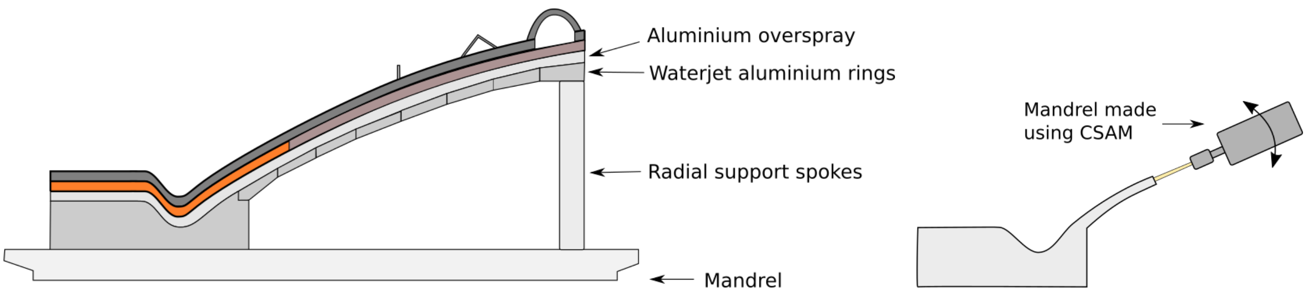


Figure 9: Undissolved aluminium filler in one area of the manifold, caused by a bubble in the chemical etching bath.



(a) Oversprayed crude mandrel, made from waterjet rings *(b) Axially-sprayed CSAM mandrel*

Figure 10: Example CSAM manufacturing routes for mandrel manufacture of large LREs.

6. CSAM: BEYOND THE BUILD VOLUME

For high thrust lift engines (>100kN) with large expansion ratio nozzles the PBF process becomes increasingly uneconomic. Large volumes of powder would be required to fill the build volume, leading to high costs and also mechanical difficulties in the machine design, because of the weight of powder and the need for tight positioning accuracy in layer height. Alternative AM methods are therefore required for manufacturing large LRE nozzles efficiently in terms of both cost and time, without a build volume limit. These methods can be divided broadly into two groups.

First, techniques that can form closed channel geometries. Foremost amongst these is DED, which has been successfully used to create nozzle geometries up to 44" in diameter and 48" in height [11], and can create coolant channels with variable geometries [13]. DED techniques have been used to create channels with wall thicknesses down to 1.0mm [11], but thinner than this is difficult because the channels are build vertically and the powder must be accurately blown onto the end of a thin wall and a melt pool sustained without warping the wall. DED techniques are also still slow for large parts, although related emerging techniques such as EHLA may improve manufacturing speed if they can be combined with robots that have sufficient positioning speed and accuracy.

Second, techniques that can rapidly deposit material but need several intermediate steps of deposition, machining and filling to create closed channels. Examples of these techniques are wire-arc additive manufacture (WAAM) or cold spray additive manufacture (CSAM). For CSAM, where the spray deposition is fast, the practicality of this manufacturing route relies on a fast machining techinique suitable for accurately machining small channels. One technique investigated in the literature for a variety of channel shapes is abrasive water jet milling [18], which could be an effective partner for CSAM.

For large LRE chambers and nozzles, CSAM is a fast and effective technique for material deposition and there is very little powder loss. It is therefore cost effective when using expensive alloys and virgin powder can be used each time, which simplifies part qualification. CSAM can also be used to create the mandrels themselves. Figure 10 shows two example methods for this. The first method uses a crude initial mandrel made from aluminium rings cut using a 5-axis waterjet (Figure 10a), where smaller rings can be nested inside larger rings during cutting to minimise material use. These crude rings can be roughly assembled and fixed together by hand (e.g. by tack welding). A quick overspray layer then bonds the rings together and provides a clean surface to post-machine to the exact LRE internal profile. The second method uses CSAM spraying in an axial direction to build the mandrel, with some rotation of the spray gun to provide a more perpendicular angle at the mandrel edges. Due to the variable spray angle, is not possible with such axial spraying to obtain optimal material properties, and therefore it would not be appropriate for manufacturing the copper liner, but it is likely acceptable for the mandrel production where mechanical properties are less critical.

7. CONCLUSION

Cold spray additive manufacture can produce high-quality bimetallic parts with no build volume restrictions, and is therefore one of the only contending methods for additive manufacture of high-performance, high-thrust lift engines. It has advantages for adding structural jackets to copper alloy liners and for creation of the liners themselves, and the ability to join additional parts (e.g. injector heads) without welding. CSAM can also be used to create other ancillary LRE components, such as high pressure tanks (e.g. for ignition or turbine start) or nozzle extensions.

A demonstrator combustion chamber was designed for a 20kN thrust level, suitable for manufacture by CSAM. Sample sections of this demonstrator were then manufactured by Impact Innovations GmbH at their research spray-lab. These proved the ability of CSAM to create high aspect ratio coolant channels and to create one-piece structural jackets and manifolds, without requiring high-temperature brazing or welding processes that might degrade the properties of the copper alloy liner. Subsequent work would refine this geometry and build a complete part for hot-fire testing.

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