ADDITIVE MANUFACTURE OF ROCKET ENGINE COMBUSTION CHAMBERS FROM CUCRZR (C-18150) USING THE DMLS PROCESS

VIRTUAL CONFERENCE / 17 - 19 MARCH 2021

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KEYWORDS:

Additive manufacture, combustion chamber, CuCrZr

ABSTRACT:

This paper describes the initial evaluation of an additively manufactured copper alloy (CuCrZr) for the production of high performance liquid rocket engine combustion chambers. A variety of small test pieces were evaluated geometrically and with flow testing. A small demonstration combustion chamber was printed and tested at a range of chamber pressures using a throttleable pintle injector. The additively manufactured combustion chamber showed excellent thermal performance but higher than expected pressure drop due to high surface roughness in the coolant channels.

1. INTRODUCTION

Additive manufacture of rocket engine combustion chambers has the potential to greatly simplify the manufacturing process, but the resulting performance of the engine is limited by the geometric constraints of the printing process and by the mechanical properties of the printed and heat treated material. Whilst it is possible to print complex geometries with small coolant channels, which are excellent for heat transfer, the reproducibility of such features is heavily dependent on the laser process and requires careful depowdering.

High-performance rocket engines commonly use copper alloys because the higher thermal conductivity lowers the thermal stress in the firewall at high heat fluxes. Additive manufacture of copper alloys for combustion chambers has been proved using GRCop-84 and GRCop-42 (CuCrNb) by some institutions [1, 2] and C-18150 (CuCrZr) [2, 3], but copper alloys have only recently been made commercially widely available for additive manufacture, most notably by 3T AM in Newbury, UK. 3T AM have developed processes for printing a copper alloy (CuCrZr) that has good heritage for combustion chambers using conventional machining, because it has high thermal conductivity and has comparatively good mechanical properties at high temperature [4]. In recent years this process has been notably used by Launcher (US) for its LOX/RP-1 engine at both 3.5kN scale [5] and at 100kN scale [6] using an AMCM extended build volume machine.

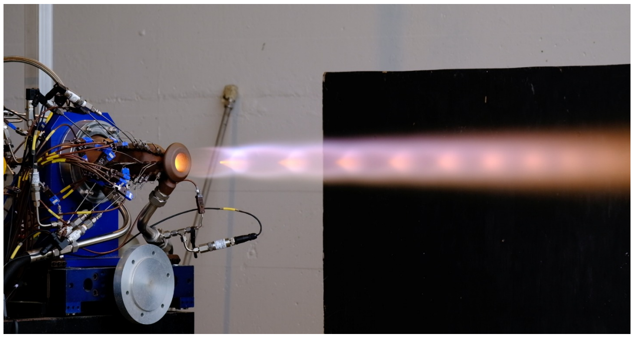
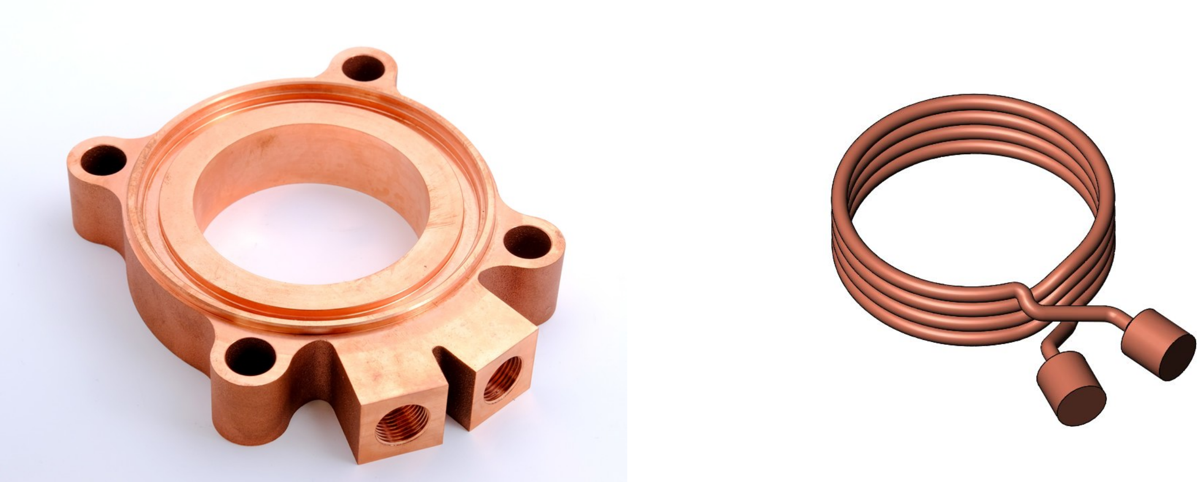


Figure 1: Firing of the additively manufactured CuCrZr combustion chamber using liquid bipropellants.

In a UKSA Pathfinder funded programme (Q4 2018 - Q2 2019), Airborne Engineering (AEL) and 3T AM collaborated to develop and demonstrate a combustion chamber printed in CuCrZr. This began with small test pieces for evaluating as-printed geometries and for flow testing small holes such as could be used for injectors or film cooling. A small demonstrator combustion chamber was then printed and tested at a range of chamber pressures.



(a) Printed and postmachined

(b) Helical coolant path

Figure 2: The CuCrZr combustion chamber segment test piece. This has a single inlet and outlet boss, and a single pass helical coolant channel near the firewall. The part also has an o-ring groove for sealing, a male and female alignment shoulder, and ears for stacking segments together with threaded rods.

2. TEST PIECES

2.1. Chamber segment demonstrator

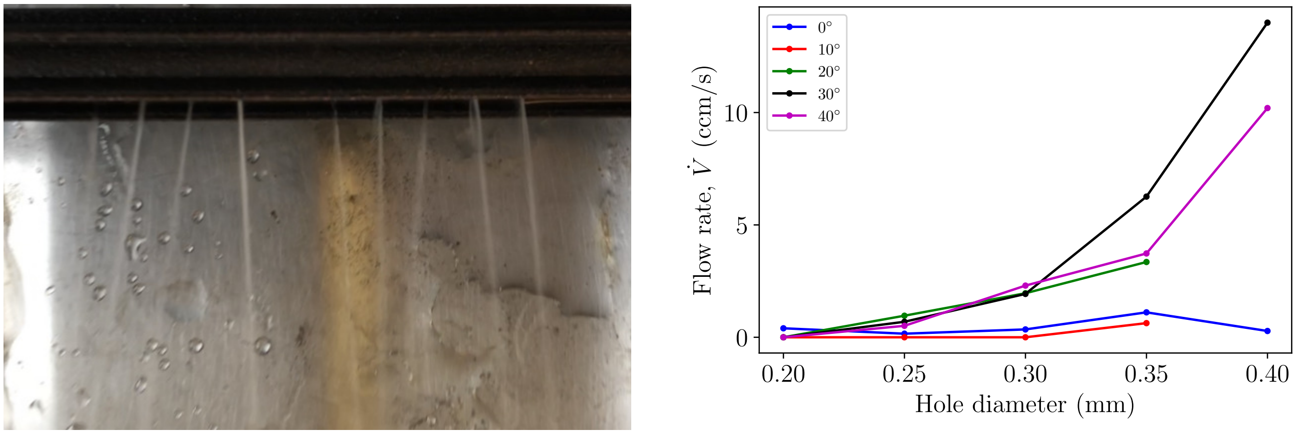
Much of AEL's rocket focused research has involved injector or propellant studies, which often require the evaluation of wall heat flux as a function of axial position in the chamber, and evaluation of the combustion efficiency as a function of the total combustion chamber length. Typically this involves the use of copper 'workhorse' chambers that are segmented in order to easily change the combustion chamber length by stacking together repeated segments. For high heat flux or prolonged firings, these must be actively cooled, typically with water, and the heat flux into the water captured by calorimetry [7].

A single segment of a 'workhorse' chamber was printed to evaluate the additively manufactured CuCrZr material in this application. The segment contains a single helical coolant channel, an inlet and outlet boss, an o-ring groove for sealing and a male and female alignment shoulder. Each segment would then be stacked together using a threaded connection through four ears. Fig. 2 shows the successfully printed and post-machined chamber segment.

2.2. Regenerative coolant channel test pieces

Small representative test pieces were printed with coolant channels of different sizes, in order to gauge the minimum feature size of channels that was achievable. Fig. 3 shows the channel size test pieces. Whilst the square shape of the channels was reproduced well even down to 0.5mm, the small channels would likely have large variations in hydraulic performance due to the increased sensitivity to surface roughness, and would be liable to blockage during de-powdering operations. Larger coolant channels were therefore used in the demonstrator combustion chamber.

Figure 3: The CuCrZr test pieces for channel hole sizes for 1.0mm, 0.8mm, 0.6mm and 0.5mm.



(a) Hole variability in water flow tests

(b) Air flow tests

Figure 4: Film cooling test pieces were printed with variations in hole size, build angle and hole angle. They were flow tested in water (a) to evaluate flow rate and uniformity and (b) air to evaluate lower flow rates.

2.3. Film cooling test pieces

Even with a regeneratively cooled chamber, it is likely that a high performance engine would benefit from some film or transpirative cooling in high heat-flux areas. If film cooling holes could be printed into the combustion chamber near the throat, where cooling is most required, then this would increase performance compared to simple head-end injection. These film cooling holes would need to be small such that they can be distributed around the chamber, in order to give effective cooling and not unduly affect combustion performance by using too high a fraction of the propellant mass flow.

Additive manufacturing of small holes is difficult however, and for each material and set of laser parameters there is a practical limit to the hole sizes that can be repeatably achieved, and this may depend on the build angle. A series of 70 test pieces, each with 10 small holes was designed and printed, with variations in build angle, hole size and hole shape. These used a novel geometry where the flow is fed through a circumferential hole in the radial rib between coolant channels, which then meets another hole to the firewall that proceeds down the centre of the rib. This has the advantage of not placing a film cooling hole in the centre of the channel at the weakest point.

Fig. 4a shows that flow non-uniformity was seen for small holes using water flows. Flow testing was undertaken with both water and air. Fig. 4b shows some example results, which demonstrated that the flow rate is dependent not only on the printed hole diameter but also on the build angle of the part. Together, the results were positive and suggested the sizes and angles that would be most reproducible for a flight-like chamber, although further testing would be required to qualify the reproducibility of the final geometry.

2.4. Vertical gap test piece

In high-performance LREs, combustion chamber lifetime is often limited by thermal racheting, whereby there is local bulging and thinning of the firewall driven by the thermal and pressure stresses, typically ending in a “doghouse” failure. Eliminating the racheting failure mode by improving material properties is difficult, because large differences in these properties are required to make to cause a significant effect [8]. Allowing some physical compliance, however, can reduce racheting dramatically by reducing the maximum strain.

The maximum strain in the firewall arises from the combination of the coolant pressure stress and the thermal stress. There is a steep thermal gradient in the firewall requiring large differences in thermal expansion, but the channel symmetry prevents expansion in the circumferential direction and a resulting stress is generated. However, it is possible to reduce the maximum stress in the firewall by using slots or gaps between coolant channels to allow some thermal expansion [8]. In the literature, slots made by EDM methods [9] or made with a tube-bundle and electroforming process [10, 11] have been shown to dramatically increase chamber lifetime by over 2 to 3 times.

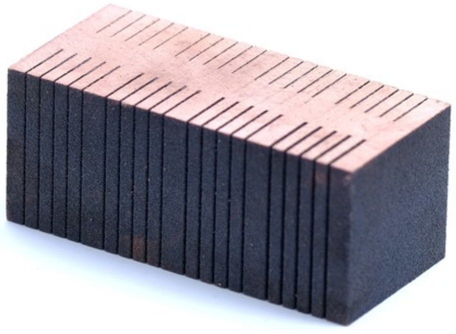


Figure 5: The CuCrZr test piece for vertical slots of different slot widths, to evaluate the surface roughness and powder removal as a function of slot width.

In the literature there is no record of slots or expansion gaps being printed using additive manufacture, but this should be possible for shallow slots, which is all that is required because the bulk of the relief required is across the firewall. For deep slots it is unlikely that complete depowdering would be successful. Fig. 5 shows a test piece that was printed with vertical slots of different widths, which were evaluated optically and with feeler gauges. Each width has several repeated slots to give better certainty about the process. The test piece suggested that there is good potential to increase chamber lifetime using this method, although this was not verified experimentally under this programme.

2.5. Combustion chamber

The main focus of this study was to evaluate the use of additively manufactured CuCrZr to form rocket combustion chambers. A chamber with integral cooling channels, manifolding and instrumentation ports was therefore designed. Water cooling was used in order to separate the cooling and combustion processes and therefore make it easier to throttle the combustion whilst safely measuring heat flux - although a segmented chamber would be better for high accuracy heat transfer profiles (see sec 2.1).

The chamber has a throat diameter of 25mm and combustion chamber diameter of 70mm, firewall thickness of 1mm with 64 channels in the combustion chamber, halving to 32 in the contraction, throat and expansion. The combustion chamber has a coolant manifold and boss at both ends. The total length of the chamber and nozzle (284mm) was limited by the build height of the printer used (300mm).

The chamber had three rows of instrumentation tappings. Two rows entered the coolant channel itself, for measuring coolant temperature in order to use an enthalpy balance to estimate heat flux, and for measuring coolant pressure in order to estimate the surface roughness of the as-printed channel. The third row has blind holes that end 1mm from the firewall, and allow small thermocouples to pass down the fin (in between channels) to measure the copper temperature at the coolant side of the firewall.

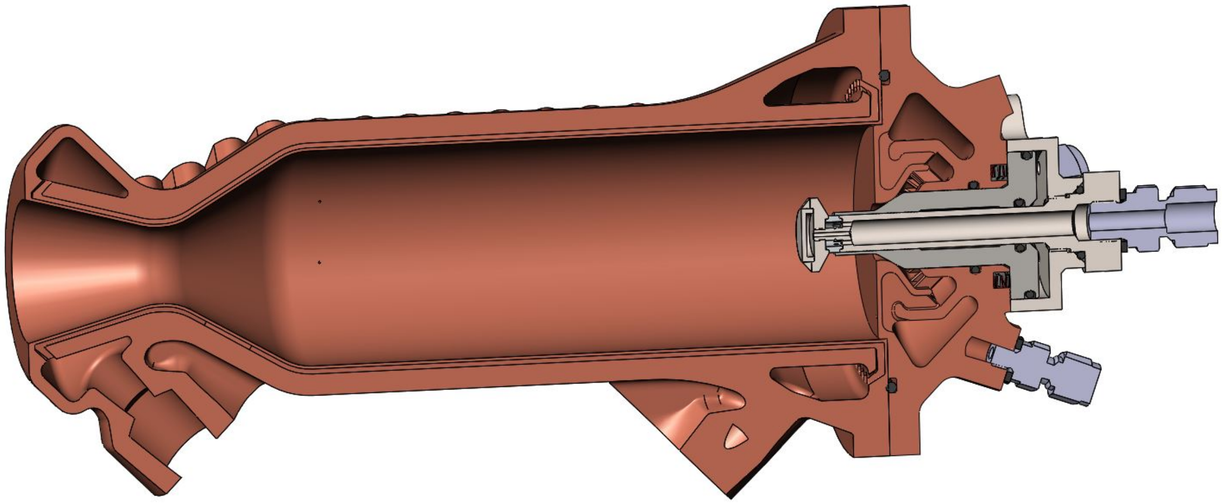


Figure 6: The additively manufactured chamber and injector, in a cross section view with the conventionally machined pintle injector components. The pintle injector has a sleeve that can move axially to close off both the fuel and oxidiser injector orifices to throttle the flow. The coolant enters from a boss at the nozzle end and leaves from a boss at the injector end.

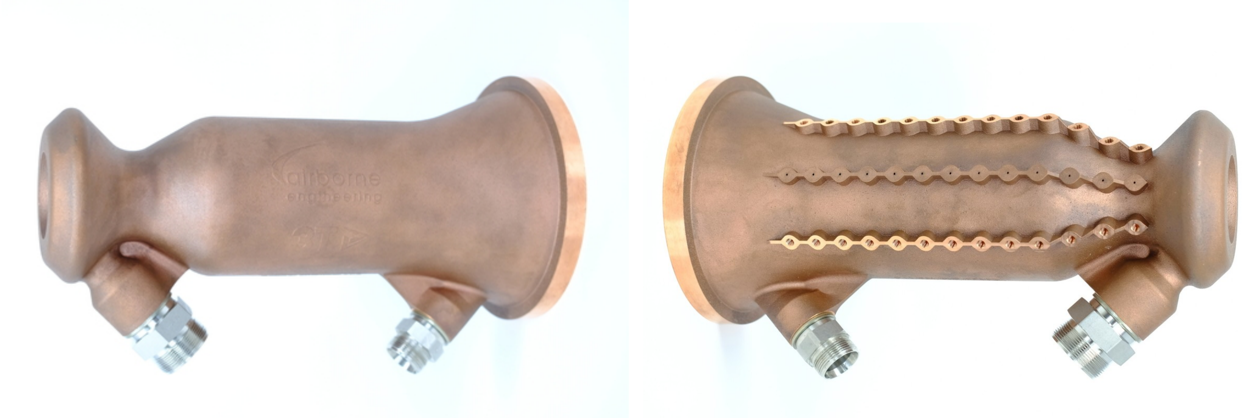
(a) As printed

(b) Close-up of cracks

Figure 7: The first CuCrZr combustion chamber immediately after printing. Cracks were visible at several locations on the chamber where powder dosing had been insufficient.

An initial print failed, due to insufficient powder dosing during the process, likely caused by a powder particle distribution that included finer powder than had been qualified. Fig. 7 shows the first printed chamber and the cracks at the layers where dosing issues occurred. Because the cracks formed an almost complete layer, using the chamber as a pressurised vessel was deemed unsafe.

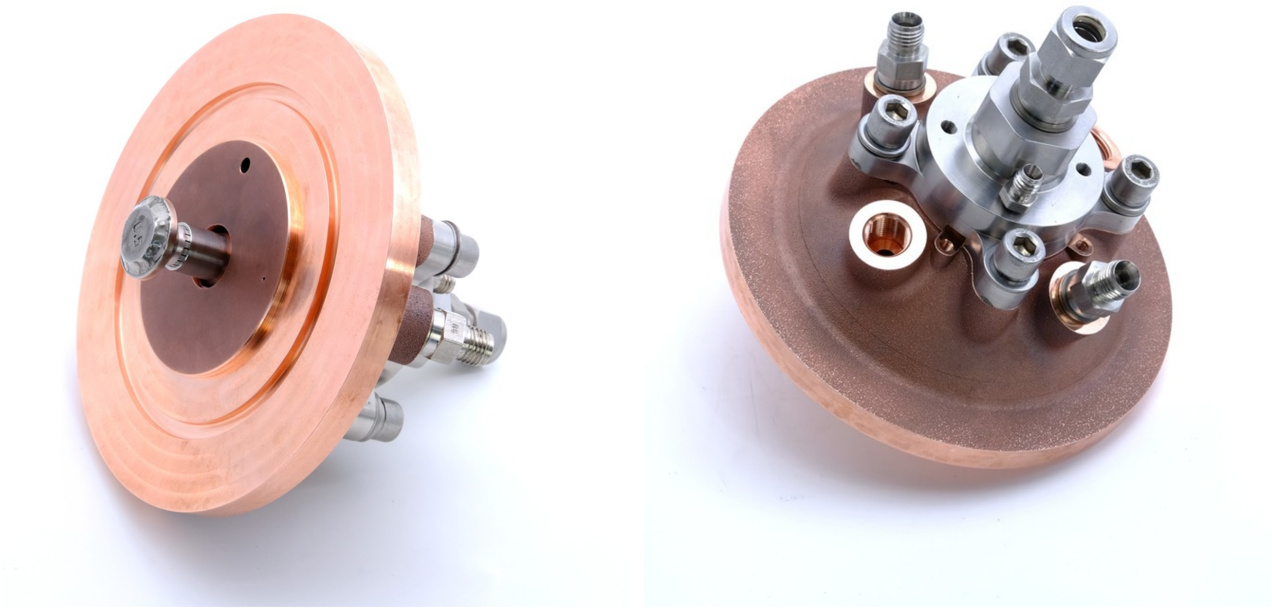
Fig. 8 shows the second print of the combustion chamber which was successful, as were the heat treatment and machining steps. Post-machining was only required for tapping bosses and for cleaning up the sealing surfaces at the flange and injector interfaces. No surface treatment was used on the hot-gas side of the firewall in order to find a baseline heat transfer with the as-printed surface roughness.



(a) Front

(b) Back

Figure 8: The second CuCrZr combustion chamber as printed, heat treated and post-machined, showing the coolant inlet and outlet bosses, and instrumentation bosses.



(a) Front (b) Back

Figure 9: The CuCrZr injector head after successful print and post-machining steps, with pintle injector installed. It has cooling channels across the injector face, pressure tappings for the chamber pressure, injector pressure and a port for a gas torch igniter feed.

2.6. Injector head and pintle injector

The injector face of a liquid rocket engine is also subject to high heat load and may also be suitable for printing in the CuCrZr alloy, particularly if printed as one piece with the combustion chamber. A demonstrator injector head was therefore designed and printed for the liquid bipropellant combination of N_2O/IPA, which is comparatively safe to handle and could use existing infrastructure. Ports were included for propellant inlets, a chamber pressure tapping and an inlet for a hydrogen-oxygen gas torch igniter feed.

A throttleable injector was required in order to evaluate the CuCrZr chamber at different chamber pressures and corresponding heat fluxes. A conventionally machined pintle injector with moveable sleeve was therefore designed and manufactured to work with the CuCrZr injector head. Pintle injectors have been shown to give efficient mixing for liquid-liquid [12] and gas-liquid flows [13] when propellant axial and radial momentums are well matched.

Fig. 6 shows the injector head and pintle injector, which is non-standard for two reasons. First, that it has a porous tip that is designed to prevent melting of the pintle tip by the recirculated combustion gases. Second, that it features a splash plate, due to the difficulty in balancing the axial and radial propellant momentums, because the nitrous oxide will flash boil to different extents dependent on the mass flow and heat load into the injector face. This is a particular problem associated with using a self-pressurising fluid. The initial pintle tip design therefore used a modified porous filter element welded to a machined splash plate. The material of the splash plate was thicker than ideal for high heat fluxes but deemed acceptable for initial short-duration firings. The porous tip was successful in withstanding the heat load in all tests, but for high throttle tests the splash plate size was reduced for latter firings due to overheating at the outer extent where the material is thickest. The combustion performance of the injector ranged up to 99%.

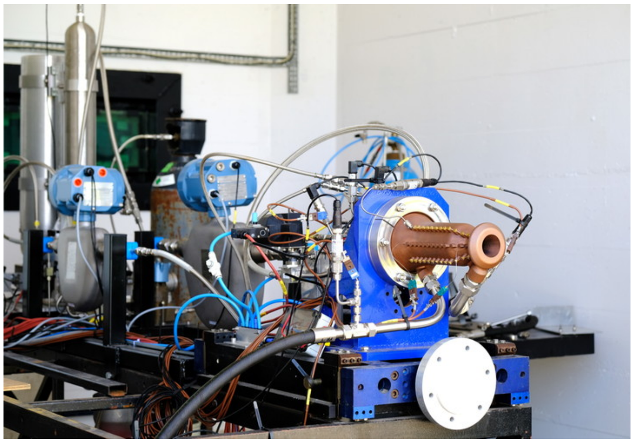


Figure 10: The test rig used for evaluating the CuCrZr material under hot firing conditions, showing the propellant tanks, valves, Coriolis mass flow meters, and the combustion chamber mounted on a table hung on flexures and connected to a load cell.

3. HOT FIRING TESTS

3.1. Test rig

A test rig was built in order to evaluate the performance of the CuCrZr combustion chamber during hot firing conditions. Fig. 10 shows the test rig, which uses Isopropyl alcohol (IPA) and Nitrous Oxide propellants and consists of some high pressure tanks, valves, Coriolis mass flow meters and tank filling equipment. An existing high pressure water line was used in the neighbouring test bay to provide coolant, and mechanical adapters and fittings were manufactured to attach the combustion chamber and connect it to propellant lines. A nitrogen pressurant system is connected to both propellant tanks, although the nitrous oxide can be used in a self-pressurising mode. The feed system is mounted on a removable sled in the J1 firing bay at the AEL test site in Westcott (UK).

Instrumentation such as pressure sensors and thermocouples were used to monitor propellant injector supplies, and to record the pressure drop and temperatures in the coolant channels and the temperature of the coolant side of the firewall. An exit choke provided backpressure to the water coolant supply to raise the boiling point and increase the maximum heat flux permissible. By using a pressure sensor upstream of the choke the coolant massflow could be calculated using a catch-and-weigh calibration procedure. Data was recorded using AEL's in house data acquisition system at 10kHz, simultaneously across all sensors.

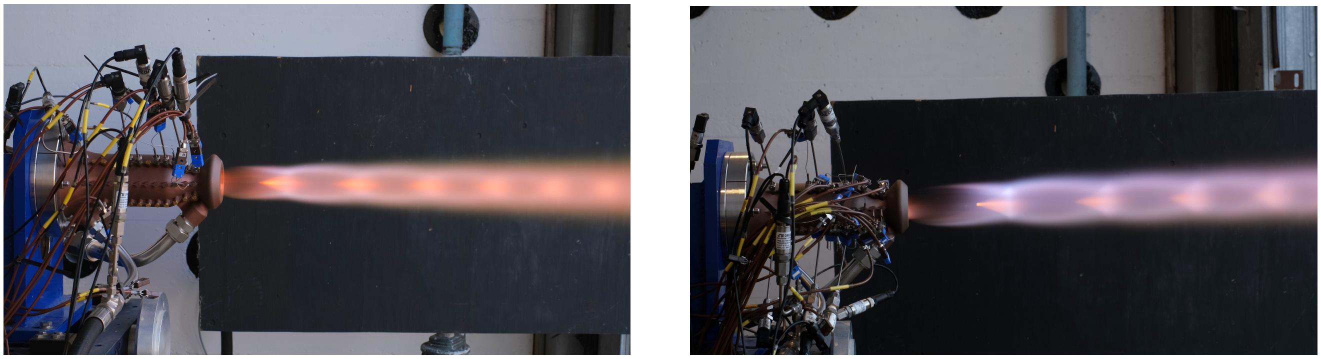
3.2. Results

Hot firing tests were carried out at several throttle settings. Fig. 11 shows the combustion chamber during the hot firing at both a low and a high throttle setting. To the authors' knowledge, these were the first firings of a liquid rocket engine combustion chamber in the UK built with additive manufacturing from metal alloys, and the first firing of an additively manufactured copper combustion chamber in Europe. The firings were successful, with no damage visible to either the combustion chamber or injector face.

During these initial tests, the pintle injector was successfully used to throttle the chamber pressure to between 14 and 45 bar(a), such that the total thrust was up to the 3kN level. Combustion performance was best at high throttle settings with efficiency up to 99%. The increased performance at high throttle is likely because the nitrous oxide flashboils less during injection, and therefore there is a better momentum balance and mixing where the nitrous oxide meets the radial IPA jets. Some modifications were required to the pintle splash plate for the higher throttle tests in order to prevent overheating at the splash plate extremity.

Pressure sensors were used to measure the pressure drop through the coolant channels. The pressure drop was found to be significantly higher than modelled, suggesting a high internal surface roughness. Some variation in coolant flow rate between coolant channels was inferred from the coolant temperature measurements in the two instrumented channels, which is likely due to variations in surface roughness. This variation could be reduced by using larger channels, improvements to the printing process or by using chemical or physical surface treatment techniques. This is worthy of further investigation.

Heat transfer data suggested roughly 20% higher heat fluxes than predicted using an empirical equation, but within the expected bounds of accuracy of this technique. Testing has not yet been undertaken with surface treatment of the hot-gas side of the firewall, so the effect of roughness cannot be estimated. The total heat flux into the chamber was up to 500kW. Once the increased surface roughness of the printed channels was taken into account, the coolant heat transfer and coolant-side copper temperatures matched the modelling well. Peaks in heat transfer were seen at the nozzle throat and also in the early part of the combustion chamber where the pintle injector flows impinge on the firewall. This was the location of the highest copper temperature because the coolant velocity was much lower than at the throat.



(a) Lower throttle

(b) Higher throttle

Figure 11: Firing of the additively manufactured CuCrZr combustion chamber using liquid bipropellants in AEL's J1 test facility. This is believed to be the first firing of a liquid rocket engine combustion chamber in the UK built with additive manufacturing from metal alloys, and the first firing of an AM copper combustion chamber in Europe.

4. CONCLUSIONS

Additively manufactured CuCrZr was used to evaluate small test pieces and manufacture a demonstrator combustion chamber. The firings demonstrated good thermal performance, suggesting that this a viable method for manufacturing high performance rocket engines with complex coolant channels. Further testing at higher heat flux is recommended.

5. ACKNOWLEDGEMENTS

The authors would like to thank former AEL member Nick Jamieson for his work on the programme, and Luke Rogers and the team at 3T AM in Newbury, UK, for their printing expertise and partnership in this programme, and the UK Space Agency for funding it under Pathfinder project PF2-058 and the ESA GSTP.

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