Extreme Environment Hot Fire Durability of Post-Processed Additively Manufactured GRCop-Alloy Combustion Chambers in LOX/Hydrogen and LOX/Methane

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Extreme environment survivability of metal additive manufactured (AM) GRCop-alloy thrust chambers has been demonstrated in different bi-propellants at near stoichiometric and even oxygen rich combustion. GRCop-alloy chambers tested at NASA Marshall Space Flight Center (MSFC) have accumulated over 26,000 seconds of hot fire duration and over 500 starts. These chambers are produced using an AM process called laser powder bed fusion (L-PBF). A major feature of this process is high wall surface roughness which can be customized in post processing to leverage various performance advantages. Post-processing can include heat treatment, final machining, polishing, and welding and is key to hardware survivability in extreme environments. Surface finish enhancement techniques were applied to the hot wall and coolant channels to reduce the overall total heat load to the chamber walls. Performance optimization of various thrust class TCA's is a strategic technology goal of NASA MSFC. Three different chamber geometries using cryogenic methane and de-ionized water as coolants were hot fire tested to obtain their life cycle, pressure drop, and heat load performances. Several 1.2K lbf LOX/H2 chambers, 1K lbf LOX/CH4 chambers, and 7K lbf LOX/CH4 chambers were tested. All post-processed configurations performed remarkably well when subjected to extreme hot fire test conditions. Streaking and blanching due to localized oxygen rich conditions were observed on some test articles in their as-built surface finish state. However, this is actually a function of the injector mixing and only serves to further establish the durability of L-PBF GRCop-alloy thrust chambers. Several different polishing techniques were applied to the hot wall and integrated coolant channels prior to hot fire testing and their performances assessed. Overall, AM produced GRCop chambers are extremely reliable, durable, and customizable to the desired performance metrics.

I. Nomenclature

AM	=	additive manufacturing
AFM	=	abrasive flow machining
ALPACA	=	advanced lander propulsion additive cold-spray assembly
B	=	barrel section
CC	=	coolant channels
CMP	=	chemical mechanical polishing

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CM	=	chemical milling
COMET	=	composite overwrap methane engine thruster
CT	=	computer tomography
*C**	=	characteristic exhaust velocity
EB	=	electron beam
EDM	=	electrical discharge machining
GRC	=	Glenn research center
HIP	=	hot isostatic pressing
HW	=	hot wall
SIM	=	in space manufacturing
Isp	=	specific impulse
ISS	=	international space station
LRE	=	liquid rocket engine
L-PBF	=	laser powder bed fusion
LLAMA	=	long life additively manufactured assembly
LOX	=	liquid oxygen
LP-DED	=	laser powder directed energy deposition
*L**	=	chamber characteristic length (volume / throat area)
MET1	=	methane engine for 1K
META4X4	=	methane engine for 4K
MP	=	manual polishing
MSFC	=	Marshall Space Flight Center
N	=	nozzle section
NASA	=	National Aeronautics and Space Administration
SOA	=	state of the art
SSME	=	space shuttle main engine
T	=	throat section
TCA	=	thrust chamber assembly

II. **Introduction**

Metal Additive Manufacturing (AM) has become a viable cost-effective way to produce complex components for various engineering applications. Both NASA and the aerospace community have substantially advanced AM towards regular use in industry. AM creates opportunities to reduce lead time and subsequent costs, allows for internal complexity to be fabricated, and provides the ability to incorporate alloys that are usually difficult to obtain or process using traditional manufacturing methods. While AM has many advantages, there are challenges. One is the higher surface roughness that results from the AM process compared to traditionally machined components. Along with the advancement of AM, post-processing techniques have evolved to modify mechanical properties such as fatigue life, flow characteristics, and aesthetic appeal. These post-processing surface enhancement techniques are often thermal, mechanical, or chemical in nature, or a combination therein [1]. There are a variety of metal AM build techniques that each have advantages and disadvantages based on the end use component requirements. These techniques may be selected based on several criteria including scale of the component, desired feature resolution, material properties, integrated complex structures, or utilization of a specific material. Some of these AM technologies include laser powder bed fusion (L-PBF) and laser powder directed energy deposition (LP-DED), to name a few while several others are available. These build technologies and the advancement of high conductance super alloy materials such GRCop-84 and GRCop-42 are of great interest to NASA and commercial space.

These alloys have been primarily used to produce liquid rocket engine (LRE) combustion chambers and nozzles; although, other components such as injector faceplates have also been produced and tested using this alloy. GRCop has demonstrated use in extreme combustion environments and combustion performance can be modified using various post-processing methods. For this reason, the development of AM GRCop-alloy combustion chambers has been a major focus of the combustion devices branch at NASA MSFC since the early 2010’s. Substantial advances in the technology development have been made with numerous test programs conducted ranging from 1.2K lbf class thrusters to 35K lbf class chambers. As of this publication, various chambers have accumulated over 500 starts and more than 23,000 seconds of mainstage duration in LOX/Hydrogen, LOX/Methane, and LOX/RP-1. Several images of AM GRCop-alloy and other LRE application alloy chambers, injectors, and nozzles are shown in the figure below, all successfully tested.

Fig. 1 Images of various combustion device hardware that utilize L-PBF and LP-DED techniques.

Many of these test articles were fabricated at NASA MSFC while more recent chambers were fabricated at the growing supply chain for GRCop AM service vendors. All chambers and mechanical witness specimens complete hot isostatic pressing (HIP) at the parameters for GRCop. For each given application, chambers are then further post-processed to reduce surface finish to improve fatigue life, reduce flow pressure losses, and reduce total heat loads.

Reduction of hot wall surface finish is a primary post-processing technique for alteration of heat transfer performance in liquid rocket chamber liners. As the surface finish, or the friction factor along the wall, is reduced the total heat added to the coolant is also reduced. This has been quantified as being as much as a 30% reduction if just the barrel section of a chamber liner is mechanical hone polished [2]. It is expected that the reduction in total heat load could be as much as 40% when proper polishing techniques are applied compared with AM GRCop-alloy chamber liners in their as-built state. It is apparent there are inherent advantages in customized heat load performance of these combustion devices depending on their application of use. To this end, alteration of the total heat load could substantially impact the injector C* efficiency depending on the injector element type and the operating conditions. This was quantified during hot fire testing with several fully AM injectors and will be presented in a separate paper submitted to the 68th JANNAF Propulsion Meeting in 2021.

Several test chambers had specific interfaces polished in order to optimize their resilience and reliability to extreme environments. For example, a NASA 7K lbf AM GRCop-42 chamber was chemical mechanically polished (CMP) within the coolant channels. This, in turn, improved the chambers wear resistance, fatigue life, and decreased the coolant channel pressure drop substantially. In addition, several 1.2K lbf chamber liners were post-process polished using various methods that were applied to the hot wall and coolant channels in an attempt to characterize differences between as-built and processed A before and after comparison of a CMP processing of a 7K chamber liner, dubbed LLAMA, as well as on a 1.2K chamber liner are shown in the figure below.

Fig. 2 Chemical mechanically polished 7k (left) and 1.2k (right) GRCop-42 chamber liners.

Several GRCop-84 1K lbf chamber liners, referred to as Methane Engine Thruster for 1K (MET1), were mechanically honed (polished) on the hot wall to reduce heat load and improve their survivability in extreme environment conditions. Each of these test articles are shown during hot fire test in the figure below.

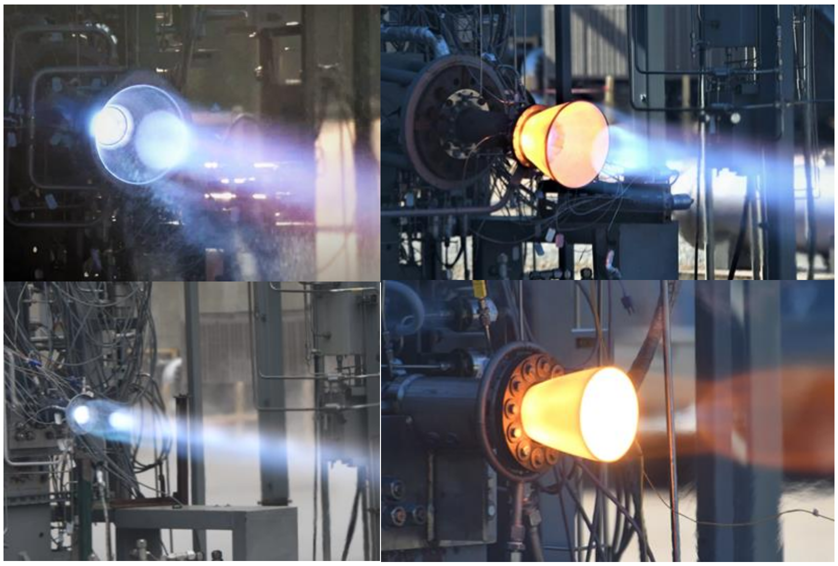

Fig. 3 (top left) Hot fire testing of 7k lbf AM L-PBF GRCop-42 LLAMA (left) chamber liner in LOX/CH4 coupled to LP-DED NASA HR-1 nozzle and 7k lbf carbon composite nozzle attached to ALPACA chamber liner (top right), (bottom left), 1k lbf L-PBF GRCop-84 LOX/CH4.

The results and impact to heat loads from hot fire testing with various polishing techniques are presented in this work. The total duration, number of starts, and select test conditions are presented. Material properties, chamber development, post-processing techniques are also discussed. Physical changes and alterations to key interfaces are documented and recommendations to improving hardware life cycle performances are postulated. The following section provides a review of GRCop-alloy material development to date.

III. Background

For several decades, NASA has been attempting to improve chamber manufacturing through investment in development processes and techniques such as low cost brazing and Vacuum Plasma Spray (VPS) [3]. However, in the last decade, NASA has begun to focus these efforts on rocket engine component development using AM. AM encompasses various techniques that allow for the advantages in complexity, novel alloys, reduction in lead time and cost, and the ability to develop and test components at a quickly recurring pace. NASA believes AM is crucial to the future of space travel and has created the In-Space Manufacturing (ISM) program to detail the agency's path forward using AM [4]. This path includes advancing AM technology readiness levels by creating properties databases and certifying inspection processes [5]. The ultimate goal of ISM is to transition these technologies in phases to the International Space Station (ISS), the Deep Space Gateway, and eventually the surface of other planets [5]. NASA believes AM can be used to print on-demand, custom components and structures on the surfaces of other planets using in-situ resource utilization [4]. The use of GRCop-Alloys in AM has been an on-going development effort at NASA MSFC since 2013. Prior to this, the thermophysical material properties for both GRCop-84 and GRCop-42 were well characterized in the extruded form. GRCop-Alloys have even been looked at for possible use in many applications including nuclear hybrid launchers subjected to fusion environments [6]. Below is a brief review of the available literature on the development and testing of GRCop-Alloys and AM produced GRCop chamber liners.

The available literature was reviewed on the development of GRCop-alloys, its integration into AM, and amalgamation into actively cooled combustion chambers at NASA. Several articles have focused on the extruded (wrought) material properties, advantages, and development of GRCop-84 [2], [7]–[16]. Other articles discussed the development of GRCop-alloys AM technology and its progress [3]–[5], [17]–[20]. Finally, several articles describe the development of AM GRCop-alloy combustion chamber and structural jacket design and fabrication [21]–[25]. Many of the articles reviewed are interrelated and crossover on all three of these subtopics.

GRCop is a copper-based alloy composed of a near-pure copper matrix with chromium-niobium (Cr_2Nb) precipitates for dispersion strengthening [11]. NASA Glenn Research Center (GRC) first developed GRCop-84 specifically for rocket engine combustion chambers, but it has applications in all high-heat flux environments (up to 700°C) [12]. At high temperatures, the material possesses excellent mechanical properties including enhanced oxidation resistance, high tensile strength retention, high creep resistance, long low-cycle fatigue lifetime, and high electrical conductivity [15]. It also requires no special production methods and can be bonded via a variety of joining techniques when in a wrought or extruded form [12]. GRCop-84 was designed to provide higher strength compared to other copper precipitate strengthened-alloys that were used in past rocket engine designs, such as NARloy-Z and AMZIRC [10]. NARloy-Z was used in the Space Shuttle Main Engine (SSME) main combustion chamber, but a 1983 study found that surface cracks could form at the throat of the NARloy-Z chamber as early as the fifth full-power test [8]. GRCop-84's material properties provide the same benefits as NARloy-Z, but without many of the drawbacks.

A 1996 study found that extruded GRCop-84 had 100-250% longer creep life, 60-160% greater strength, and 50-200% longer low cycle fatigue life than NARloy-Z [16]. Another study, published in 2000, showed that GRCop-84 possessed significantly lower thermal expansion than NARloy-Z. Lower thermal expansion means lower thermal stress and increased life expectancy. The examination found that NARloy-Z had slightly better thermal conductivity, but concluded that this fact could be negated by taking advantage of GRCop-84's superior mechanical properties via optimized chamber design [13]. An additional 2008 experiment investigated the mechanical properties of multiple highly conductive copper alloys including GRCop-84, NARloy-Z, and AMZIRC. While the GRCop-84 was outperformed at lower temperatures, at high temperatures (above 500°C), GRCop-84 had superior mechanical properties that did not degrade. Specifically, GRCop-84 demonstrated superior strength, creep resistance, and ductility at high temperatures [14].

GRCop-84 was determined to be AM-friendly using a L-PBF process due to its ease of build and low mass. This capability allows regenerative cooling channels to be built within the combustion chamber [7]. A study conducted in 2020 examined how varying printing parameters and elemental powder preparations influenced the in-situ formation of Cr_2Nb precipitates while fabricating components. The study proved that L-PBF can create dispersion strengthened alloys, such as GRCop-84, in-situ with conversion efficiencies up to 89% [11]. Despite GRCop-84's inherent benefits, research is still being conducted on materials that may possess superior material properties. Shortly following GRCop-84, a fellow GRCop-alloy named GRCop-42 was developed and offers higher conductivity, 20% faster build speed, and simplified powder supply chain [9]. Much of the supply chain has transitioned towards GRCop-42 due to these advantages.

Starting in 2013, MSFC developed numerous AM L-PBF channel-cooled combustion chambers using Inconel 625 and GRCop-84 amongst other materials [20] and incorporated bi-metallic and hybrid AM techniques. MSFC fabricated and hot fire tested the Additive Manufacturing Demonstrator Engine (AMDE) starting back in 2012. This upper stage prototype engine had more than 150 additively manufactured parts and demonstrated reduced cost, schedule, and part count [18]. Other groups such as GRC and Aerojet Rocketdyne have also tested AM injectors and participated in the RL10 Additive Manufacturing Study (RAMS) [19]. Most importantly, in October 2017, Marshall published MSFC-STD-3716 and MSFC-SPEC-3717 for AM space flight hardware [18]. This standard and specification create a standard methodology for consistent evaluation and certification of AM processes and components. Unfortunately, AM techniques do present a few problems. For example, many AM techniques are limited in the size of components that can be fabricated due to build box size, joining bimetallic interfaces has proven difficult, and powders can have varying sizes and chemistries while still meeting specifications [3].

To research and demonstrate the feasibility of AM LREs, NASA MSFC began the Low-Cost Upper Stage Propulsion (LCUSP) program in 2014. Researchers fabricated several regeneratively cooled thrust chamber assembly designs, including a 35k-class chamber [24], with multiple AM techniques and materials [22]. Two of these designs were hot-fire tested a total of 10 times with a total burn time of 147 seconds [20]. These tests successfully demonstrated the feasibility of bimetallic thrust chambers composed of AM L-PBF GRCop-84 combustion chambers and AM EBF ^{3} Inconel 625 structural jackets [23]. The program also characterized the microstructure and mechanical properties of L-PBF GRCop-84, EBF ^{3} Inconel 625, and their interface layers [24]. After LCUSP's success, NASA partnered with Virgin Orbit in 2017 and continued to advance and improve these bimetallic designs and AM fabrication techniques [21]. As a follow-up to these ventures, NASA MSFC started the Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) program. The program is still ongoing, but it aims to advance blown powder DED (BP-DED), develop composite overwrap technology, develop multi-metallic AM radial and axial joints, and advance analytical modeling [23]. So far, RAMPT has designed, manufactured, and tested several pieces of LP-DED hardware, overwrap chamber configurations, AM techniques for axial and radial bimetallic deposition, as well as AM techniques for material transitions[23]. With these programs, Marshall has made great strides in the advancement of additively manufactured rocket engines and has additively manufactured combustion device components such as injectors, regeneratively-cooled combustion chambers and nozzles, and pre-burners that have been capable of producing thrusts anywhere from 100 to 35K lbf [20]. MSFC has also designed, developed, and tested numerous lines of AM hardware including the Methane Engine Thrust Assembly for 4K lbf (META4) series and the Workhorse chamber liner series which utilized GRCop-84 and Inconel 625 [20]. They've also fabricated, and hot-fire tested 9 different monolithic, bimetallic, subscale nozzles using AM LWDC and integrated-channel LP-DED techniques. Since 2015, MSFC has fabricated and tested >50 GRCop-alloy combustion chambers with integral channels. A single GRCop-42 liner has also been tested with 168 starts and 7400 seconds of burn time [2]. The ultimate goal of these programs and tests is to advance the knowledge and experience base of AM LREs in order to disseminate the information to industry partners and make space travel more easily attainable.

IV. Chamber Liner Development and Design

The post processing techniques applied to the chamber hardware tested in this work include heat treatments, final machining, weldments, and various polishing methodologies described in a later section. All chambers were produced using GRCop-42 for the 7K and for most of the 1.2K chamber liners. Three of the 1.2K and all of the 1K chamber liners were produced using L-PBF GRCop-84. The figure below shows several instrumented test articles on the test stand for the various hot fire test projects considered in this work.

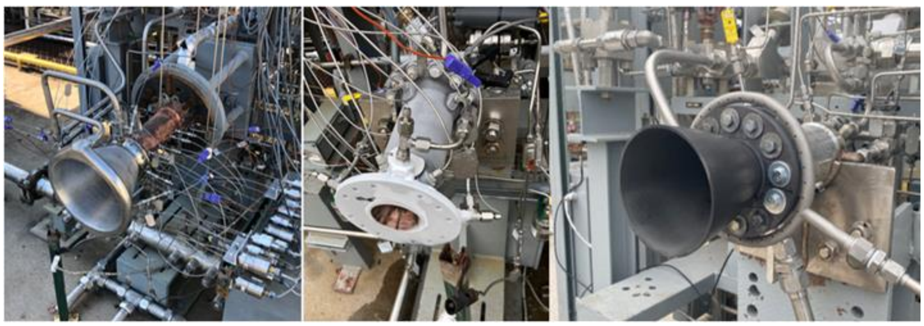

Fig. 4 (Left) 7k lbf class L-PBF GRCop-42 chamber and LP-DED HR-1 nozzle, (middle) 1k lbf class L-PBF GRCop-84 chamber, and (right) 1.2k lbf L-PBF GRCop-42 chamber and carbon composite nozzle.

Testing for all 7K and 1K TCAs was conducted in LOX/methane propellants with the methane fuel routed through a fully regenerative circuit as channel wall coolant. The 1.2K TCAs were conducted in LOX/hydrogen propellants with de-ionized water as the active coolant.

Regardless of thrust class or propellants used, the inlet and outlet temperatures and pressures were measured for the regenerative fuel and water coolants. These data sets are presented in the results section primarily in terms of total heat load, calculated peak hot wall temperature for select cases, and total pressure drop through the coolant channels. The net response of each chamber liner with various polishing techniques is also explored and expands on the previous work of the authors [26]. All chambers tested in this work were integrated with axial running square coolant channels with more information on their design and nomenclature in [27]–[29].

The following section describes the AM production process, post processing, and preliminary cold flow testing of L-PBF chamber liners.

A. L-PBF GRCop-Alloy Hardware Production

Regardless of thrust class, several AM vendors were used to produce the combustion chamber hardware. Once printed, the cooling channels were cleared of residual powder. The chambers were then computer tomography (CT) scanned as an additional check to ensure all channels were free of powder prior to HIP. Removal from the build plate is accomplished with wire EDM and final machining was then completed. The manifolds, typically built from GRCop-alloy, were match machined to their respective chambers. The applicable chamber/manifolds were electron beam (EB) welded, and the assembly waterproof and flow tested. The final operation was application of polishing techniques or surface enhancements. Images of the 7K lbf chamber hardware during fabrication process are shown below.

Fig. 5 L-PBF build process, chamber powder removal/heat treatment, EDM removal/EB manifold weldment/post-process polishing, and final product of a 7k lbf class chamber.

Flow and proof testing were conducted with water to check for any blockages, uniformity of flow, and to identify any leaks from porosity or build seams. Testing showed no major blockages of coolant channels and reasonable flow uniformity. The line head pressure was approximately 60 psi for low pressure tests. Waterproof testing was conducted up to 1400 psig and found that most chamber liners did not have any leakage. There were a handful of 7K chamber liners that did have hot wall leaks and closeout leaks due to a build seam. These chambers were still hot fire tested with no serious concerns. Images of a 7k LLAMA test article during flow and proof testing are shown in the figure below.

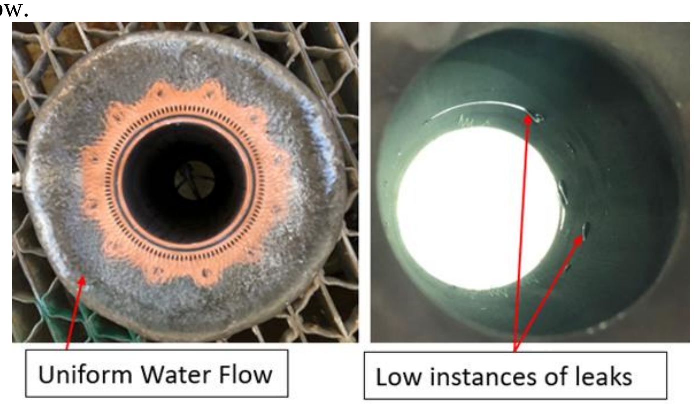

Fig. 6 (left) Results of 7k lbf LLAMA chamber liner with integrated manifold during water flow testing at water main line head pressure (~60 psi) and (right) waterproof testing at psig.

This figure provides a visual representation of ideal flow through the channels. Water is flowing freely from each coolant channel outlet with no visible signs of non-uniformity. Only slight “weeping” of water through the hot wall is visible at elevated pressures with no significant pin hole leaks. In a worst-case scenario, a single chamber was found to have approximately a dozen small leaks predominantly around build seams on the both the hot wall and closeout. These chambers were not considered for test due to structural weak points and significantly reduced coolant mass flow rates through the channels.

The following section describes the experimental design and varying thrust classes of AM GRCop-alloy chamber liner hardware.

V. Experimental Design and Facility

As mentioned above, three different thrust classes of GRCop-alloy chamber liners were hot fire tested over the course of several different projects at NASA MSFC. Each of these test articles were tested at test stand 115 (TS115), which is capable of supporting thrusts up to 10K lbf using cryogenic liquid oxygen as the oxidizer and various propellant fuel types such as hydrogen, methane, and RP-1. The facility is also capable of supplying high-pressure de-ionized water to the test articles for cooling and routing bypass regenerative cryogenic or gaseous propellants to a burn stack or dumped directly into the test article injector manifold. In addition, the facility has high-frequency data acquisition using piezoelectric pressure transducers and thermocouples. Various high-speed videography, infrared thermography, and multi-vantage point video / imagery is used during testing.

A. Test Article Description

The AM L-PBF produced 1.2K lbf chamber liners are a work horse LOX/GH2 combustion chamber used primarily as a scientific test article. This design has the capability to run for several hundreds of seconds in a single duration burn, to achieve multiple cycles in a single test, and to allow for quick changeout of chamber liners between tests. A rendered cross-section of a 1.2K lbf TCA is shown in the figure below with a carbon composite nozzle attached during a hot fire test at NASA MSFC.

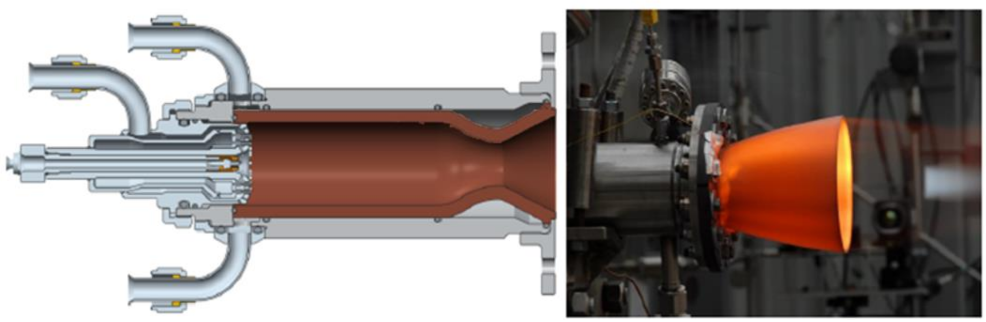

Fig. 7 Cross-section of 1.2K lbf chamber / injector and hot fire test with carbon composite nozzle [14]. Integral coolant channels not to scale.

The chamber liner shown in the figure above is a copper color while the surrounding housing is a 304 stainless steel housing or slip in jacket. The liner has an internal diameter of 2.5 inches in the barrel section and a 1.2-inch diameter throat. This design has the capability to attach an optional carbon composite or channel wall nozzle and heritage design shear coaxial injector. Lastly, this configuration is actively cooled with de-ionized water.

The AM L-PBF produced MET1 chamber liners utilize AM GRCop-84 and is not a quick-interchangeable liner like that of the 1.2K lbf chamber but can still be removed, post-processed, and re-configured on the stand within a very reasonable timeframe. This chamber is fully regenerative utilizing cryogenic CH4 as the coolant and is directly dumped to the injector fuel manifold. Tests performed include throttling to low mass flow rates, long duration operation at high mixture ratio, and even lean combustion.

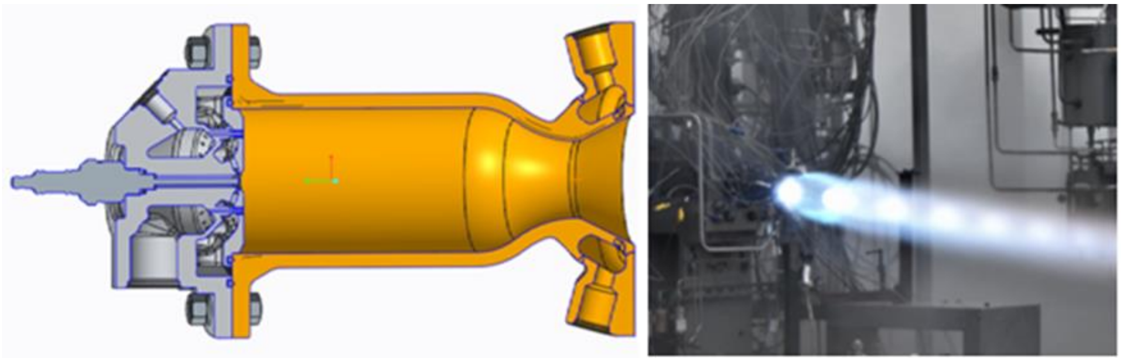

Fig. 8 Computer generated cross-section of 2k lbf chamber and hot fire test.

Finally, the 7K lbf chamber design utilizes an L-PBF AM GRCop-42 liner with variations on closeout material and geometry. This thrust class of chamber liner has many different configurations with nearly identical coolant channel geometry. The identifying acronyms for the chambers are Long Life Additive Manufacturing assembly (LLAMA), Advanced Lander Propulsion Additive Cold-spray Assembly (ALPACA), Composite Overwrap Methane Engine Thruster (COMET), and Methane Engine Thruster Assembly for 4k-lbf (META4X4). The META4X4 chamber was the first iteration to demonstrate proof of high-performance methane engine for 4K lbf (META4X4), however, this chamber liner can achieve thrusts up to 7K lbf with an optimized nozzle attached. The LLAMA, ALPACA, and COMET chambers were second generation versions of the META4X4 to demonstrate life cycle performance advantages with multiple starts and high duration burns, reduced mass savings through unique light weight closeout configurations, and achieve high characteristic exhaust velocity performance metrics in methane combustion. An image of each chamber liner is shown in the figure below.

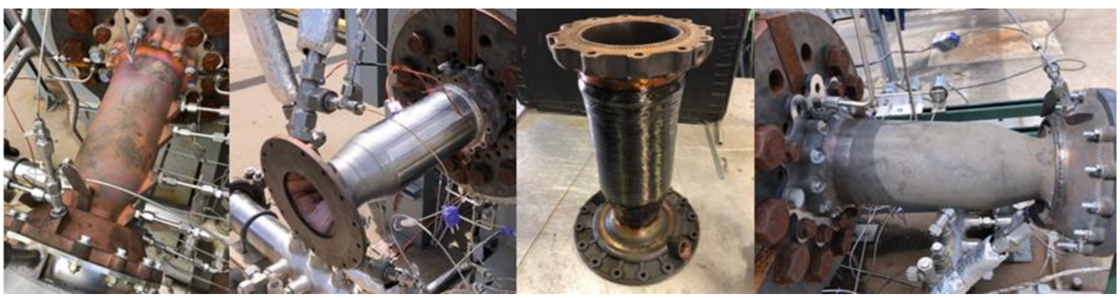

Fig. 9 7k lbf chamber liner configuration from left to right: LLAMA, ALPACA, COMET, META4X4

Each of these chambers are fully regenerative with cryogenic CH_4 as the coolant which is then directly dumped to the injector fuel manifold. A general cross-sectional image of the TCA is shown in the figure below along with a picture from hot fire testing.

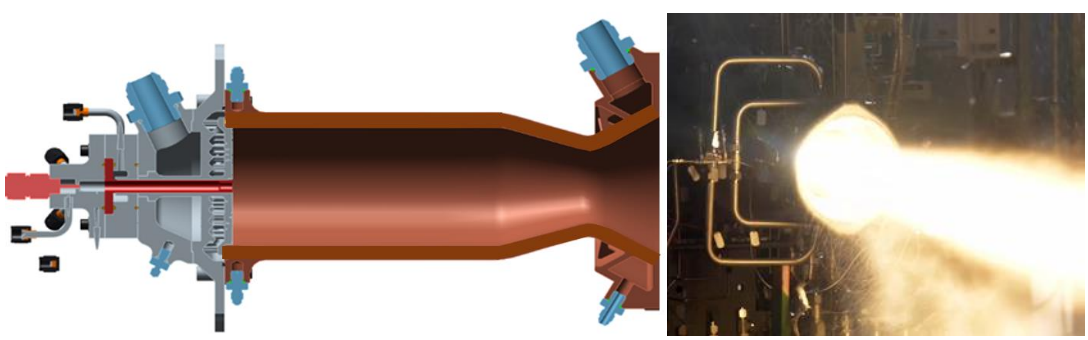

Fig. 10 Cross-section of 7k lbf chamber/injector and hot fire startup transient test with channel wall NASA HR-1 nozzle.

Each of the test articles described above have accumulated several thousands of seconds of mainstage duration and multiple restarts across a range of equivalence ratios and chamber pressures. Some of the experimental data obtained during hot fire test was from long duration burns and some from cyclic testing. In all cases, data was taken near the end of the run or during thermal steady state conditions.

B. Polishing Types and Methodologies

Polishing of the chamber liners was achieved by several means including CMP, chemical milling (CM), abrasive flow machining (AFM), and manual polishing (MP), or a combination therein. The specific section in the chamber that was polished is also indicated including the barrel section (B), the throat section (T), the nozzle section (N), a combination of each, or in the coolant channels (CC).

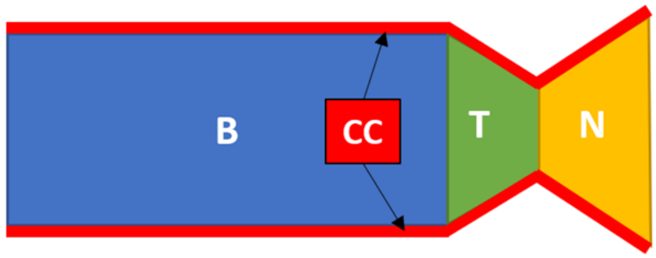

Fig. 11 Visual representation of chamber sections subjected to various polishing methodologies. [Barrel section (B), throat section (T), nozzle section (N), a combination of each, or in the coolant channels (CC)].

Several examples of the pre and post polished chamber hot walls are shown below. The reader is referred to Ref. [26] for a better understanding of the as-built surface finish of several different L-PBF GRCop-alloy test articles and their polished states.

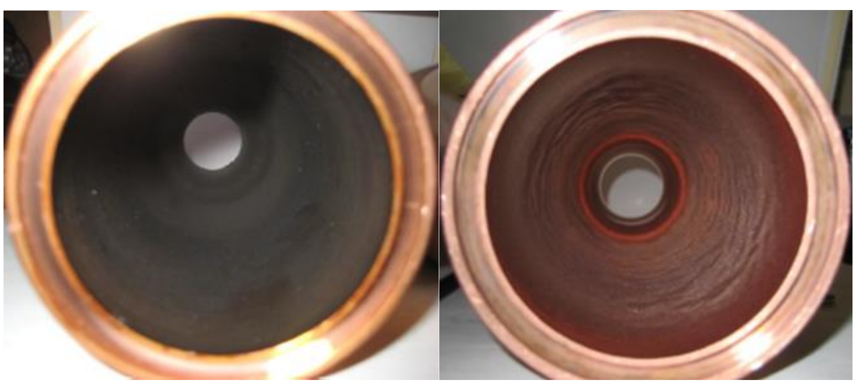

Fig. 12 L-PBF GRCop-42 1.2k lbf chamber liner as-built hot wall (left) and chemical mechanically polished (right) throughout the entire chamber hot wall.

The chamber in the figure above was measured to have an average surface roughness of about 400 micro inches (Ra) prior to CMP and a surface roughness of about 74 micro inches (Ra) post CMP. This chamber was sent to the vendor to have the hot wall in one chamber liner AFM processed and the coolant channels in another chamber undergo the same process. A tolerance of approximately 0.003" of material was targeted for removal from the wall. The low tolerance left some "rippling" or valleys of slightly rougher regions and plateaus of significantly higher quality surface finish.

The figure below shows the surface finish quality attained using MP methodologies such as abrasive scouring pads similar to Scotch Brite on the throat section of the MET1 GRCop-84 chamber.

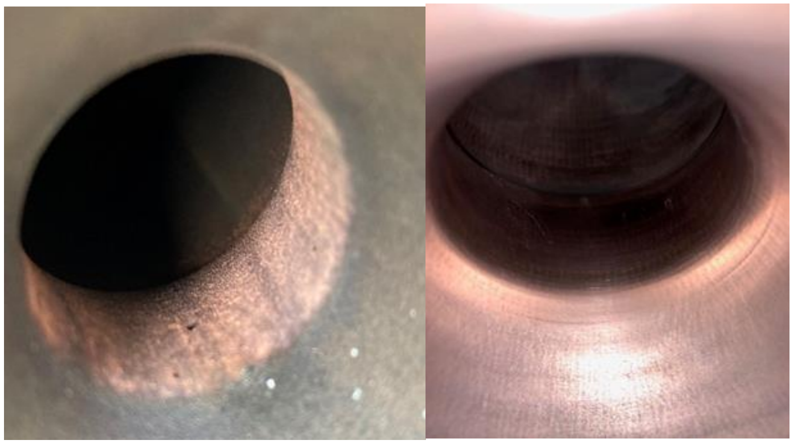

Fig. 13 Surface finish of AM GRCop-84 2k lbf throat section pre-manual polish (left) and post-MP (right).

Qualitatively speaking, this polishing method produced a very high-finish polish with minimal setup and was completed in approximately 30 minutes. It is an extremely cost-effective method with no observable detriment to any TCA performance metric after hot fire testing but does rely on manual methods and repeatability needs to be fully determined. This identical process was applied to a single 7K chamber liner as described in the results section.

Similarly, flexible cylinder hones were used to mechanically polish the barrel and throat sections of each chamber with consecutively increasing grit quality. The grits used were classified as 180, 320, 600, and 800 and were all procured from standard hardware supply vendors in various sizes to appropriately fit the specific chamber desired. The end result of cylinder honing compared to an as built hot wall is shown in the figure below.

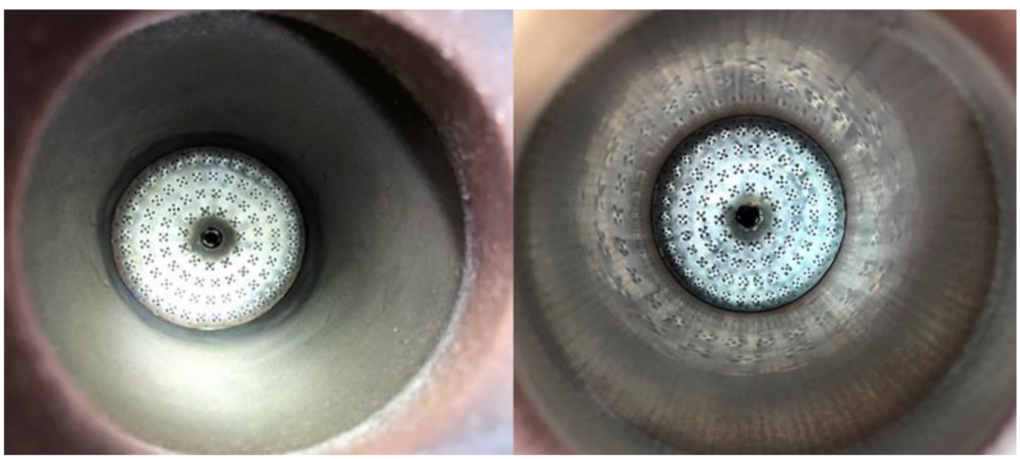

Fig. 14 As built hot wall surface finish (left) and final results of honing bit hot wall polishing (right).

The example 7K chambers were of the identical chamber prior to and post cylinder honing. Qualitatively, the chamber liners' surface roughness was substantially improved. The surface roughness after polishing was found to be approximately 10-40 micro inches (Ra), however, these results were obtained with significant difficultly and only at the first half inch at the injector interface. It is expected that the actual on average surface roughness is somewhat less than these measured values. This method was also extremely cost effective and easily applied within the span of 30 minutes between hot fire tests in the same day.

Finally, CM and CMP was applied to several chamber liner's hot wall as well as coolant channels from various external vendors. Qualitatively speaking, the surface finish appeared to be similar to what was achieved with the cylinder honing methodology described above, at least on the hot wall. However, the primary advantage of these methods is their use in difficult access locations such as the integrated coolant channels. Previous results using CM alone found a significant reduction in the total pressure drop through the coolant channels [26]. Application of CMP may result in an even better reduction in pressure drop.

Images of these flexible cylinder hones along with the abrasive pads and a 7K test article being CM/CMP processed through the coolant channels and hot wall are shown below.

Fig. 15 Honing bits used on all chamber liner hardware thrust classes (left), Scotch Brite abrasive pads (middle), and chemical mechanical polishing setup (right).

VI.Results and Discussion

To date, hot fire testing of GRCop-alloy chamber liners has been highly successful and demonstrated substantial performance advantages with the technology development path. For one, the additive hardware has demonstrated exceptional improvements to programmatic cost, schedule, and simplification of development tasks when compared to equivalent traditional manufacturing methods. Combustion, flow, and life cycle performances have also been demonstrated to be equivalent or greater than the state of the art (SOA) traditionally manufactured TCAs. In addition, AM affords a designer to specifically tailor and modify existing chamber liner performance metrics. Alteration of the hot wall surface roughness, for example, extends the life cycle performance of the hardware by decreasing the severity of thermal cycling. To give the reader an idea of hot fire test statics for GRCop-alloy chamber liners to date, a table is provided below with all projects and programs that used this AM technology.

Table 1 Hot fire test statistics for NASA AM GRCop-alloy chamber liners.

NASA Test Series	Dates Conducted	Total Starts	Cumulative Duration (sec)
PK111	05/2021-06/2021	24	1763
PK076	03/2021-04/2021	15	741
PK129	01/2021-02/2021	48	822
PL013	11/2020-12/2020	13	1198
PK058	10/2020-11/2020	24	345
PJ030	08/2020-09/2020	15	94
PK020	10/2019	6	780
PJ141	10/2019	15	2448
PI100/PJ038	06/2019	188	8030
PJ026	03/2019	14	83
PI084	02/2019	18	622
PJ024	12/2018	20	880
PI043	10/2018	20	2210

PI051	04/2018	9	106
PH135	02/2018	17	141
PF086	11/2017	12	147
PH171	11/2017	15	2193
PH034	11/2017	14	1055
PH127	08/2017-09/2017	5	21
PG055	03/2017	4	26
PG034	11/2016	25	2365
PF037	05/2015	12	34
Totals	**22 Test Series**	**533***	**26,105***

*PJ062 currently underway during writing of this paper.

The statistics presented above bolster AM GRCop-alloy chamber feasibility for use in development and potential use in flight systems. The following sections presents peak hot wall temperatures for select hot fire tests.

A. 7k Chamber Liner Performance Results

Several 7K lbf GRCop-42 chamber liners were tested and their performances evaluated for this work. Each of these chamber liners were produced using the AM L-PBF process but at different vendors. They were also tested in their as-built surface finish and some were tested in a post-process polished state on their hot walls as previously outlined. Each chamber liner was produced with identical coolant channel geometry but with slight differences in the closeout thickness and hot wall thickness. Finally, since there were differences in geometry, each chamber was given a unique name pursuant to the original program goals. These are ALPACA, LLAMA, META4X4, and COMET. The coolant inlet and outlet conditions were measured, and the total heat load calculated using NASA CEA calls. Each value was then scaled using Bartz equation to similar operating conditions of 700 psia, with a total fuel mass flow rate of 5.0 lbm/s, and to a mixture ratio of 2.7. These scaled total heat loads as a function of test # are shown in the figure below followed by a plot of coolant channel pressure drop as a function of test #.

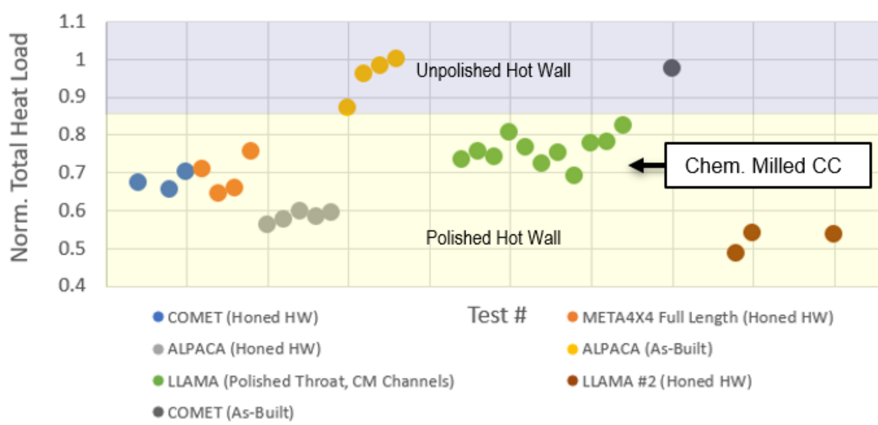

Fig. 16 Scaled total heat load (BTU/s) as a function of test # for similar operating conditions and chamber liners with various polishing techniques applied in the coolant channels (CC) and hot wall.

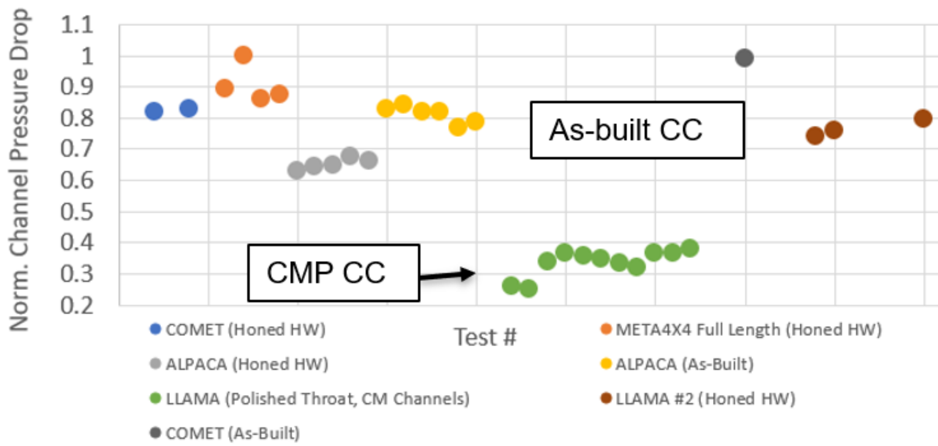

Fig. 17 Coolant channel pressure drop as a function of test # for different chamber liners.

Several inferences can be made from these data. First and most importantly, it was found that polishing of the hot wall, regardless of methodology, substantially reduced the total heat load to the regenerative coolant. In addition, the pressure drop through the coolant channels was also substantially reduced. These findings are not surprising but rather expected. Comparing similar chamber liners in their polished versus unpolished states reveals further information on how much a reduction in heat load is expected. These reductions in total heat load as a percentage are listed below.

Table 2 Average percentage reduction in scaled total heat load and coolant channel pressure drop with various polishing methodologies.

Chamber Liner	% Reduction in Total Heat Load	% Reduction in Pressure Drop
LLAMA	32	56
ALPACA	39	21
COMET	31	17
META4X4	N/A*	N/A*

*Not tested in the as-built state.

The ALPACA chamber was the only chamber liner that was hot fire tested in its as built state and polished hot wall state within the span of a week. The entire hot wall was polished using a cylinder honing bit as described previously. As such, the scaled total heat load and coolant channel pressure drop were found to decrease by 39% and 21%, respectively. Based on previous findings from [26], this would suggest that polishing of the throat section alone would reduce the total heat load anywhere from 8-13% depending on channel geometry.

The COMET chamber was also tested in its as-built condition on the hot wall as well as in a completely polished state using the same honing methodology. However, the injector type was different from the original and demonstrated a significant improvement in C* efficiency. This is expected to contribute to total heat load to the coolant and skew the expected % reduction in heat load. As such, the % reduction in scaled total heat load and pressure drop was found to be 31% and 17%, respectively. These values are lower than those of the ALPACA chamber, but not unexpected due to the difference in injector performances.

The LLAMA chambers that were tested were more difficult to compare than the previous two chambers. The original chamber was polished using scotch Brite pads in the throat section to reduce the onset of blanching. An image of the chamber throat before and after polishing is shown below.

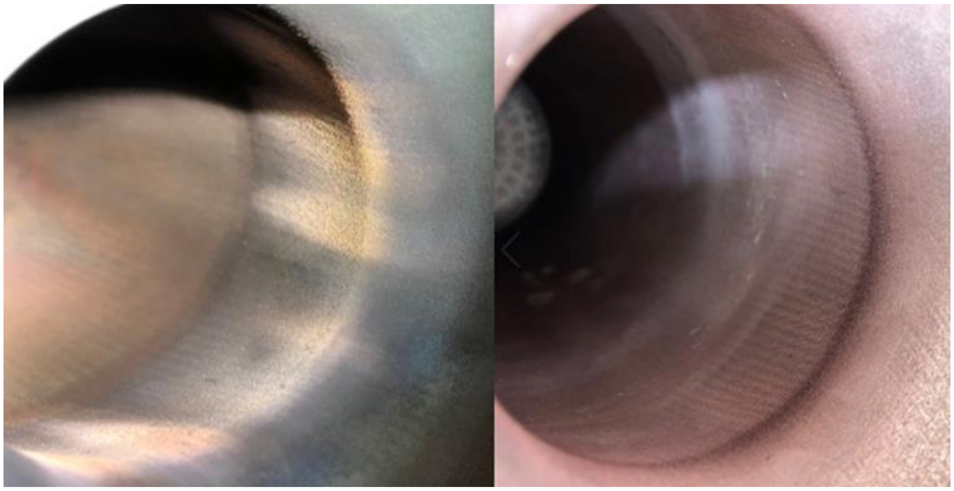

Fig. 18 7k lbf LLAMA chamber liner throat before polishing with significant blanching and streaking (left) and after polishing using Scotch Brite abrasive pads (right).

The polishing alone would reduce the total heat load to the coolant by an expected percentage. In the above figure, it shows that a partial section of the barrel was also polished and that would further contribute to a reduction in total heat load. Finally, it must be noted that the coolant channels were chemically milled to reduce the overall pressure drop in the original chamber liner. The chamber liner tested in the completely polished state had a different closeout material from the original but had identical hot wall and coolant channel geometry. The on average surface roughness was found to be slightly higher compared to the original chamber liner. This was due to differing build parameters from a new vendor compared to past builds. Regardless of this dissimilarity, comparisons can still be made since it is expected that alteration of coolant channels surface roughness would not impact the total heat load by an appreciable amount according to [26], [30].

The % reduction in scaled total heat load and pressure drop was found to be 32% and 56%, respectively. In post-test analysis both LLAMA chambers tested were found to have several hot wall leaks which would have reduced the total coolant mass flow rate and subsequently increase the total heat load. Qualitatively, the severity of hot wall leaks were nearly identical during waterproof testing of the chamber liners and can thus be neglected. With that said, the reduction in scaled total heat load was found to be comparable with the COMET and ALPACA chambers. It is expected that the % reduction in total heat load would be higher and more akin to that of the ALPACA chamber if the throat section had not been polished. The pressure drop % reduction through the coolant channels was significantly higher than that of the other chambers but is a product of chemical milling and heat load reduction. If this chamber were compared with another chamber that had identical coolant channel geometry, then the resultant % reduction in pressure drop would still be in the range of 50% or higher. Further investigation is needed to understand how the severity of hot wall leakage altered the heat load and pressure drop performances of chambers with chemical milling processes applied in their coolant channels.

C. 1k Chamber Liner Performance Results

Three variations of MET1 chamber liners were hot fire tested in support of the human lander system (HLS) program and other internal NASA projects. Experimental data was obtained from each chamber liner and are presented in this section.

The original MET1, modified MET1-A, and MET1-C chambers were all similar in geometry but with slight differences. The MET1-A and MET1-C had a slightly larger L* of 25 inches compared to the original MET1 with an L* of 20 inches. The increased L* was a result of extending the barrel section thus lengthening the coolant channels by approximately 2 inches. The modified chambers had a slightly less restrictive inlet in an attempt to reduce the coolant channel pressure drop. Finally, the MET1-C chamber had a scalloped hot wall that yielded a total hot wall surface area of 110% that of the MET1-A. Hot fire test data allowed for measurement of the total heat load to the coolant which was then scaled in the identical manor as was done for the 7K data in the previous section. The scaled total heat load and scaled pressure drop through the coolant channels.

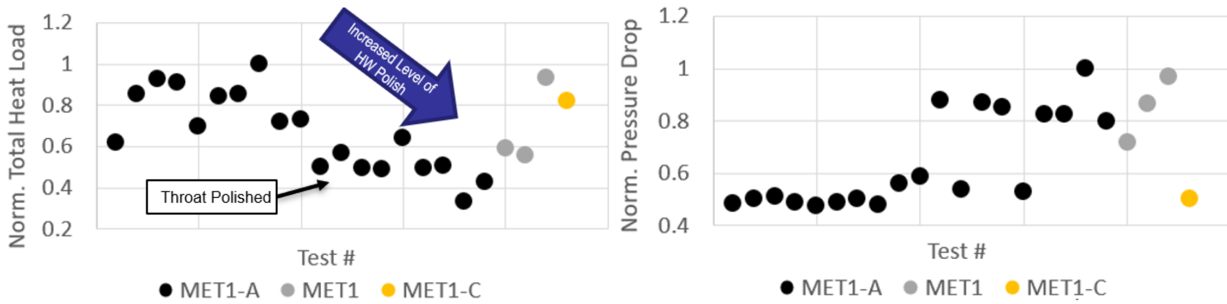

Fig. 19 Scaled and normalized total heat load to the coolant (left) and normalized pressure drop through the coolant channels (right) as a function of test #.

The total heat load to the coolant was scaled via Bartz equation presented in [30] to a common chamber pressure of 400 psia, mixture ratio of 3.5, and fuel coolant mass flow rate of 1 lbm/s. The pressure drop through the coolant channels was scaled to 1 lbm/s according to Bernoulli's equation. Several trends can be seen in the hot fire test data. First, a steady decrease in the total heat load to the coolant occurs as the total test duration and starts increase. It is important to note that between tests 10 and 11, the throat section of the MET1-A chamber was polished using the identical methodology as for the 7K LLAMA chamber. An image of this polishing before and after in the MET1-A is shown in Fig. 13. Finally, the entire hot wall of the chamber liner was honed for tests 18 and 19. Drops in the total heat load were observed in tests after each polishing methodology was applied. The average % reduction in total heat load was calculated for each polishing method applied and presented in the table below.

Table 3 Average percentage reduction in scaled total heat load and % increase in coolant channel pressure drop with various polishing methodologies.

Chamber Liner	% Reduction in Total Heat Load	% Increase in Pressure Drop
MET1-A (throat polish)	35	31
MET1-A (full polish)	53	24
MET1-C vs. MET1-A	Comparable	Comparable
MET1 vs. MET1-A	15	64

As shown in the table above, there are clear and substantial reductions in total heat load to the coolant when the chamber liners throat and entire hot wall are polished. However, it was found that the pressure drop through the channels actually increased. This is likely due to the integrated channel restrictions which do cause a substantial amount of resistance. Finally, the MET1-C chamber yielded very similar results to MET1-A but with only one data point to compare. Further investigation is needed to quantify the differences in chamber hot wall geometry.

D. 1.2k Chamber Liner Performance Results

This work expands on the results from previous efforts [2] to quantify the reduction in total heat load with various polishing techniques in addition to impacts on channel pressure drop and resistance. Several 1.2K AM L-PBF GRCop-42 and GRCop-84 chamber liners were produced, post-process polished, and hot fire tested. Several of these chambers were hot fired in that previous work [2]. Their results are presented in this section.

Several post-process polishing techniques were applied to these chambers in their coolant channels as well as on their hot walls. Qualitatively speaking, the chamber liners produced with GRCop-84 had a much higher quality of surface finish in the as built state compared to the GRCop-42 chamber liners. This was more a function of the vendors build process parameters than material. Thus, data will not be comparable between chamber liners with different material. A matrix of these chambers and polishing processes along with accumulated test durations and starts to date are shown below.

Table 4 1.2k AM GRCop chamber liner test and post-process configurations.

AM Vendor	GRCop Material	Unit	Hot Wall Polish	Channel Polish	Hot-Fire Duration to date	Starts to Date

3DMT	42	4	MP/CM	CM	142	3
3DMT	42	5	CMP	As Built	307	7
3DMT	42	6	MP/CM	CM	501	5
ASRC	84	2	CM	CM	182	3
ASRC	84	3	As Built	AFM	212	3

The scaled total heat load, channel pressure drop, and channel resistance as a function of test for all chamber liners considered in this investigation are presented in the figures below.

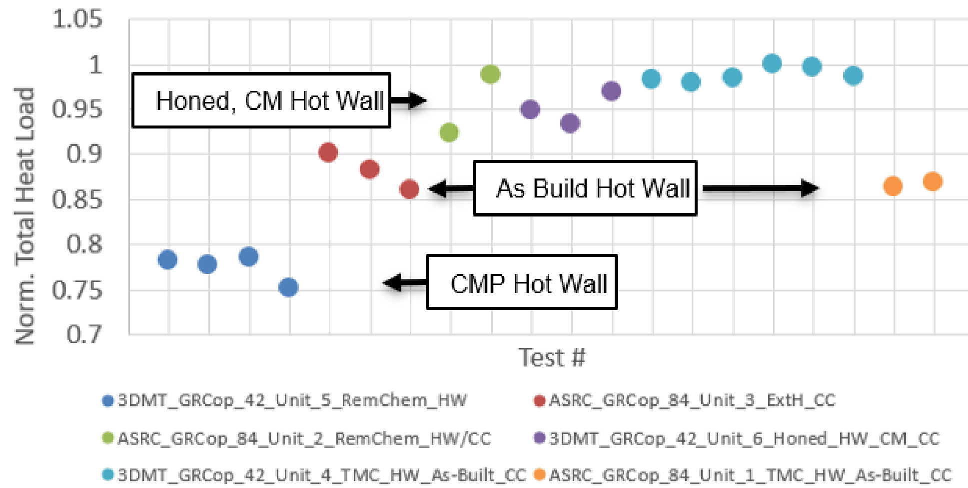

Fig. 20 Scaled and normalized total heat load as a function of test # for all 1.2k lbf hot fire tests.

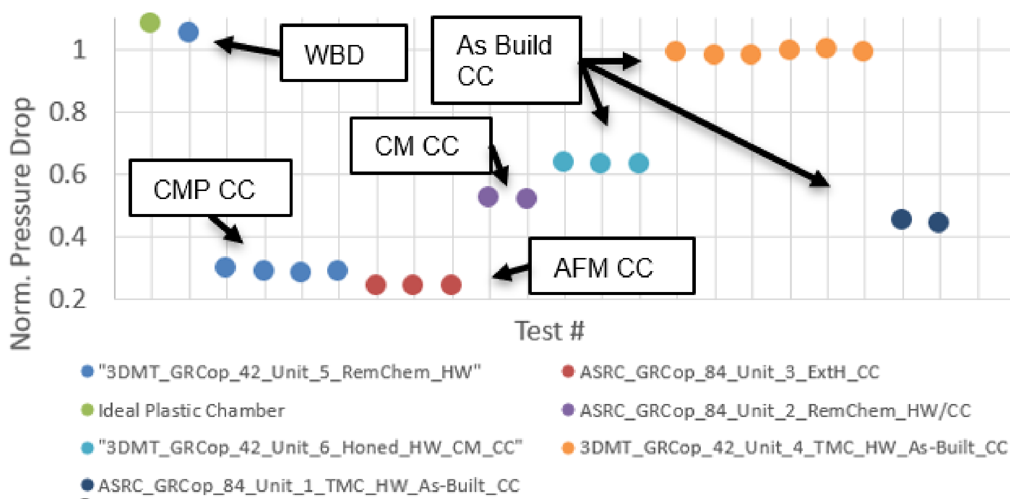

Fig. 21 Scaled channel pressure drop as a function of test # for all 1.2k lbf hot fire tests.

One goal of this work and the previous work [2] is to demonstrate that a reduction in coolant channel pressure drop does not impact the total heat load to the coolant by a significant degree. Two chambers labeled unit 6 and unit 3 were maintained on the hot wall, hot fired with as built coolant channels, polished in the coolant channels, and retested. Unit 6 had a CM process applied to the channels while unit 3 had the AFM process applied to the channels. The total reduction in pressure drop for unit 6 was found to be about 40% and for unit 3, 58%. However, the total heat load to the coolant was within margin of error prior to and post chemical milling. This shows that the impact of polishing the coolant channels on total heat load is minimal and validates theory presented in [2]. Furthermore, a reduction of pressure drop by 40% and 58% is significant and highlights two effective means to improve flow performances in regenerative AM combustion devices.

Next, the impact of AFM and CMP processes applied to the coolant channels can be compared. Both methods targeted a material removal of about 0.003" from the coolant channel diameter. The data shows that the CMP process reduced the pressure drop by 71%. As discussed above, the AFM process reduced pressure drop by 58%. However, this chamber already consisted of a high-quality surface finish due to the vendors process parameters. The AFM processed chamber did demonstrate a lower pressure drop than the CMP processed chamber suggesting that further flow performance improvements are possible with the CMP process. A material removal target of 0.005" may allow for full capturing of the best possible flow performance in this geometry. This begs the question, what is the best possible flow performance? To elucidate this, a replica ABS plastic 3D printed chamber with identical geometry coolant channels was produced. This chamber was processed in the channels using an acetone solution that yielded extremely high-quality surface finishes on other ABS plastic components. The coolant channels in this replica were thus considered to be near ideal and should produce the lowest possible pressure drop for this geometry. The replica was then water blow down (WBD) tested to obtain the cold pressure drop. Chamber unit 5 was also WBD tested for comparison. The replica produced a slightly lower pressure drop than the real chamber. It is likely that the chambers with AFM and CMP polishing have obtained 95%+ the flow performance benefits using these techniques. Further investigation with higher material removal tolerances may yield better results and will be assessed after the release of this work.

Finally, the total reduction in heat load to the coolant was assessed for a single chamber with its as built hot wall and CMP polished hot wall, unit 5. The reduction was found to be about 28% which is consistent with the findings of [2]. To further bolster the data presented above, the calculated resistances for each test are shown below.

Table 5 Average percentage reduction in 1.2k chamber liner performance parameters.

Comparison	% Change in Total Heat Load	% Change in Pressure Drop
As-Built CC vs. CM CC	No Impact***	40
As-Built CC vs. AFM CC	n/a**	58
As-Built CC vs. CMP CC	n/a**	71
As-Build CC vs. Ideal	n/a**	Likely > 75
As-Built HW vs. AFM HW	6****	-
As-Built HW vs. CMP HW	28	-

*CC = coolant channels, HW = hot wall, AFM = abrasive flow machining, CM = chemical milling, MP = mechanical polishing.

**Not tested

***No apparent impact on total heat load.

****Calculated but likely had little impact.

VII. Summary and Conclusions

Data was obtained from three different NASA thrust chamber assemblies in LOX/H2 and LOX/CH4 propellants. Four 7K lbf chamber configurations and three 1K lbf chamber liner configurations utilized regenerative cryogenic methane for the coolant and a 1.2K lbf chamber liner configuration used de-ionized water as coolant with LOX/H2. To highlight the success with GRCop-alloy chambers a single GRCop-42 7K lbf chamber achieved 51 starts at 973 seconds of cumulative mainstage duration. In addition, a single GRCop-84 1.2K lbf chamber liner achieved 168 starts at > 7400 seconds of cumulative mainstage duration. It was found that polishing of the hot wall on 7K chambers reduced the total heat load to the coolant by as much as 39% when compared to the as built surface roughness. The pressure drop through the coolant channels was reduced by 56% after polishing techniques in the channels were applied. In addition, several key conclusions were taken from hot fire testing of AM GRCop-alloy chamber liners which are summarized below.

- Polishing of the hot wall qualitatively extends chamber life cycle performance metrics. The severity of chamber discoloration at similar operating conditions suggests lower material temperatures.
- Polishing of the coolant channels is only feasible via chemical or abrasive flow machining techniques and substantially extends the liquid engine system performances by reducing pressure drop. Other techniques may be applicable but were not explored in this study.

- There was no significant difference in total heat load reduction when comparing various methods for hot wall polishing if the surface roughness is below approximately 100 micro inches (Ra). As such, the most cost-effective means for polishing that meets this criterion may be preferred.
- Changes in the total heat load to the coolant for regenerative cycle chamber liners will cause alteration to the combustion performance. Thus, downstream components, such as injectors, will need to be designed to the desired total heat load.

These conclusions give valuable insight into future combustion device designs towards maximizing their performance metrics. AM GRCop-alloy chamber liners represent an effective technology for future flight vehicle propulsion system components.

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