LOW COST GLASS-CERAMIC MATRIX COMPOSITES FOR HARSH ENVIRONMENT HEAT EXCHANGER APPLICATIONS

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ABSTRACT

High-temperature, high-pressure heat exchange is a ubiquitous need in power generation, industrial components and aerospace systems, including supercritical CO2 cycles. In these applications, higher cycle temperatures and pressures provide a significant driver to overall thermal efficiency and fuel consumption as well as a challenge to metallic material capability. To enable operation in these harsh operating regimes, United Technologies Research Center (UTRC), Materials Research and Design (MR&D) and Oak Ridge National Laboratory (ORNL) are developing a high temperature, lightweight, low-cost heat exchanger technology made from a Glass-Ceramic Matrix Composite (GCMC) material system, denoted UT-16, which is capable of long operational life over a wide range of harsh environments. While this GCMC material system is broadly applicable to a variety of high temperature components, this effort focuses on the development and demonstration of a Counterflow Tube Heat Exchanger (CTHX). The CTHX geometry has been configured specifically for the GCMC material which can be fabricated orders of magnitude faster than most conventional CMCs. The as-fabricated material has extremely low porosity resulting in very low leakage rates and can also be coated with a chemically inert layer for additional protection.

1. INTRODUCTION AND MOTIVATION

1.1 Introduction

The utilization of high-temperature, high-pressure heat exchange is an abundant requirement in power generation and industrial applications, including steam cycles, supercritical CO2 (SCO2) cycles, industrial gas turbines, and thermal rectifiers. In these applications, higher cycle temperatures and pressures remain a significant driver to overall thermal efficiency and fuel consumption. To enable operation in these harsh operating regimes, United Technologies Research

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Center (UTRC), Materials Research and Development (MR&D) and Oak Ridge National Laboratory (ORNL) are developing a high temperature, high strength, and low-cost heat exchanger (HX) technology made from a Glass-Ceramic Matrix Composite (GCMC) material system, denoted UT-16, which is capable of long operational life over a wide range of harsh environments. While this GCMC material system is broadly applicable to power generation components, this development program utilizes a Counterflow Tube Heat Exchanger (CTHX) configuration as the specific demonstration application. Figure 1 overviews the GCMC heat exchanger concept and enabling technologies under development.

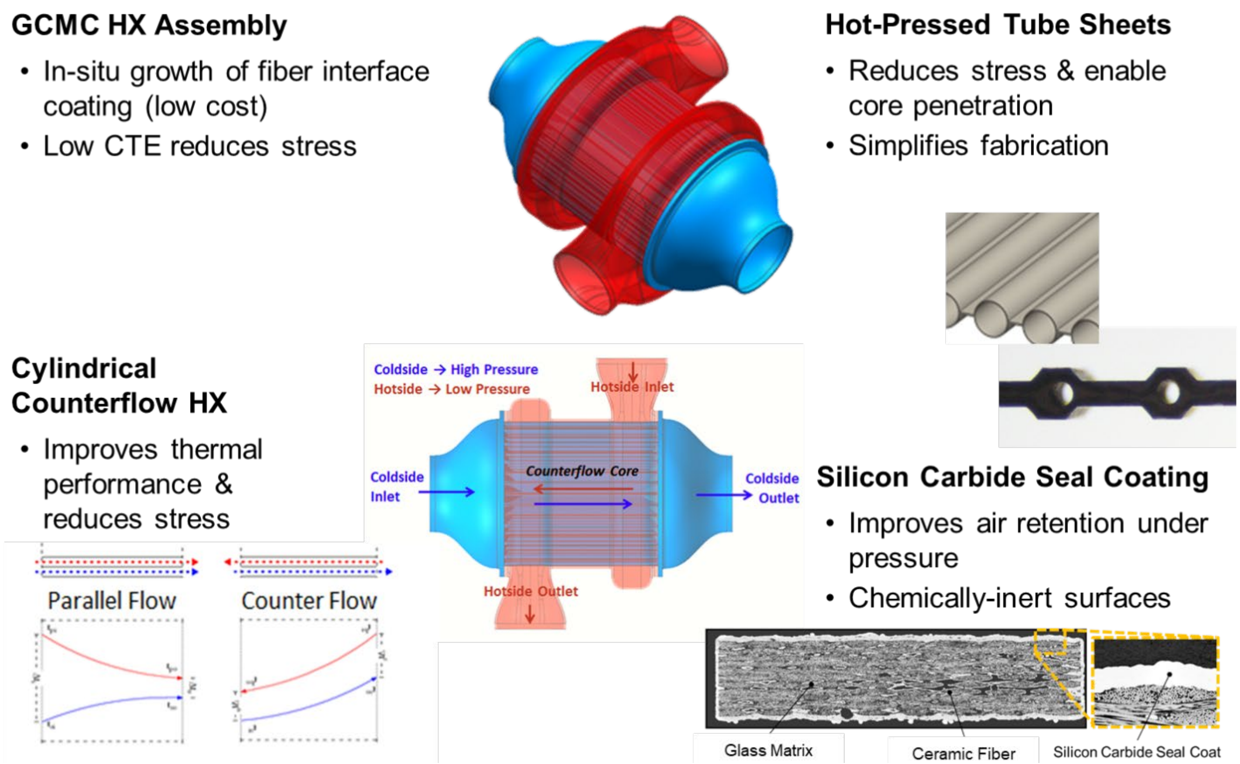


Figure 1. GCMC heat exchanger concept overview showing key technologies.

The CTHX geometry has been configured specifically for the GCMC material and its manufacturing approach. The CTHX features cylindrical components and arrays of simple webbed-tubes and baffles to simplify manufacturing and assembly and to reduce stresses from pressure loads and thermal growth. The CTHX eliminates nearly all secondary surfaces in the HX, increasing thermodynamic performance and substantially deemphasizing material thermal conductivity, thereby reducing the cost of the GCMC by eliminating the need for costly additives.

Chemical Vapor Infiltration (CVI) of Silicon Carbide (SiC) is also being explored as a multifunctional surface coating to provide a chemically-inert and air-tight seal on HX surfaces. The program is being supported by the U.S. Department of Energy-Advanced Manufacturing Office (DOE-AMO) and leverages prior U.S. Department of Defense and United Technologies Corporation (UTC) investments in low-cost GCMC materials, high-effectiveness HX architectures, and chemical-resistant air-barrier seal coatings.

1.2 Motivation

The project goal is to develop and demonstrate heat exchanger technology capable of long operational life in an approximately 1600°F (871°C) and approximately 1000 psi (6.89 MPa) differential pressure (between hot and cold HX sides) operating environment at a cost and reliability consistent with commercialization requirements.

Reaching the higher efficiencies of SCO2 cycles has been challenging due to the high temperature and pressure limitations of metallic superalloy HX materials, so if successful, it is expected that GCMC HX technology will help to increase the impact of SCO2-based power generation systems. The higher operating temperatures enabled by GCMC can also reduce HX volume by 2.5X compared to a lower-temp Inconel HX of equivalent capacity and increase cycle thermal efficiency by 3-5 points based on system model predictions. In addition, the use of GCMC may provide a system volume reduction ~ 60%, weight reduction ~ 85%, superior durability, and lower cost.

Baseline performance goals for the program also includes demonstration of low internal cold-to-hot side leakage <0.1% to ensure negligible impact on recuperator effectiveness and cycle efficiency. The program has performed a preliminary demonstration of HX durability over 20 high temperature thermal cycles with leakage rates remaining orders of magnitude below 0.1% target.

2. MATERIAL R&D BACKGROUND

UTRC is the central R&D organization for UTC, and has extensive expertise in the development of CMC material systems and their fabrication in support of UTC's aerospace businesses (Pratt & Whitney, Collins Aerospace). UT-16 and similar fiber-reinforced GCMC material systems were originally developed at UTRC in the 1980s for high performance aerospace components [1-3].

Figure 2 shows several UT-16 components successfully produced for these applications, replacing nickel-based superalloy components. More recently, HX tube-sheets were successfully prototyped. The CTHX architecture has been studied extensively at UTRC using CMCs as well as conventional materials/manufacturing and 3D printing. Thermal-fluid models have been developed and validated for low temperature applications, improving the confidence of performance predictions in the program.

Misc Disks, Cones and Platefin HX Prototypes

Fintube Prototypes for GCMC HX

Figure 2. Various UT-16 GCMC components, including tube-sheet prototypes for GCMC HX.

ORNL has extensive experience in Chemical Vapor Deposition (CVD) and CVI of SiC and other high temperature ceramic coatings for a variety of applications, including advanced nuclear fuel kernels, SiC/SiC CMCs for gas turbine engine applications, and fuel elements for nuclear thermal propulsion for space power. ORNL also has extensive experience in CVI of SiC matrices for SiC/SiC CMCs, and participated heavily in developing the modern CMCs that are currently in-service on aircraft.

For thermo-mechanical composites design, MR&D has decades of experience in CMC design and manufacturing. MR&D has successfully designed CMCs and components for extreme environment applications including engine turbine vanes, combustion liners, thrust chambers, exit cones, nozzle extensions, and thermal protection and hot structure control surface components for numerous hypersonic vehicles.

One can compare potential material choices for these operating conditions between metallic superalloys, monolithic ceramics, and ceramic matrix composites (CMCs). Metallic superalloys represent the conventional approach to high temperature and pressure HXs, but are expensive, have temperature limitations, and have limited operational life due to large thermal expansion and creep. Monolithic ceramics offer higher temperature capability, low thermal expansion and excellent chemical resistance, but are flaw sensitive (brittle), difficult to shape into intricate features, and present scaling challenges. Conventional CMCs have favorable properties, but are extremely expensive and issues with air retention precluded their commercialization.

3. MANUFACTURING

3.1 Processing Overview

Figure 3 shows a flowchart of the GCMC manufacturing process. As illustrated in Figure 3, ceramic fibers are impregnated with an aqueous slurry – typically containing glass powder and an organic binder – and wound into tapes to create a pre-impregnated or “prepreg” tape material. After the prepreg tape is created, individual plies are cut from the prepreg tapes and stacked in a laminated structure. The binder is then removed and the tape layup is loaded into the tooling die.

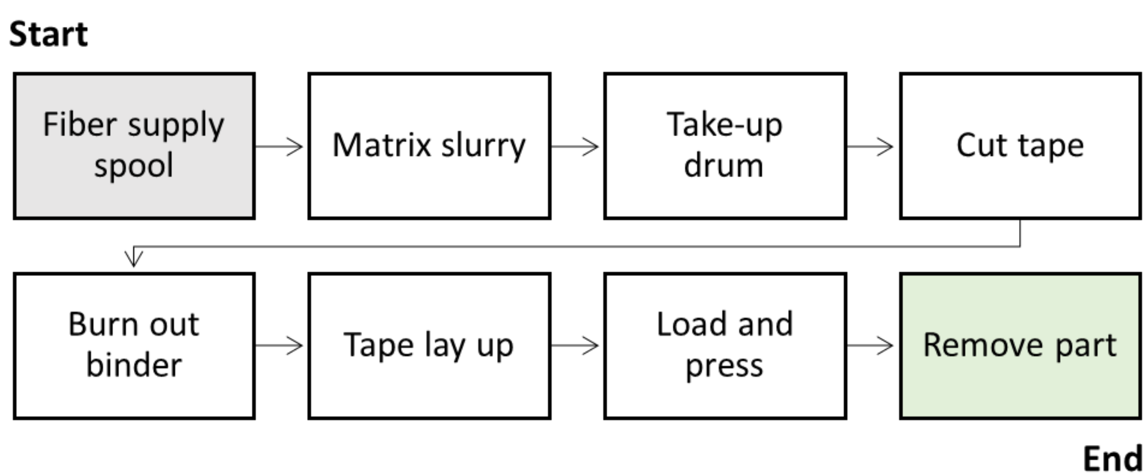


Figure 3. A flowchart of the GCMC manufacturing process.

The die is placed into a hot press and heated under high vacuum until the glass is molten. Pressure is applied and the GCMC is consolidated via molten glass flow. After consolidation, secondary operations may include heat treatments and final machining if necessary. Parts can additionally be subjected to a CVI SiC seal coat. Much of the tooling dies are also typically reusable.

3.2 Die Assembly and Tube-Sheet Forming

Figure 4 illustrates the design, build, and analysis workflow of HX tube sheets. Prototype tube-sheet samples have been fabricated and analyzed using optical microscopy and microCT imaging. A set of tube-sheets was manufactured using tooling to define passages and create external geometry. Multiple samples have also been produced with different fiber architectures. One of these panels is shown in the as-molded condition in Figure 4 (Center).

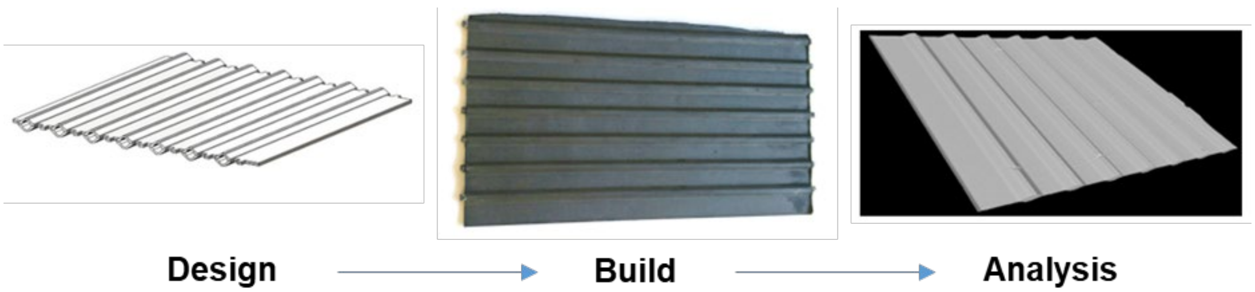


Figure 4. A schematic of tube-sheet design, build, and analysis workflow. Tooling is used to form GCMC HX geometry during hot pressing.

Figure 5 (Left) shows an image of a headered tube sheet. The header regions provide mechanical support for pressure testing. Figure 5 (Right) shows a schematic view of a headered tube sheet in a pressure testing assembly. Initial pressure testing was performed at ambient temperatures with water. Future testing aims to demonstrate high temperature and high pressure testing with gas.

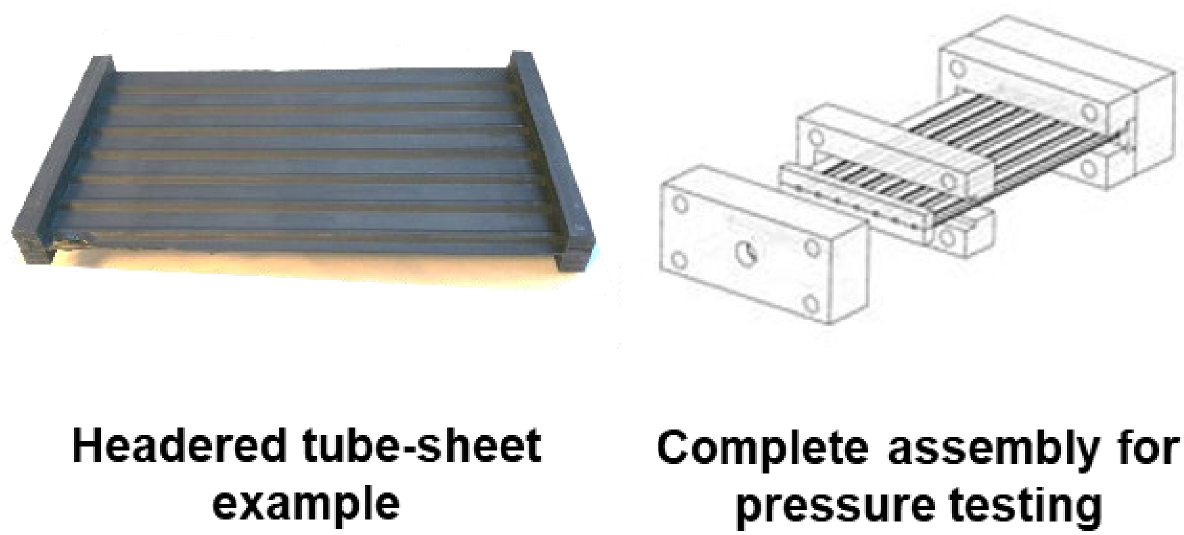
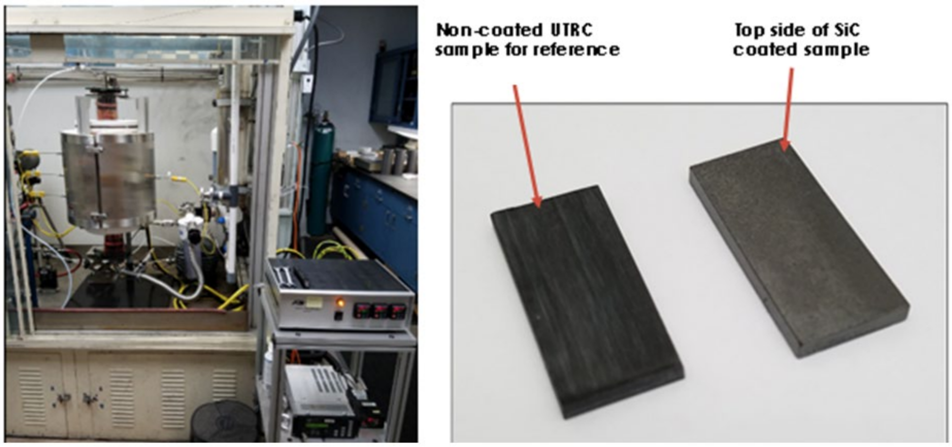


Figure 5. Headered tube-sheet joining and assembly for proof pressure testing.

4. COATING

A CVI study is ongoing to optimize coating GCMC composites with SiC. Figure 6 shows photographs of the CVI reactor setup at ORNL and an example of uncoated and coated GCMC samples. In addition, a CVD reactor is available for smaller test coupons.



(a) (b)

Figure 6. (a) A Chemical Vapor Infiltration (CVI) reactor setup at ORNL; (b) SiC coating of CMC Coupons.

Figure 7 shows optical images of a coated GCMC cross section that was performed to analyze the SiC seal coat. Shown is an original rectangular sample cut in half for metallography. The coating appears well adherent with no separation observed at the interface. Initial trials indicated some periodic cracking in the seal coat, possibly due to CTE mismatch.

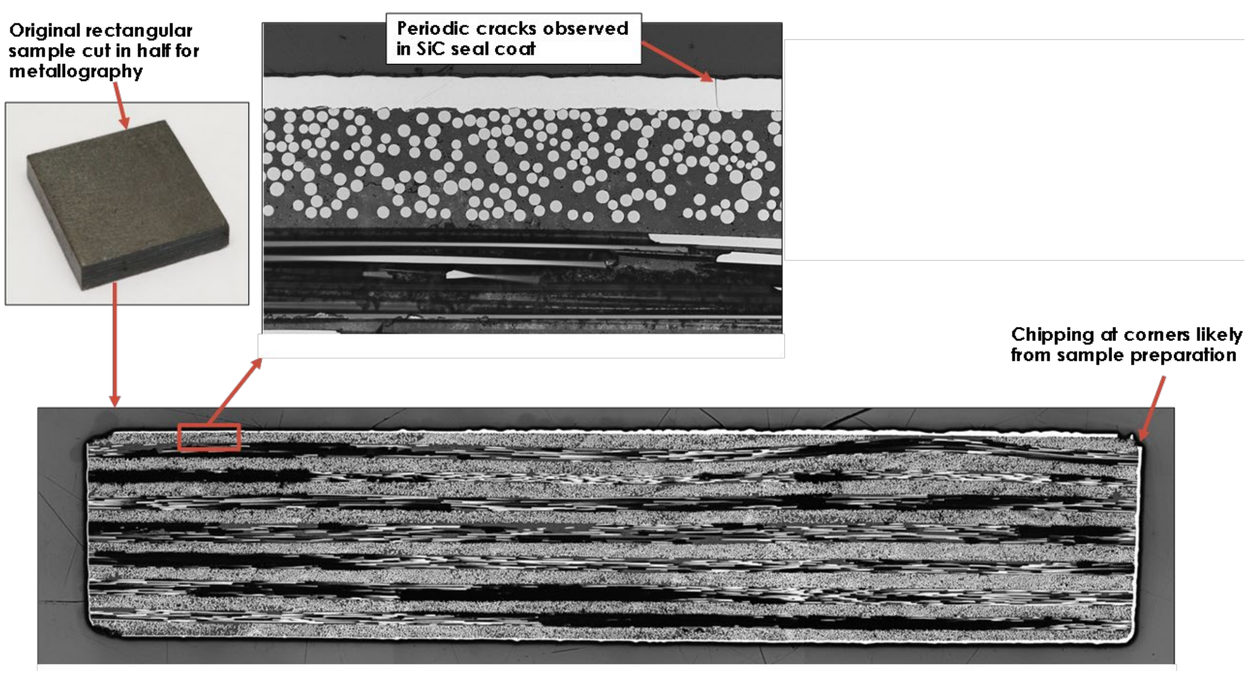


Figure 7. A SiC-coated GCMC example for optical image analysis of coating process quality.

5. CHARACTERIZATION

Permeability testing was performed on a series of GCMC coupons. Figure 8 shows elements of the permeability testing development, including coupon configuration and heat treatment. The aim was to create simulated GCMC joints subjected to manufacturing process conditions and perform testing of gas leakage before and after thermal cycling at the simulated GCMC joints.

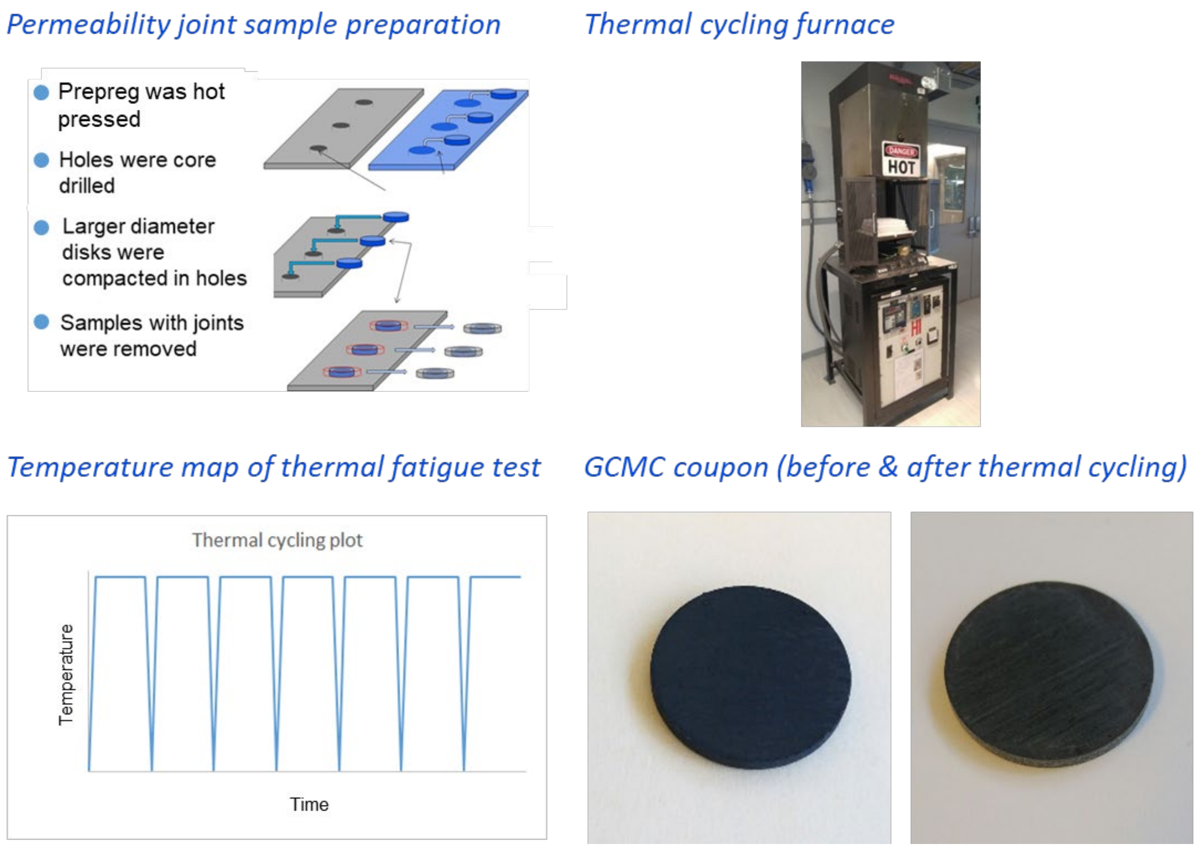


Figure 8. GCMC gas permeability test sample preparation and thermal cycling before testing.

Permeability joint samples were first prepared by hot pressing two flat panels. Circular holes of one diameter were drilled in one flat panel, while circular core samples of a larger diameter were core drilled and extracted from the other panel. The larger diameter core samples were then hot pressed into the panel with the smaller diameter holes to create a panel with circular joints. The circular joint samples were then core-drilled and extracted for gas permeability testing. Some circular joint samples were subjected to thermal cycling before permeability testing.

Figure 9 shows images documenting the permeability test setup and some results compared to the project baseline. The permeability test setup consists of a gas flow with pressure control into a permeability cell that holds the GCMC samples. The permeability is calculated based on rate of change of the gas pressure before and after the permeability cell.

Initial permeability tests show ultra-low permeability when compared to the program's target. Also, the thermally cycled gas permeability samples showed ultra-low permeability when compared to the program's target. The measured leakage rate can be considered negligible compared to the program target – it is believed that it may be likely system-level leakage. Another key observation was no reduction in bending strength after 100 cycles at the program criteria temperature. Samples that were coated did not show a permeability change.

Note that, the permeability joint sample represents how the tube-sheet will be joined to other tube-sheets and to gas flow headers. Establishing that the GCMC process could produce samples of acceptable gas loss limits was key for progressing to larger scale heat exchanger manufacturing process development per program targets.

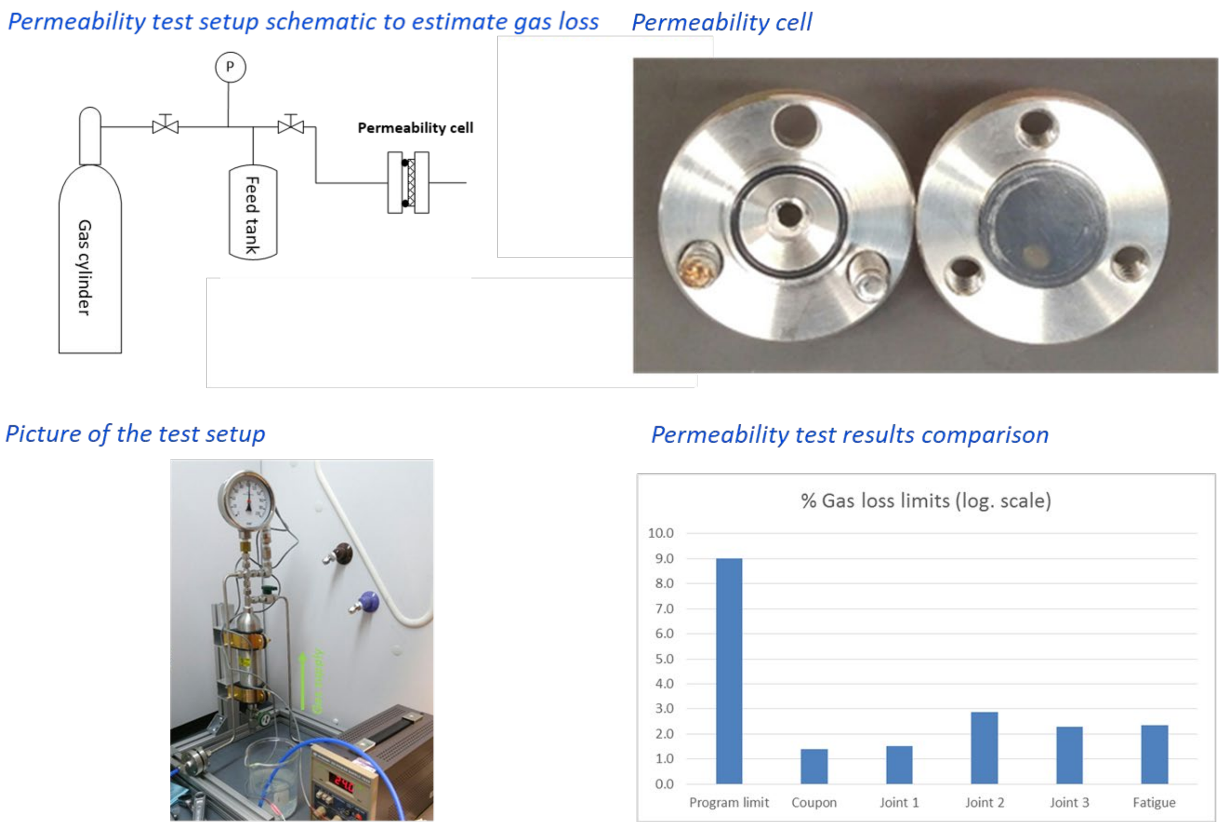


Figure 9. GCMC gas permeability test setup. The results show very low gas losses through joints.

6. SUMMARY

Low-cost glass-ceramic matrix composites are under development for harsh environment heat exchanger applications. Experiments have been completed for coupon fabrication, with the aim of demonstrating part reliability and reproducibility. Tube-sheet manufacturing trials are underway, with a focus on how to replicate complex flow features and part joining.

The benefits of the GCMC material system under investigation are potentially lower cost and lighter weight applications for harsh environments, compared to conventional nickel-super alloys or other similar materials. GCMCs are able to be manufactured in a near-net shape and with complex features, such as the heat exchanger components explored in this work.

Chemical Vapor Infiltration (CVI) trials have been demonstrated with initial SiC seal coating results analyzed. This effort is being led by Oak Ridge National Laboratory. CVD and CVI reactors have been setup to coat different length scales of GCMC samples and coupons. Evaluation is ongoing to study seal coating uniformity.

GCMC gas permeability samples have been pressed by UTRC and coated by ORNL. The gas permeability samples are designed to capture tube-sheet joint interfaces. The aim of the permeability testing is to establish that the formed heat exchanger joints between tube-sheets and header components will not leak beyond a design limit. The gas permeability test results have shown that joints are performing multiple orders-of-magnitude lower than the design target.

Key next steps for this program are further refinement of tube sheet manufacturing regarding repeatability and efficiency, CVI coating of prepared tube sheets with demonstration of coating uniformity. These next steps with aid in the evaluation of tube sheet HX performance under relevant SCO2 conditions.

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