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MECHANICAL PERFORMANCE EVALUATION OF THE PRINTED CIRCUIT HEAT EXCHANGER CORE EXPERIMENTS UNDER TENSION AND PRESSURE LOADING

Changing the World's Energy Future

Heramb Prakash Mahajan, Tasnim Hassan, Lucas Maciel, Gracious Ngaile

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ABSTRACT

The printed circuit heat exchanger (PCHE) has small channels with high surface area, making them an efficient solution for next-generation nuclear plants (NGNPs). These PCHEs are fabricated through a diffusion bonding process. This fabrication step changes the microstructure of wrought metal plates. The current ASME design code does not support the PCHE design for NGNPs due to a lack of test data. Hence, there has been initiative towards elevated temperature mechanical property characterization of the diffusion bonded material. One of the most common channel shapes is a semicircular channel with sharp corners. These corners act as a stress riser at the diffusion bonding interface. Evaluating elevated temperature mechanical performance of diffusion bonded material in the presence of stress risers is an essential step towards the ASME code development of PCHE design. This study selected two specimen geometries: the first is a PCHE bar specimen for tensile loading with three rows and three columns of channels, and the second is a lab-scaled PCHE with six rows and eight columns of channels. A set of elevated temperature monotonic and cyclic tests were conducted on the PCHE bar specimen to evaluate the mechanical performance under axial tensile loadings to study the failure mechanism. The lab-scaled PCHE specimens were tested under overpressure loads at room temperature, and pressure creep and pressure creep-fatigue loadings to mimic the realistic loading conditions observed in typical NGNPs. The X-ray scans of channeled specimens show interesting observations. The test results and observations are presented in the paper.

Keywords: Creep, Diffusion bonding, CHX, NGNP

INTRODUCTION

High compactness and efficiency of Printed Circuit Heat Exchangers (PCHEs) make them suitable for Generation IV nuclear power plants. Typical PCHE have thousands of millimeter size channels embedded in a meter size block, which allows a very high thermal area for heat exchange. Performance of PCHEs have been investigated through analysis and thermohydraulic experiments with different fluid cycles and demonstrated the potential of PCHEs for high temperature nuclear service [1,2,3,4].

However, to the authors' knowledge, studies to determine the mechanical performance at elevated temperature are yet to be performed.

This paper is a part of followup work on the diffusion bonded 800H material performance evaluation for PCHE design code rule development and aims to address gaps in the current design code rule [5]. The initial work comprises of the mechanical performance evaluation of the diffusion bonded 800H at elevated temperature under tensile, creep, fatigue, and creep-fatigue loading on ASTM specimens is documented by authors [6]. This work has established the material performance of diffusion bonded 800H and failure mechanisms under different loading conditions. Similar failure mechanisms have been demonstrated for diffusion bonded Alloy 617 and Haynes 230 specimens [4, 7, 8]. The failure mechanisms of diffusion bonds in presence of channels at elevated temeprature under creep and creep-fatigue loading are not known. This study addresses the failure mechanisms and the behavior of diffusion bonds at elevated temperature in the presence of channels under creep and creep-fatigue type loading.

Two novel specimen geometries are designed and fabricated to evaluate elevated temperature mechanical performance of diffusion bonds in the presence of channel corners. The first specimen is a bar specimen with three rows and three columns of semicircular channels. This specimen is designed to investigate failure mechanisms of diffusion bonds near stress raisers under monotonic tension, creep, and creep-fatigue loads. The second specimen is a lab-scaled PCHE specimen with six rows and eight columns of semicircular channels with integrated headers. The lab-scaled PCHE specimen is used to investigate diffusion bond integrity under channel over-pressure at room temperature, and under creep and creep-fatigue channel pressure loading at elevated temperatures. The performance of these two specimens are compared against the equivalent ASTM tests. The obtained results are presented in paper.

PCHE DESIGN

Two different types of PCHE specimen geometries are selected. The first specimen is a 'PCHE bar specimen' with three rows and three columns of semicircular channels as shown in Fig. 1. This component is designed per ASME Section VIII, Division 1 rules with diffusion bonded allowable stresses of 800H [9]. The target design temperature is 750°C and design life of 1000 hours with a channel pressure of 5 MPa. The channels were machined (instead of etching) on plates before diffusion bonding. These plates were subsequently diffusion bonded into a 200 mm cube block. Round coupons of 200 mm length were machined through electrical discharge machining (EDM) technique. The reduced region was machined with EDM technique to facilitate the square cross section where channels are located as shown in Fig. 1. The gauge length of reduced region is 70 mm and consists of about 50 bond lines as shown in Fig. 1.

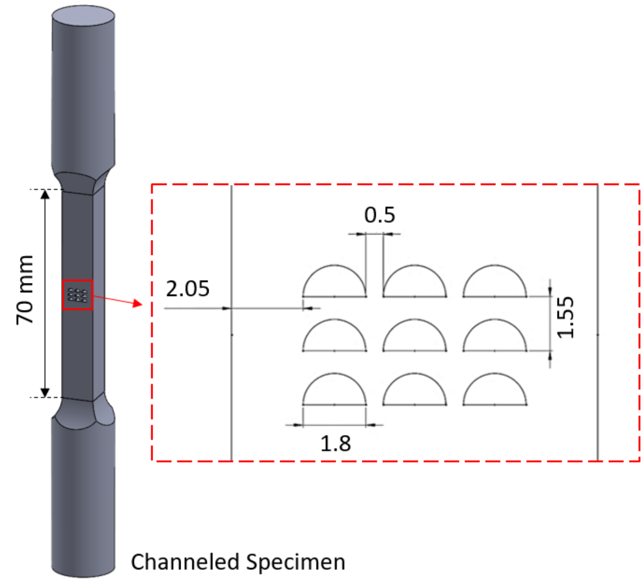

FIGURE 1: PCHE bar specimen to investigate diffusion bond performance in the presence of channels

Figure 2 shows the geometry of the miniature PCHE core specimen. This specimen was used for over-pressure, creep and creep-fatigue performance evaluation. This PCHE geometry was selected to capture the representative channel scale performance of real size PCHE. A lab-scaled PCHE component is designed with design pressure of 5 MPa and 750°C, with a target life of 1000 hours and the plate thickness is 1.55 mm. The PCHE dimensions are presented in Fig. 2a. A typical heat exchangers have four headers; two headers for hot fluid inlet and outlet, and two headers for cold fluid inlet and outlet [10]. The external dimension of the lab-scaled PCHE is 300 x 27.3 x 18.6 mm. One of the main goals of this study is to evaluate the pressure creep and creep-fatigue performance of PCHE channels, which can be performed without fluid flow cycles. Hence, the lab-scaled PCHE specimen is designed with two integrated headers at each end as shown in Fig. 2; one header is open to alternate rows of channels, whereas the other header is open to the other rows of channels. This configuration allows for differential pressure loading.

EXPERIMENTAL SETUP

Tension tests at different temperatures are performed on the PCHE bar specimens by prescribing a linearly increasing displacement history through a servo-hydraulic test system. Specimen temperature was raised through induction heating technique, which actively controlled specimen temperature through feedback from thermocouples attached to specimen. An extensometer is attached to record the deformation between two points equally spaced from central channel row. The digital image cor-

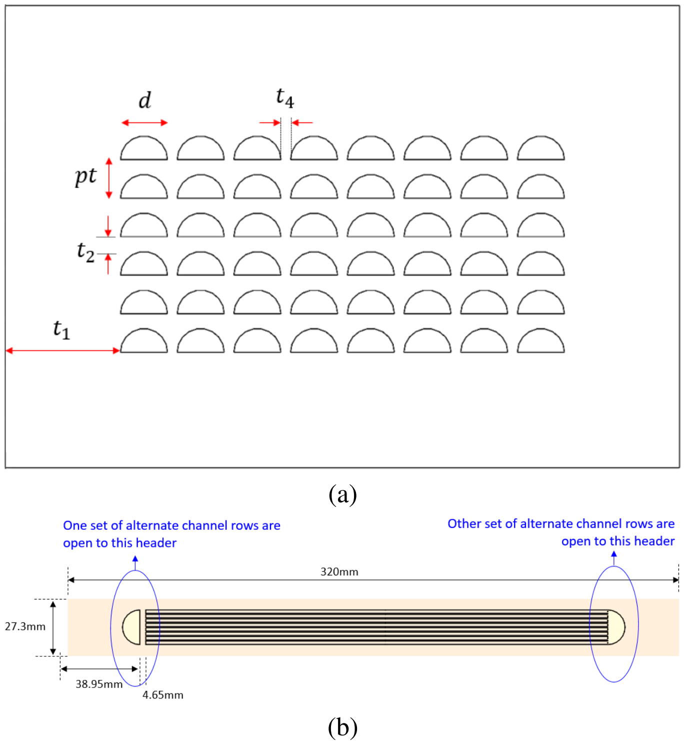

FIGURE 2: The lab-scaled PCHE specimen designed to perform over-pressure and creep tests; (a) cross section of the specimen, and (b) top view of the specimen showing that the header is integrated to the PCHE core. PCHE dimensions: pt = 1.55 mm, d = 1.9 mm, t_2 = 0.6 mm, t_4 = 0.4 mm, and t_1 = 4.65 mm

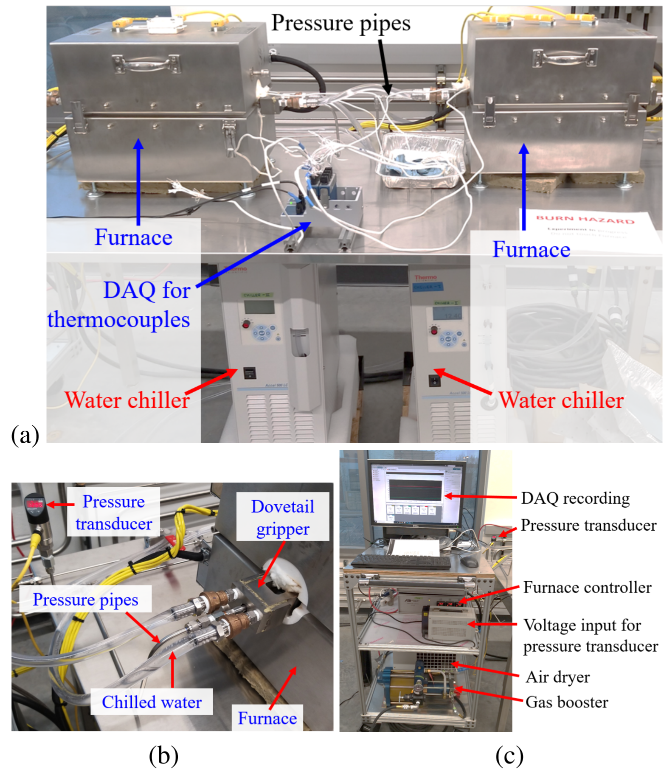

FIGURE 3: The lab-scaled PCHE specimen test setup for elevated temperature cyclic pressure tests, (a) furnaces and chillers, and (b) gripper end outside furnace showing channel pressurization and water cooling pipe connections, and (c) data acquisition, furnace controller, air dryer and gas booster

relation technique measured the strain field on the specimen surface.

A custom made test system is developed to perform the elevated temperature tests of the lab-scaled PCHE specimens as shown in Fig. 3. The test system can apply cyclic pressure and temperature loading, and is designed to operate at elevated temperatures for long operating time. The test system can test two specimens at the same time. Specimen is placed in a three zone electric furnace to raise temperature. Different zones allows a better controls in the central 100 mm length of specimen. A water cooled dovetail gripper griped two ends of specimen and facilitated pressurization pipe to pressurize PCHE channels to target test pressure. Air dryer removed moisture from shop air, gas booster raised dry air pressure to the target test pressure, and pressure transducer measured the applied pressure. For detailed design and geometry of the test setup, readers are directed to [11]. Thermocouples were attached to specimens to record temperatures at different locations.

FLAT CHANNEL SPECIMEN RESULTS
Monotonic tension tests

A room temperature displacement controlled tension test was conducted on the PCHE bar specimen. The pretest, during first crack initiation, and post-test specimen picture, and force-displacement response are presented in Fig. 4. A good correlation is observed between strain measurements from digital image correlation and extensometer. The first crack initiation was followed by a sudden force drop, indicating a rupture of the internal wall. The adjacent channel wall failed subsequently with increase in displacement loading, resulting in a failure along the diffusion bond of the top channel row. The fractured specimen in Fig. 4 showed necking with shear lips at fractured channel walls, indicating ductile failure mechanism.

The force-displacement response from the tension test at 760 °C is shown in Fig. 5. The first crack in this test initiated at the same channel wall location as the room temperature test, but no immediate rupture or force drop was was observed. The adjacent channel wall fractured with increase in specimen end displacement. This fractured progressed to the lower channel row

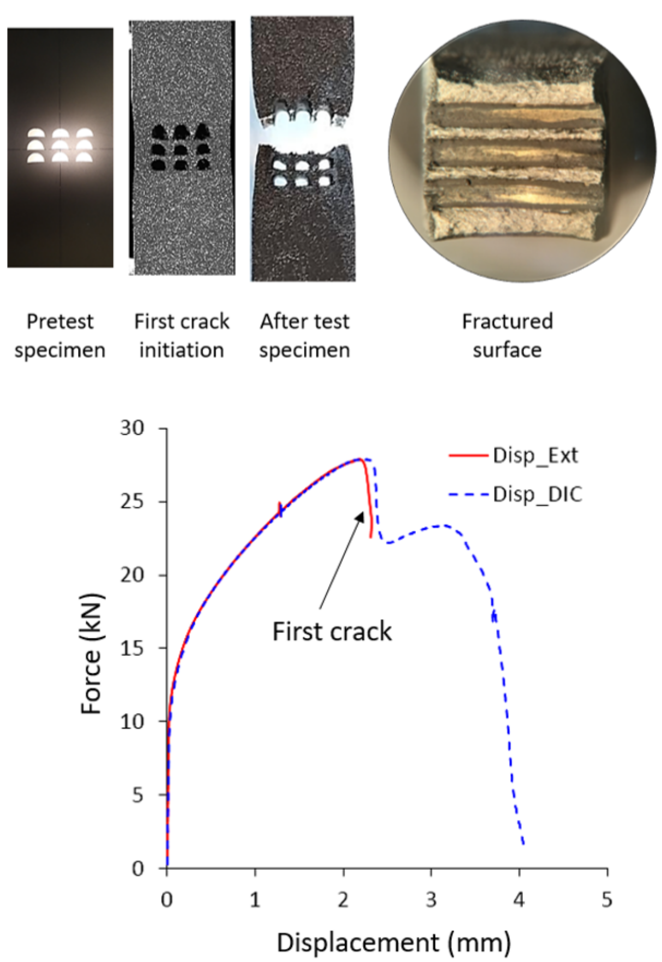

FIGURE 4: The front view of bar specimen before test, during test and after test, fractured surface, and force-displacement response at room temperature under tensile loading

as shown in Fig. 5. The fractured surface are observed to be flat surfaces because of the bond delamination similar to the ASME specimen elevated temperature tests [6].

Fracture across two-channel rows in a PCHE has high failure consequence per failure mode effects analysis for Section III [12]. Hence, elevated temperature failure modes needs further investigation through testing of Lab-scale PCHE specimens. A question that needs to be addressed is whether a pressure loading in the channel at elevated temperature can result in crack propagation from one row to the adjacent row.

The third test performed on the PCHE bar specimen is a tension test at 550°C, which showed a similar force-displacement response as the room temperature test. The crack initiated in the right internal wall along with a force drop as shown in Fig. 6. The fractured surface also showed signs of ductility at 550°C. Significant decrease in strength and ductility at 760°C is shown

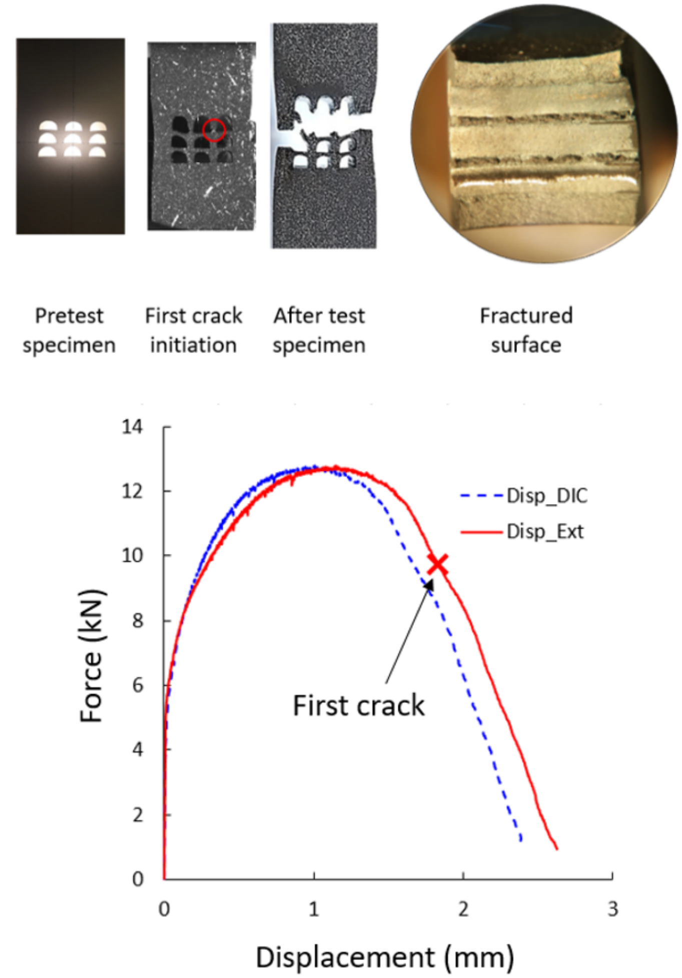

FIGURE 5: The front view of bar specimen before test, during test and after test, fractured surface, and force-displacement response at 760°C under tensile loading

in Fig. 6. The fractured surface of the PCHE bar specimens under tension tests at different temperatures are presented in Fig. 5. As discussed before, the test results at room temperatute and 550°C show necking and shear lips on internal walls. The elevated temperature test shows flat fracture surfaces indicating the bond delamination type fracture. The failure surface observations are consistent with the standard ASTM specimens' fractography, where above 500°C, fracture mechanism shifts from ductile to bond-delamination type [6].

Constant force test

To study the creep performance of diffusion bonds, a constant force hold test was conducted on PCHE bar specimen. From the Larson-Miller Parameter (LMP) developed from ASTM creep

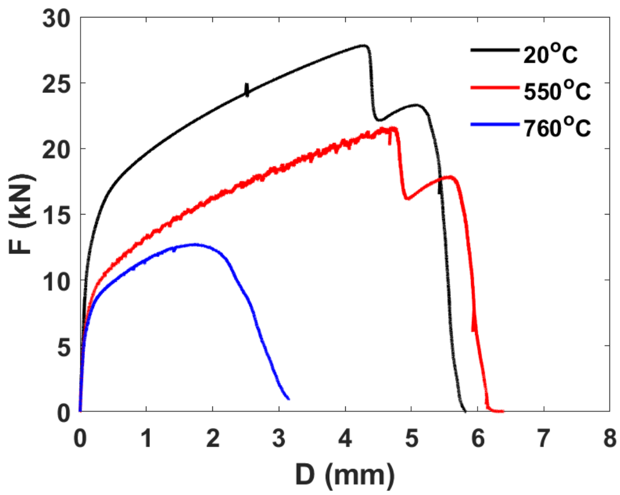

FIGURE 6: Comparison of tensile force-deformation responses of the PCHE bar specimen tested at different temperatures

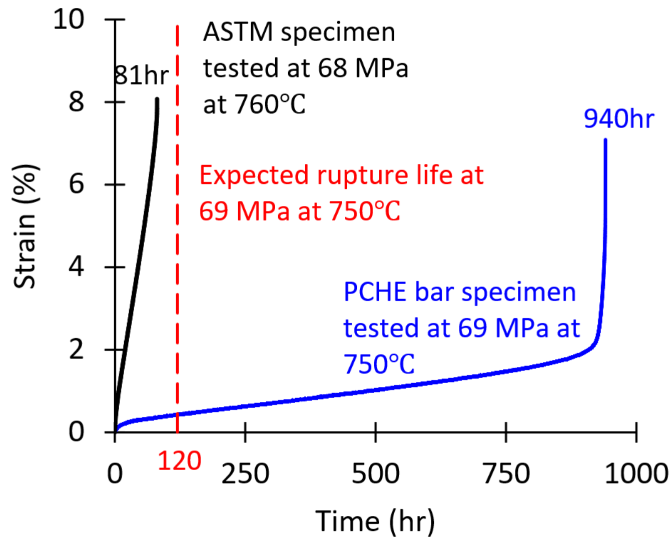

FIGURE 7: Comparison of the ASTM creep test at 68 MPa and 760°C (observed rupture life = 81 hours [6]) against the constant force test on PCHE bar specimen at 69 MPa and 750°C (observed rupture life = 940 hours). The dashed line indicates expected rupture life of the PCHE bar specimen (120 hours).

tests conducted in the previous work [6], a creep rupture stress with rupture life of 120 hours at 750°C was selected. This rupture stress and critical area at channeled plate in the PCHE bar specimen was used to calculate the total force. PCHE bar specimen temperature was raised with 1°C/s rate and soaked at 750°C for 20 minutes before applying the force of 4000 N gradually over 30 seconds. The maximum temperature and force were held steady until fracture. Extensometer of gauge length 25 mm was attached to the specimen such that extensometer arms are equidistant from the central channel plate. The average strain results from PCHE bar specimen is compared against strain from the ASTM creep specimen in Fig. 7. Note that PCHE bar specimen is not a standard specimen, and strain field within gauge length is non-uniform. However, comparison with the ASTM creep specimen provides information about the ductility of specimen and the creep rupture life. The PCHE bar specimen ruptured at 940 hours, about a order of magnitude larger than the expected rupture life of 120 hours. These observation shows that the predicted bond performance based on ASTM tests severely under-predicts the bond performance at channel walls.

Cyclic force test

The creep-fatigue performance at elevated temperature is evaluated through force-controlled cyclic tests on the PCHE bar specimen. The peak axial force of 3000 N induced an average stress of 53.57 MPa at the channeled section. The force controlled creep-fatigue cycle consists of force ramp-up to peak value in 30 seconds, peak force dwell for 1 hour followed by force ramp down to zero force in 30 seconds. The creep-fatigue load cycle was prescribed at 750°C. At 750°C and 53.57 MPa stress, the expected creep rupture life is 520 hours [6]. Note in Fig. 8 that the PCHE bar specimen creep-fatigue life exceeded the estimated creep life based on ASTM specimen data. Test data showed no signs of any damage and imminent rupture till 2500 hours, so the test was discontinued at 2500 hours. The elongation is calculated by multiplying the strain data from extensometer with the gauge length of 25 mm. The elongation time history of PCHE bar specimens from cyclic force is compared against the constant force with respective rupture life in Fig. 8.

All these observations show that the diffusion bonds at the channel wall sections are stronger than the diffusion bonds of solid specimens. The X-ray tomography investigated the microvoid map in the PCHE bar specimens along diffusion bonds is shown in Fig. 9. The microvoid distributions along two sections 1-1 and 2-2 are shown in Fig. 9. The section 1-1 do not have channels whereas section 2-2 is have channels. The dark spots indicate voids in a perticular cross section. Larger number and size of voids distributed continuously along the diffusion bonded interface at section 1-1 compared to the channel wall interface at section 2-2. During diffusion bonding process, externally applied stress in Glebble furnace flows around channels resulting in the non-uniform stress intensities along a continuous interface (Section 1-1) adjacent to channels. Higher stress intensities at channel wall interfaces results enhanced bonding quality resulting better bond performance with less number and size of voids. However, the void size at section 1-1 is much larger in order of 100 μm and the void count map in Fig. 10 presents the void size distribution. The red planes in this figure indicates the location of

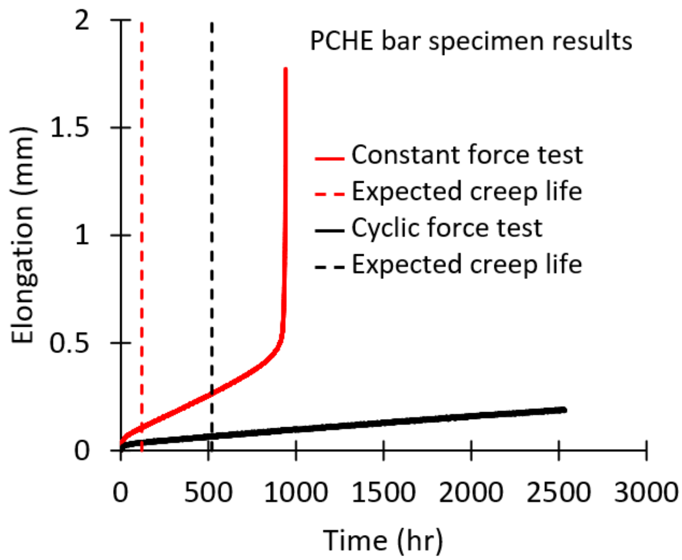

FIGURE 8: Comparison of test results from PCHE bar specimen under constant force of 69 MPa and cyclic load of 53.6 MPa with 1 hour dwell at 750°C. Dashed lines indicate expected creep rupture life of the PCHE bar specimen for different applied stress.

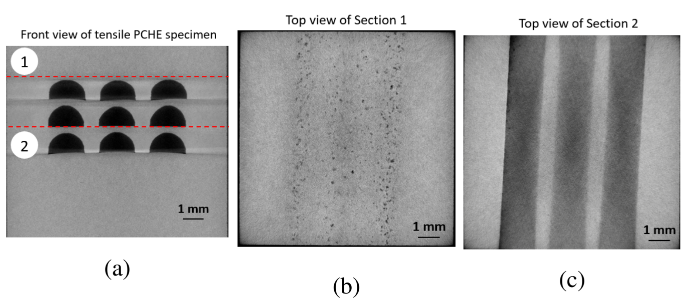

FIGURE 9: X-ray tomography images of a PCHE bar specimen, (a) front view showing channels and two selected diffusion bond (DB) interfaces 1 and 2 for void mapping, (b) void distributions along DB interface section 1, and (c) void distributions along DB interface section 2 along channel wall

measurable void detection. Note that the section 2-2 at channel wall interface did not showed any measurable void. The smallest resolution of X-ray tomography machine is 15 μm. Hence, void size at the channel wall interface is smaller than 15 μm. These smaller void number indicates better bonding, and elevated temperature test results so far matches with this observation.

Lab scaled PCHE

Overpressure test

The overpressure test at room temperature determines the integrity of the diffusion bonds of PCHEs. The goal of this test

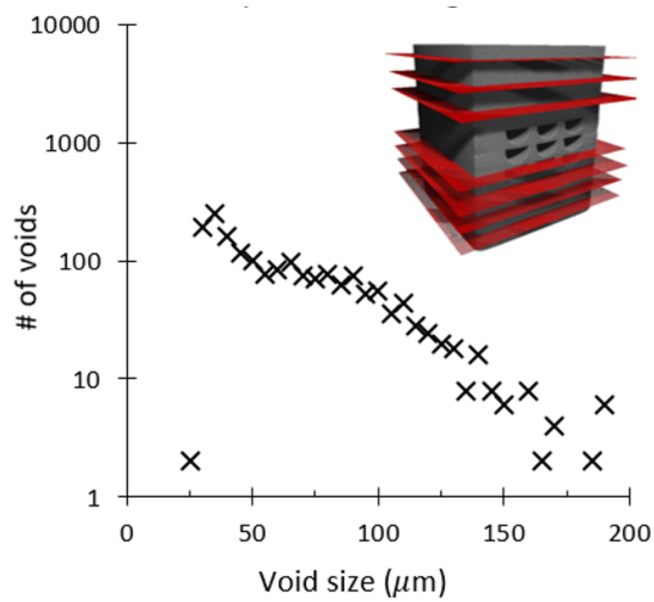

FIGURE 10: Void count map determined by X-ray tomography scans along diffusion bonded planes (red highlighted planes) in the PCHE bar specimen

to study structural integrity and potential failure mechanisms under higher pressure at room temperature. The lab-scaled PCHE specimen is tested by prescribing hydraulic pressure to channels at room temperature. Hydraulic pressure was raised to 131 MPa, a maximum pressure loading capacity of test system. No external leakage or failure is observed at peak load, and the specimen did not show any bulging or excessive deformation. This test further validates that the diffusion bonds of the channel walls and sidewalls are strong enough for nuclear service.

Pressure creep

The design pressure and temperature of the lab-scaled PCHE specimen is 5 MPa and 750°C. The first test is the component intigrity test per HBB-6000 in Section III, Division 5. A channel pressure of 10 MPa is prescribed at room temperature and maintained for 30 minutes. No pressure leak is detected in 30 minutes indicating that the lab-scaled PCHE specimens passed component integrity test. A channel pressure of 8.3 MPa was selected for two tests at 650°C and 750°C. This channel pressure is expected to cause rupture at 750°C and expected to satisfy the ASME design criteria at 650°C. Two specimens are placed in the custom made test setup shown in Fig. 3. Electric furnaces raised specimen temperature and a constant temperature value is maintained in the central region of the 100 mm length specimens. Channel pressure is raised to 8.3 MPa in 60 seconds and maintained for 1000 hours through a gas booster. Tests were discontinued after 1000 hours to study microstructure examination to explore accumulated creep damage. Both specimens did not show any signs of leakage or any other failure until 1000 hours. This observation suggests that the PCHE design procedure and the developed allowable stresses for the diffusion bonded 800H are adequate.

DISCUSSION AND ONGOING WORK

This study continued the diffusion bond performance evaluation of the Alloy 800H PCHE design through designing and fabricating two types specimens: PCHE bar specimen and lab-scaled PCHE specimen. The PCHE bar specimen with 3 rows and 3 columns of channels, tested under tension, creep and creep-fatigue loading. Observed results show that the bonds at channel interface are stronger than bonds away from channels. The PCHE bar specimen under tensile loading show ductile fracture at room temperature. However, bond delamination fracture governs the fracture mechanism at elevated temperature. This observation is consistent with failure mechanisms observed in tension tests on the standard ASTM diffusion bonded 800H solid specimens. The elevated temperature tension test showed higher strength and ductility which confirmed the better performance of channel walls in the PCHE bar specimens.

The constant force and cyclic force tests showed significant differences in performance of the PCHE bar specimen compared to the ASTM solid specimens. Actual life of PCHE bar specimen is much larger compared to the predicted rupture life of PCHE bar specimen based on ASTM creep specimens. During diffusion bonding process, stress flow near channels is non-uniform, and channel walls are subjected to much higher stresses compared stress away from the channel walls. This difference in stress is suspected to improve the local diffusion bond performance and minimize the voids. The X-ray tomographic scans have demonstrated the lower void size in the channeled interface compared to solid interface. This observation indicates that the bond performance at channel walls is superior compared to bonds away from channels. These differences in material properties between PCHE bar specimen and standard ASTM specimen also highlights the importance of using representative PCHE test article in diffusion bond performance evaluation strategy.

The over-pressure test at room temperature prescibed 131 MPa on lab-scaled PCHE. No external failures/leakages were observed under this load condition. A custom made test setup for creep and creep-fatigue performance evaluation of lab-scaled PCHE specimen evaluated the creep performance of specimen at 650°C and 750°C for 1000 hours. Both of these tests did not show any signs of failure or external leakages. The specimen with 750°C temperature was expected to rupture within 1000 hours based on the solid ASTM specimen material properties, but as discussed before no external failures were observed.

A set of creep-fatigue tests on lab-scaled PCHE are in progress. The performance and observation from these tests will be published in future. All lab-scaled specimens will be dissected and the cross section will be studied for internal failures and bond delamination. Small miniature specimens will be extracted from channel wall interface and solid interface. These two specimen sets will subjected to tension and accelerate creep tests. Result comparison from these two sets of miniature specimens will give detailed insight in to mechanical results and respective bond qualities.

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