Testing Ceramic Matrix Composites for Gas Turbine Combustion Chamber Panels

L. Lebel (a), S. Turenne (b), R. Boukhili (b)

(a) Pratt & Whitney Canada, Longueuil QC. Larry.Lebel@pwc.ca, (450) 677-9411, ext. 74240
(b) École Polytechnique de Montréal

Abstract

In a goal of better understanding durability of ceramic matrix composites (CMC’s) under the cyclic thermal stresses of combustion chamber panels, this paper proposes a simple test procedure and equipment for subjecting the materials to similar conditions in laboratory. An experimental apparatus was assembled that produces a temperature gradient across the thickness of a CMC sample, while holding the sample at its two extremities, in order to simulate the bending stress that would be observed in a combustor panel. Heating system validation tests were performed where an oxide-oxide CMC sample was heated up to 1200 °C on surface, which allowed calibrating heat losses and material conductivity. Test conditions achieved so far with the proposed experiment did not match real engine conditions, because of the lower than expected performance of the selected infrared heater. Nevertheless, the shape of the stress profile in the test specimen promises to be representative of the gas turbine application when a more powerful heating system is made available.

Introduction

Over the last 15 years, aircraft engine manufacturers and research centers have conducted many demonstration tests of combustion chambers made of ceramic matrix composites (CMC’s) [1-4]. However, still relatively small amount of data is available for predicting life and reliability of CMC’s in such high temperature static components. Potential deterioration modes of CMC’s, and general conditions under which these deterioration modes may develop have been identified, but no clear methodology is available yet to correlate stress and temperature fields with damage to be expected in combustors.

Complexity of this task is increased by the fact that deterioration modes are multiple and may differ from one CMC system to another. For example, very different observations were made on non-oxide and oxide CMC’s after high temperature exposure. Kim et al. [5] reported reduction in tensile fatigue life of SiC-SiC (non-oxide) specimens due to oxidation at the matrix-fiber interface, while Mall and Ahn [6] reported increase in tensile fatigue life of an oxide-oxide CMC due to increased cohesion between matrix and fiber. Due to the multiple possible combinations of various effects, characterization of a CMC material in laboratory for a specific gas turbine application would ideally require careful reproduction of the specific corresponding gas turbine conditions.

Up to now, in laboratories, most durability characterization tests have simulated tensile loading, for example high temperature tensile fatigue [5, 6] and tensile creep [7, 8], which are typical of rotating components. Thermomechanical fatigue tests were also reported, for both in-phase and out-of phase type of temperature cycling, but again under tensile type of loading [9]. In static components like a combustor, compressive thermal stress can arise at various locations, including hot spots. Some CMC properties are available under compression, following for example the compressive creep tests done by Jackson et al. on an oxide-oxide CMC [10]. However, applicability to a static component subjected to thermal stress, where stress is likely to evolve with damage accumulation, remains questionable.
In a general goal of being able to understand deterioration modes and to predict durability of a CMC in a combustor application, a simplified laboratory experiment subjecting the material to conditions similar to engine conditions is being developed. The proposed procedure and test setup attempt to match the cyclic thermal stress and temperature variations in a combustor heat shield panel. The current paper summarizes the design and validation work that was completed so far, and compares the generated laboratory stress and temperature conditions with estimated engine conditions.

**Test apparatus and procedure**

The proposed experimental apparatus produces a temperature gradient across the thickness of a CMC sample, as shown in Figure 1. In this figure, the test sample is observed from the side, i.e. the thickness of the sample is shown. The material sample is heated on the front face with an infrared lamp heating system, and cooled on the opposite face by radiation and forced convection. A front view of the sample is presented in Figure 2. It is narrowed down at its center, with the intention to maximise stress and concentrate potential damage in this region.

![Figure 1: Experimental setup (infrared heater cross section taken from Research Inc. [11])](image)
The infrared heater is a 5194-04 line heater from Research Inc. that uses a 2000 W, T-3 style, tubular quartz halogen lamp with a tungsten filament. As seen in the heater cross section of Figure 1, radiation from the lamp is reflected and converged onto a line by an elliptical reflector, which is water cooled. The CMC sample is located close to the heater focal point. The radiating length of the lamp is 75 mm, and the reflector is 102 mm long.

The air cooling device at the sample back side was not fabricated yet, but is thought of as an array of impingement jets fed from a plenum connected to the laboratory air supply.

Two test setups are possible with the same apparatus. The first one leaves the top extremity of the sample free to move, with possibility of measuring the displacement of this top extremity with an LVDT under the thermal load. With a temperature gradient applied through its thickness, the sample tends to bend away from the heat source. The extent of measured displacement at the top end may be used to assess residual rigidity of the sample after exposure to high temperature. Variations in bending response from one test to another may indicate variations in rigidity, and hence potential structural damage of the sample. Even under minimal stress or absence of stress, material properties may evolve under high temperature, which may be detected with this first setup.

The second setup uses an additional anchor to prevent motion of the CMC sample at its top extremity, both in rotation and perpendicular displacement, in order to simulate the bending thermal stress that would be present in a combustor panel. Maximum bending stress is expected at the center of the sample, in the narrow region. It is still possible to measure the bending response before and after the test by removing the top anchor and using the LVDT. Damage monitoring may easily be performed in this way, by measuring the bending response of the sample periodically.

Currently, type K, 1/32 inch diameter bare thermocouples are used to measure sample surface temperature. They are bonded to the sample using Omega OB-600 cement. Type K thermocouples are recommended for usage below 1000 °C, but for short durations may be exposed to higher temperature without damage.

The LVDT is a model LD500-2.5 from Omega. Within the current experimental setup, and with the current data acquisition system, repeatability and resolution of the LVDT measurements were evaluated to 13 µm.
Preliminary heating tests

A test specimen of A-N720 oxide-oxide CMC material from COI Ceramics was heated with the infrared heater up to 1200 °C on the hot surface, under laboratory atmosphere, with no forced convection cooling on the back face. To reach this temperature, the CMC sample was painted with HiE-Coat 840-C high emissivity black coating from Aremco. With the bare A-N720 white material, peak temperature was about 300 °C less, which suggests a relatively low emissivity for the bare material. Figure 3 shows the test setup, with the white back face of the test sample visible, and Figure 4 shows the black painted front face of the sample prior to test. Three thermocouples were used during this test: two on the front face, including one at the peak temperature location, and one on the back face, at the peak temperature location.

Temperature measurements are shown in Figure 5, along with the transient results of a calibrated thermal analysis. At the center of the sample, a temperature drop of about 200 °C was observed across the material thickness. Calibration of the analytical model was conducted by adjusting various parameters, in particular the factors for radiation (emissivity*view factor) and the through thickness conductivity of the material. Since no forced convection was present during the test, convection heat losses remained small compared to radiation heat losses. Good match with the experiment, both in the rise and in the decent in temperature, was obtained using an emissivity*view factor of 0.3 for radiation loss to the heater reflector from the hot front face, and an emissivity of 0.9 for radiation to the ambiance from the back face. Through thickness conductivity of the CMC was adjusted down to 1.8 W/(m·K), from the initial value of 3 W/(m·K), in order to match the temperature drop across the sample thickness. Surprisingly, per this calibrated model, only about 350 W, or 18% of the electrical power dissipated by the lamp was absorbed by the test sample.
Figure 5: Measured surface temperatures in a preliminary heating test, and calibrated transient analysis results

Test sample analysis

Using the heat transfer parameters of the calibrated model just described, a heat transfer analysis of the test sample proposed in Figure 2 was performed, under the same infrared heating. Then a stress analysis was completed, assuming that the sample was maintained at its two extremities in the test setup. The A-N720 CMC was modeled using properties of Table 1. Damage-free elastic model of the material was used, with isotropic elasticity, as in ref. [12].

Figure 6 shows the results of this stress analysis, with longitudinal stress $\sigma_{xx}$ comprised between -72.8 and 49.2 MPa in the narrow observation section, at the center of the sample. Considering the 181 MPa ultimate in-plane tensile strength of the material under 1200 °C, rupture is unlikely to happen under this test condition, at least in the first cycle of testing. Rupture may happen due to interlaminar shear $\tau_{xz}$, but outside the reduced area center region. Design of the extremities of the test sample will need to be improved to reduce the probability of sample rupture outside the narrow center region.

Figure 7 shows the analysis results with the same test sample, but exposed to a more powerful heat source (~1700 W laser), with back side forced convection. Heat loss parameters were kept the same. In this case, the longitudinal stress, reaching up to 246 MPa at sample center, exceeds the limit of the material. Material rupture should happen in the first cycle of testing.
### Table 1 – Properties of the A-N720 oxide-oxide CMC used in analysis

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.73 g/cm³</td>
<td>COI Ceramics [13]</td>
</tr>
<tr>
<td>Young’s modulus (isotropic)</td>
<td>70 GPa</td>
<td>COI Ceramics [13]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>Guess</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (isotropic)</td>
<td>$6.0 \times 10^{-6}$ /°C</td>
<td>COI Ceramics [13]</td>
</tr>
<tr>
<td>Conductivity (orthotropic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-plane</td>
<td>3 W/(m·K)</td>
<td>Van Roode et al. [14]</td>
</tr>
<tr>
<td>Through-thickness</td>
<td>1.8 W/(m·K)</td>
<td>From current experimental calibration</td>
</tr>
<tr>
<td>Specific heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 °C</td>
<td>753 J/(kg·K)</td>
<td>Alpha (corundum) alumina [15]</td>
</tr>
<tr>
<td>727 °C</td>
<td>1216</td>
<td></td>
</tr>
<tr>
<td>1327 °C</td>
<td>1255</td>
<td></td>
</tr>
<tr>
<td>Ultimate strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile, in-plane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 °C</td>
<td>181 MPa</td>
<td>Ruggles-Wrenn and Braun [7]</td>
</tr>
<tr>
<td>1330 °C</td>
<td>120 MPa</td>
<td>Ruggles-Wrenn and Braun [7]</td>
</tr>
<tr>
<td>Shear, interlaminar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 °C</td>
<td>8.25 MPa</td>
<td>Ruggles-Wrenn and Laffey [16]</td>
</tr>
</tbody>
</table>

![Figure 6: Stress analysis results of a test sample heated with the infrared lamp, with no forced back side convection](image)

-37.5 MPa < $\sigma_{yy}$ < 34.5 MPa
-11.1 MPa < $\tau_{xz}$ < 11.1 MPa
Figure 7: Stress analysis results of a test sample heated with a high power source (~1700 W), with forced back side convection

Figure 8 shows that the simulated longitudinal stress at the center of the sample may be representative of the stress in potential combustor panel applications. Combustor panel stress was taken from prior work [12], where A-N720 panels were analysed under real gas turbine engine conditions. In terms of stress, the option of heating with the infrared heater is more representative of a curved segmented panel heated on the convex side. The option of a more powerful heating (laser) compares better with a 360° panel option, where bending stresses at panel center are much higher.

In terms of temperature, previous work [12] concludes that the hot CMC surface of an A-N720 combustor panel may reach 1570 to 1750 °C without a hot side insulation layer, or 1180 to 1280 °C with an insulation layer. The temperature difference between hot and cool sides could vary from 890 to 1040 °C in a non insulated panel, or from 550 to 630 °C in an insulated panel. In the proposed experiment, the infrared heater allows reaching the hot surface temperature level of an insulated combustor panel, but without the full through thickness temperature gradient of a real panel. A more powerful heating system would allow reaching realistic temperature levels and gradients. Table 2 summarizes these temperature comparisons.

Discussion of the procedure

Conditions that are achievable with the proposed experiment are compared to conditions of a combustor panel under real engine operation by analysis. Even though the simplified material sample is subjected to bending stress in one direction only, and its stress distribution certainly does not represent all possible combustor panel geometries and conditions, it is expected to show deterioration modes that are representative of typical gas turbine static components.
However, the infrared heater tested so far did not demonstrate enough heating capacity to match temperatures and through thickness temperature gradients that would be present in a real combustor. An alternate heating system may be considered for continuation of this experimental work, including a more powerful infrared heater, a laser, or a torch (plasma or combustion). Ideally, the selected heating system should be easily controllable, in order to allow thermal cycling of samples, and have low operating costs. The infrared heater was selected mainly for these two reasons initially, in addition to expected heating power.

Once the appropriate temperature levels are achieved, stress levels in the material may be adjusted by varying the width of the test sample, both in the narrow section at the center and in the wider section.
Ideally, for stress prediction, higher accuracy material model should be used in future work, including anisotropic elasticity, variations of modulus with temperature, and damage modelling.

**Conclusion**

Test apparatus and procedure was designed for simulating the conditions of operation of a CMC material under a gas turbine combustor panel application. An elongated material sample is heated on one side and cooled on the other side, with blocked displacements at extremities in order to generate bending stress at its center. Bending response is monitored periodically in order to detect potential material damage.

Current infrared heating equipment allowed reaching 1200 °C surface temperature, on an A-N720 CMC sample, but did not input enough heat into the sample to reach representative through thickness temperature gradient. Preliminary testing nevertheless allowed calibrating the heat losses from the sample, and obtaining the through thickness material conductivity.

With a more powerful heating system, analysis showed that the designed experiment should be well suited to represent a real combustor panel application, in terms of both temperature and stress. Improvements or simply replacement of the heating system may be attempted in upcoming work.

**References**


