Thermal Barrier and Protective Coatings to Improve the Durability of a Combustor Under a Pulse Detonation Engine Environment

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Abstract

Pulse detonation engine (PDE) concepts are receiving increasing attention for future aeronautic propulsion applications, due to their potential thermodynamic cycle efficiency and higher thrust to density ratio that lead to the decrease in fuel consumption. But the resulting high gas temperature and pressure fluctuation distributions at high frequency generated with every detonation are viewed to be detrimental to the combustor liner material. Experimental studies on a typical metal combustion material exposed to a laser simulated pulse heating showed extensive surface cracking. Coating of the combustor materials with low thermal conductivity ceramics is shown to protect the metal substrate, reduce the thermal stresses, and hence increase the durability of the PDE combustor liner material. Furthermore, the temperature fluctuation and depth of penetration is observed to decrease with increasing the detonation frequency. A crack propagation rate in the coating is deduced by monitoring the variation of the coating apparent thermal conductivity with time that can be utilized as a health monitoring technique for the coating system under a rapid fluctuating heat flux.

I. Introduction

The pulse detonation engine (PDE) concept has been studied at NASA Glenn Research Center to assess the feasibility of creating a hybrid gas turbine engine in which the constant pressure combustor is replaced by a detonative combustor. In the hybrid PDE, a detonative combustor would be burned in a cyclic detonation process at several hundred cycles per second and achieve near constant volume burning (ref. 1). The constant volume burning process is more efficient thermodynamically than constant pressure combustion at the current operating pressures of aero turbine engines (refs. 2 and 3). The fuel in a detonative combustor would be burned in a cyclic detonation process at several hundred cycles per second (refs. 3 and 4). In a PDE process, a mixture of fuel and air fills the detonation tube, and a spark is ignited to initiate the detonation at the end tube. When a detonation is initiated, a sharp pressure and temperature peaks are observed for a short duration on the order of 1/10 ms, followed by a sharp decrease to a plateau region of constant values for duration of several milliseconds prior to a final decay to the lower fuel mixture fill pressure. As the burned gases exhaust the device, a new fuel-air mixture is supplied to initiate a new cycle. The process is repeated at a rate sufficient to provide the enthalpy required by the turbine to drive the cycle. However, for the success of a hybrid PDE concept, the material of choice should be capable of enduring the severe pulsing environment created by the repetitive detonations (ref. 5).

The design of a long life pulse detonation combustor is essential to the successful implementation of detonative combustor technology in future engines. Preliminary studies of materials exposed to high cycle pulsating thermal loads using laser heating have resulted in the induction of significant surface cracking (refs. 5 and 6) due to a creep/fatigue interaction that is expected to reduce the life of the component. Various techniques such as film cooling (refs. 7 and 8), aspiration cooling (ref. 9), and thermal barrier coating (ref. 10) are attractive techniques that have been successfully used for many years in steady constant pressure combustors to increase the durability of hot components such as turbine blades and combustor liners. This paper summarizes a numerical and experimental effort to demonstrate the feasibility of a thermal barrier coating concept to protect a typical combustor material, Haynes® 188 (Kokomo, IN), and Nickel base alloys, in the presence of repetitive pulsed heat flux resulting from high cycle detonation waves.

In previous studies (refs. 5 and 6), a high cycle thermal fatigue test rig incorporating a CO₂ laser was used to evaluate the performance of Haynes® 188. The material is a commercially available cobalt-nickel-chromium-
tungsten alloy. It was chosen due to its high temperature strength and good oxidation resistance up to 1100 °C (2000 °F). It is currently used in commercial and military gas turbine engines for components such as combustion cans, transition ducts and after-burner components (ref. 11).

The cyclic thermal fatigue of Haynes 188 was investigated under a 30 Hz pulsed laser exposure. A total of 33 ms pulse period included a 0.2 ms high temperature spike and a 10 ms plateau to simulate the detonative heat loads. The specimens were tested with the high frequency laser pulsed at an average surface temperature of 800 °C and a backside temperature of 650 °C. About 40 °C temperature fluctuations resulting from the pulse caused significant thermal cyclic stresses to form an oxide scale along the exposed surface, see figure 1. The oxide scale induced extensive surface cracking that penetrated the substrate under repeated pulsed heating, as seen in figure 2. The micrographs of figure 2 indicate that oxidation and creep-fatigue interactions at the oxide scale/alloy interface was a damaging mechanism for surface crack initiation and propagation under simulated PDE heating conditions.

The extent of the damage is a clear indication to the necessity of a thermal protection system for PDE combustor materials. The protection system studied here is a ceramic coating acting as a thermal barrier with an oxidation resistance bond coat. This system has been applied successfully in hot sections of standard constant pressure combustion engines (ref. 10), but not applied under high speed pulsed heat flux conditions. This paper investigates the feasibility for improving the durability of coated combustor liner materials such as Haynes 188 and Nickel-based alloy specimens under various simulated pulsed detonation scenarios for future applications in a pulse denotation engine environment. The variation of the coating apparent thermal conductivity with time is utilized as a health monitoring technique for the coating system under a rapid fluctuating heat flux assuming a coating cracking pattern.

**II. Analytical Modeling of Haynes-188 Under a High Speed Pulsed Heat Flux**

Finite element studies are conducted using ABAQUS standard (ref. 12) to determine the temperature and resulting thermal stress distributions on coated and uncoated circular samples of Haynes 188 substrate. The samples are about 25.4 mm in diameter and 1.575 mm thick. The coating system is a baseline system with a 0.127 mm thick Ni-17(wt.%)Cr-6%Al-0.5%Y (NiCrAlY) bond coat and a 0.381 mm thick ZrO₂-8wt%Y₂O₃ (YSZ) ceramic top coat. Table 1 compares the material thermal and mechanical properties of Haynes 188, NiCrAlY and YSZ, at temperature, as well as a Nickel base-alloy. The simulated heat flux applied to the hot face is a three stage heat flux, with a high
spike of 1200 W/cm$^2$ for 0.2 ms, followed by a 170 W/cm$^2$ plateau for 9.8 ms, and finally followed by a cooling flux of 10 W/cm$^2$ for a 10 ms duration, simulating the cool down of the PDE combustor liner by the filling effect of the new fuel/air mixture. A back cooling boundary condition is imposed to cool down the sample with a 23 °C air with a corresponding 0.152 W/cm$^2$·°C convective film coefficient, to maintain the substrate back face temperature at 615 °C. The time average heat load is equal to 90 W/cm$^2$ with a 50 Hz frequency. The surface temperature distributions as a function of time are shown in figure 3 (a) and (b) for uncoated and coated specimens. For the uncoated specimen, the maximum Haynes 188 top face temperature swings from 706 to 676 °C with each pulse, while the back face temperature remains at around 615 °C. With the application of the coating system, the substrate hot side temperature is maintained more or less around 680 °C with a less than 2 °C temperature swing. On the other hand the temperature of the hot surface of the protective coating is now increased to a maximum temperature of 1084 °C and a minimum temperature of 923 °C with each pulse, due to the low thermal conductivity of the top ceramic top coating. Although the temperature variation in the top coat is increased, it is accomplishing the role of shielding the substrate from the pulsed heat flux. A closer look at the temperature variation with depth reveals that the depth of the temperature swings is limited to be within the top coat layer only with a depth of 0.111 mm as compared to a 0.360 mm for the uncoated specimen as seen in figure 4. The resulting thermal induced stresses are then calculated for the coated and uncoated specimens as a function of the distance from the cooled substrate back face for various time increments and shown in figure 5. For the uncoated specimen, the maximum stress is on the hot face of the specimen with a maximum hoop stress of 31 MPa that decrease to -114 MPa for every cycle resulting in a stress range of 144 MPa. For the coated substrate, the maximum temperature is a negative 8 MPa with a minimum stress of -116 MPa for a resulting compressive/compressive hoop stress range of 108 MPa. The decrease of the stress range with the application of the coating demonstrates clearly the benefit of the coating system in protecting the substrate.
Table 1.—Assumed Thermal and Mechanical Material Properties for the Coating and Substrates.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Density</th>
<th>Elastic Modulus</th>
<th>Poisson's Ratio</th>
<th>Thermal Expansion Coefficient</th>
<th>Thermal Conductivity</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>GPa</td>
<td>x10^-6</td>
<td>C to C</td>
<td>W/m-C</td>
<td>KJ/Kg-C</td>
</tr>
<tr>
<td>Haynes-188</td>
<td>RT</td>
<td>23.2</td>
<td>0.30</td>
<td>11.9</td>
<td>10.4</td>
<td>0.403</td>
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<td></td>
<td>600</td>
<td>18.4</td>
<td>0.30</td>
<td>15.8</td>
<td>21.1</td>
<td>0.523</td>
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<td>900</td>
<td>16.1</td>
<td>0.30</td>
<td>17.9</td>
<td>25.5</td>
<td>0.573</td>
</tr>
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<td>Ni-base alloy</td>
<td>RT</td>
<td>21.3</td>
<td>0.30</td>
<td>12.2</td>
<td>10.7</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>18.0</td>
<td>0.30</td>
<td>15.0</td>
<td>19.0</td>
<td>0.575</td>
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<tr>
<td></td>
<td>900</td>
<td>15.8</td>
<td>0.30</td>
<td>17.7</td>
<td>24.1</td>
<td>0.590</td>
</tr>
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<td>NiCrAlY</td>
<td>RT</td>
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<td>15.0</td>
<td>10.5</td>
<td>0.455</td>
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<tr>
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<td>0.25</td>
<td>15.4</td>
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<td>0.567</td>
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<td>13.5</td>
<td>0.25</td>
<td>17.5</td>
<td>29.0</td>
<td>0.750</td>
</tr>
<tr>
<td>YSZ</td>
<td>5.24</td>
<td>50.0</td>
<td>0.20</td>
<td>10.8</td>
<td>1.0</td>
<td>0.582</td>
</tr>
</tbody>
</table>

Figure 3.—Variation of temperature as a function of time under a pulsed heat flux of 50 Hz, for a) an uncoated 1.575 mm thick Haynes188 substrate and b) a coated Haynes188 substrate with 0.127 mm thick NiCrAlY bond coat and a 0.381 mm YSZ top coat.
Figure 4.—Variation of the temperature as a function of depth at various time increments under a pulsed heat flux at 50 Hz, for (a) an uncoated 1.575 mm thick Haynes188 substrate and (b) a coated Haynes188 substrate with 0.127 mm thick NiCrAlY bond coat and 0.381 mm YSZ top coat.

Figure 5.—Variation of the hoop stresses as a function of the distance measured from cooled substrate side at various time increments under a pulsed heat flux at 50 Hz, for (a) an uncoated 1.575 mm thick Haynes188 substrate and (b) a coated Haynes188 substrate with 0.127 mm thick NiCrAlY bond coat and a 0.381 mm YSZ top coat.

The effect of increasing the pulsed frequency from 50 to 100 Hz and 150 Hz is analyzed next assuming the same time average heat flux of 90 W/cm². The sharp spike of 1200 W/cm² for 0.2 ms is maintained for all three frequencies, but the plateau time and the fill time are now decreased according to the applied frequency. The plateau heat flux is maintained at 170 W/cm². But the fill cooling flux is increased with increasing frequency to maintain the back face temperature at 615 °C and to provide for the constant time average heat load of 90 W/cm². For the 100 Hz simulation, the fill time is now shortened to 5 ms with a fill cooling flux of about 30 W/cm², and for the 150 Hz simulation, the fill time is now 3.33 ms with a fill cooling flux of 51 W/cm². Table II summarizes the finite element results showing the variation of the hot surface maximum temperature and stress with the pulsed frequency.

The maximum temperature decreases from 1190 °C at a 50 Hz pulsed frequency to about 1129 °C at 150 Hz. The depth of the temperature variation is also decreased from 0.111 mm for the 50 Hz pulse to only 0.048 mm for the 150 Hz. Also shown in Table II is the maximum stress and the stress ranges as they vary with the pulsed frequency. Due to the decrease in the depth of the temperature swing with increasing frequency, the hoop stress range at the surface of the top coat is also decreased from 108 MPa at 50 Hz to 71 MPa at 150 Hz. This decrease in stress range is expected to reduce the damage accumulation in the ceramic coating and thus increase the life of the coating as seen next.
III. Experiments on the Effect of Pulsed Heat Flux Frequency on Coating Durability

To verify the effect of the pulsed frequency on the damage accumulation in the coating, pulsed laser tests are performed on a Nickel base alloy substrate with a 0.381 mm thick YSZ top coat and a 0.127 mm thick NiCrAlY bond coat. The controlled tests are performed to maintain the coating surface and coating/substrate interface temperatures at 1300 and 900°C, respectively, with a time average heat flux 120 W/cm², with two pulsed frequencies of 50 and 100 Hz. Pyrometers and thermocouples are used to monitor and record the temperature variation with time, at the coated hot surface, the coating/substrate interface and the cooled back substrate. Figure 6 shows the temperature variation with time of the top face, interface and back face for the two frequencies. Also shown are the normalized apparent coating thermal conductivity variation with time calculated from the measured the temperatures of the top face and the coating/substrate interface. It is postulated that the coating apparent thermal conductivity decreases with increasing coating cracking and delamination (refs. 13 and 14). As shown in figure 6, the apparent coating thermal conductivity at 50 Hz decreases with time as compared to the 100 Hz. Furthermore, for the 100 Hz test actually the coating thermal conductivity increases slightly with time due to sintering. The sample at 50 Hz is cut out and inspected for damage. Figure 7 revealed a network of microcracks initiating from the surface and extending downward into the ceramic coating, after 50 hours of testing. The apparent coating thermal conductivity reduction is a direct result of the presence of arrays of multi-level cracks initiating from the surface of the coating. A calibration of the changes of the apparent coating thermal conductivity with various cracking morphologies is established next to be used as a coating health monitoring technique for damaged ceramic coating systems under rapid alternating heat fluxes.

<table>
<thead>
<tr>
<th></th>
<th>( T_{\text{max}}, \text{C} )</th>
<th>( \Delta T, \text{C} )</th>
<th>Depth, ( \mu \text{m} )</th>
<th>( \sigma_{\text{max}}, \text{MPa} )</th>
<th>( \Delta \sigma, \text{MPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>50 Hz</td>
<td>705</td>
<td>30</td>
<td>360</td>
<td>31</td>
</tr>
<tr>
<td>Coated</td>
<td>50 Hz</td>
<td>1150</td>
<td>190</td>
<td>111</td>
<td>-8</td>
</tr>
<tr>
<td>Coated</td>
<td>100 Hz</td>
<td>1159</td>
<td>159</td>
<td>83</td>
<td>-9</td>
</tr>
<tr>
<td>Coated</td>
<td>150 Hz</td>
<td>1129</td>
<td>129</td>
<td>43</td>
<td>-9</td>
</tr>
</tbody>
</table>
IV. Correlation of the Coating Cracking Morphology to the Apparent Coating Thermal Conductivity

In this section the apparent coating thermal conductivity is correlated with the coating cracking morphology. The apparent coating thermal conductivity is calculated for three cracking morphologies as shown in figure 8: 1) a single main single crack, 2) multiple cracks, and 3) arrays of multiple cracks. The finite element method is employed to calculate the temperature distribution in the coating for the various cracking patterns for a given heat flux. The distance between cracks is kept at about 1 mm, and for the arrays of multiple cracks the axial cracking distance is about 0.05 mm. The crack length considered in this study varies from 0.1 mm to about 0.9 mm. The apparent coating thermal conductivity is simply calculated by multiplying the applied heat flux by the coating thickness and dividing by the difference between the average top face temperature and the average bond coat top coat interface temperature for various crack lengths. The variation of the apparent thermal conductivity with crack length and morphology is also shown in figure 8. For a single crack, the thermal conductivity decays quite rapidly with crack length. For the multiple cracks, the thermal conductivity decays rather slow with increasing crack length as compared to the multi-crack arrays morphology. As shown previously the morphology observed in the 120 W/cm² pulsed heat flux, the cracking morphology can be idealized as multi-crack arrays, as seen in figure 7. Hence, if a cracking morphology is known, the crack growth rate in the coating can easily be determined as a function of the apparent coating thermal conductivity, using the calibrations of figure 8. This methodology is applied to determine
V. Conclusion

A study was conducted to assess the durability of coated combustor liner materials under pulsed heat fluxes, simulating the heat flux profile of a PDE combustor. The coating system consisted of 0.127 mm thick NiCrAlY bond coat and a 0.381 mm thick YSZ top coat. Finite element thermal and stress analyses were performed to determine the temperature and the induced thermal stress distributions on coated and uncoated Haynes-188 substrate under a 50 Hz pulsed heat flux, simulating the PDE heat flux waves. The simulated pulsed heat flux considered had a spike of 1200 W/cm² for 0.2 ms, followed by a plateau at 170 W/cm² for 9.8 ms and finally heat is taken away from the sample with cooling flux of 10 W/cm² simulating the filling segment of the cycle for the remaining 10 ms, for a time average total heat flux of 90 W/cm². Due to the low thermal conductivity of the ceramic top coat, the temperature of the surface increased, but the depth of the fluctuating temperature decreased by one third, resulting in the decrease of the magnitude of the hoop stresses and the stress ranges. Furthermore, as the frequency of the pulsed heat flux increased the depth of the fluctuating temperature decreased, as well as the stress ranges, although the applied time average heat flux was maintained at 90 W/cm². The effect of the increasing frequency was confirmed with experimental studies on a 0.381 mm YSZ top coat on a Nickel base-alloy, showing a decrease in the apparent thermal conductivity of the top coat with time for a 50 Hz pulsed heat flux. At 100 Hz, no decrease in the apparent coating thermal conductivity was observed, but a slight increase noticed. Micrographs of the coating tested at 50 Hz revealed a network of arrays of multi-level microcracks causing the observed reduction in the calculated apparent coating thermal conductivity. Finally, a calibration of the changes of the apparent coating thermal conductivity with various cracking morphologies was established to be used as a coating health monitoring technique for damaged ceramic coating systems. The calibration was used to determine the crack growth rate in a 0.254 mm thick low conductivity coating, ZrO$_2$-Y$_2$O$_3$-Gd$_2$O$_3$-Yb$_2$O$_3$ (ref. 15), at 20 Hz for a time average heat flux of 68 W/cm² providing an estimate of the normalized crack length of 0.05 at a rate 0.0003 per hour, assuming arrays of multi-level cracking morphology.
References


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