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Oxidation- and Creep-Enhanced Fatigue of Haynes 188 Alloy-Oxide Scale System Under Simulated Pulse Detonation Engine Conditions

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OXIDATION- AND CREEP-ENHANCED FATIGUE OF HAYNES 188 ALLOY-OXIDE SCALE SYSTEM UNDER SIMULATED PULSE DETONATION ENGINE CONDITIONS

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ABSTRACT

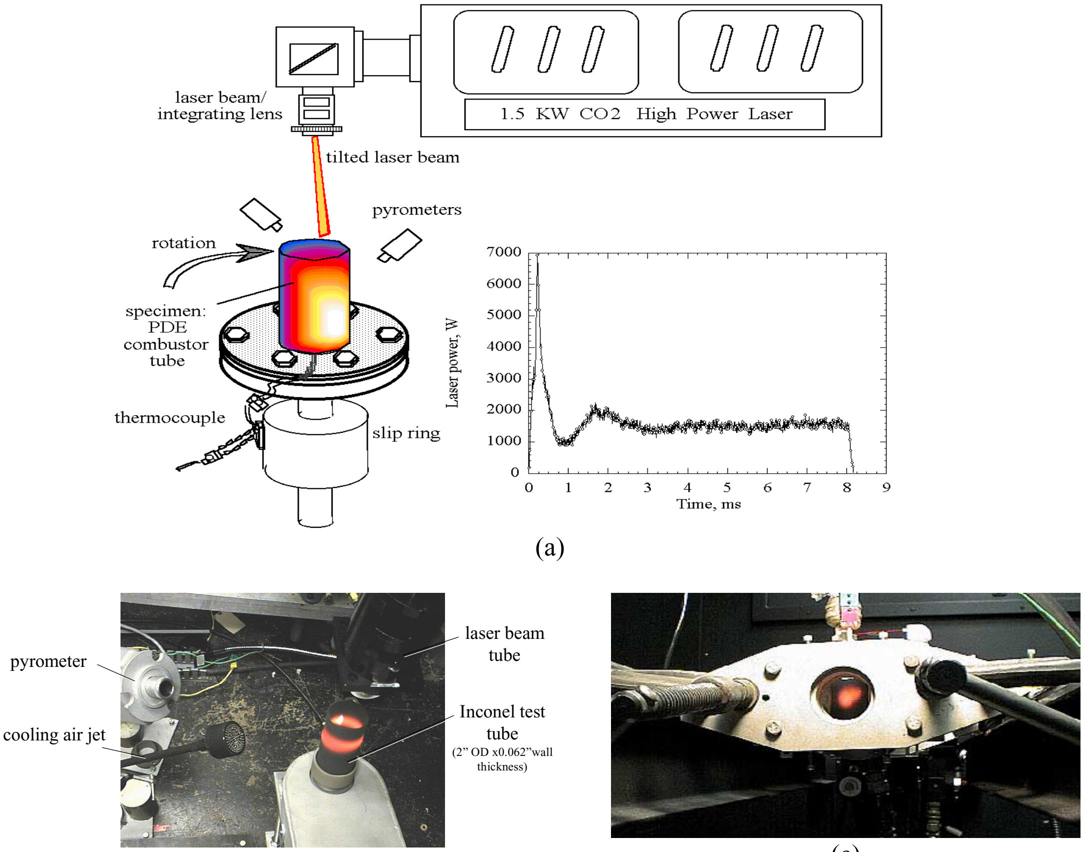
The development of the pulse detonation engine (PDE) requires robust design of the engine components that are capable of enduring harsh detonation environments. In this study, a high cycle thermal fatigue test rig was developed for evaluating candidate PDE combustor materials using a CO_2 laser. The high cycle thermal fatigue behavior of Haynes 188 alloy was investigated under an enhanced pulsed laser test condition of 30 Hz cycle frequency (33 ms pulse period, and 10 ms pulse width including 0.2 ms pulse spike). The temperature swings generated by the laser pulses near the specimen surface were characterized by using one-dimensional finite difference modeling combined with experimental measurements. The temperature swings resulted in significant thermal cyclic stresses in the oxide scale/alloy system, and induced extensive surface cracking. Striations of various sizes were observed at the cracked surfaces and oxide/alloy interfaces under the cyclic stresses. The test results indicated that oxidation and creep-enhanced fatigue at the oxide scale/alloy interface was an important mechanism for the surface crack initiation and propagation under the simulated PDE condition.

INTRODUCTION

Pulse detonation engines (PDEs) have received increasing attention for future aerospace propulsion applications. Because the PDE is designed for a high frequency, intermittent detonation combustion process, extremely high gas temperature and pressure can be realized under the nearly constant-volume combustion environment. The PDEs can potentially achieve higher thermodynamic cycle efficiency and thrust density as compared to traditional constant-pressure combustion gas turbine engines [1]. However, the development of these engines requires robust design of the engine components that are capable of enduring harsh detonation environments. In particular, the detonation combustor chamber, which is designed to sustain and confine the detonation combustion process, will experience high pressure and temperature pulses with a very short duration [2, 3]. Therefore, it is of great importance to evaluate PDE combustor materials and components under simulated engine temperature and stress conditions in the laboratory. In this paper, a laser impulsive thermal fatigue testing approach for evaluating materials to be used in PDE combustor applications is described. The failure mechanisms of the combustor materials under the simulated PDE conditions are also presented.

EXPERIMENTAL

A high cycle thermal fatigue test rig for PDE combustor materials has been established using a 1.5 kW CO_2 laser. A schematic diagram showing the laser test rig approach and examples of the test specimen configurations are shown in Fig. 1. The high power laser, operating in the pulsed mode, can be controlled at various pulse energy levels and waveform distributions. The enhanced laser pulses can be used to mimic the time-dependent temperature and pressure waves encountered in a pulsed detonation engine. Under the enhanced laser pulse condition, a maximum 7.5 kW peak power with a duration of approximately 0.1-0.2 ms (a spike) can be achieved, followed by a plateau region that has about 1/5 of the maximum power level with several ms duration. The laser thermal fatigue rig has also been developed to adopt flat and rotating tubular specimen configurations for the simulated engine tests. More sophisticated laser optic systems can be used to simulate the spatial distributions of the temperature and shock waves in the engine.



(a)

(b)

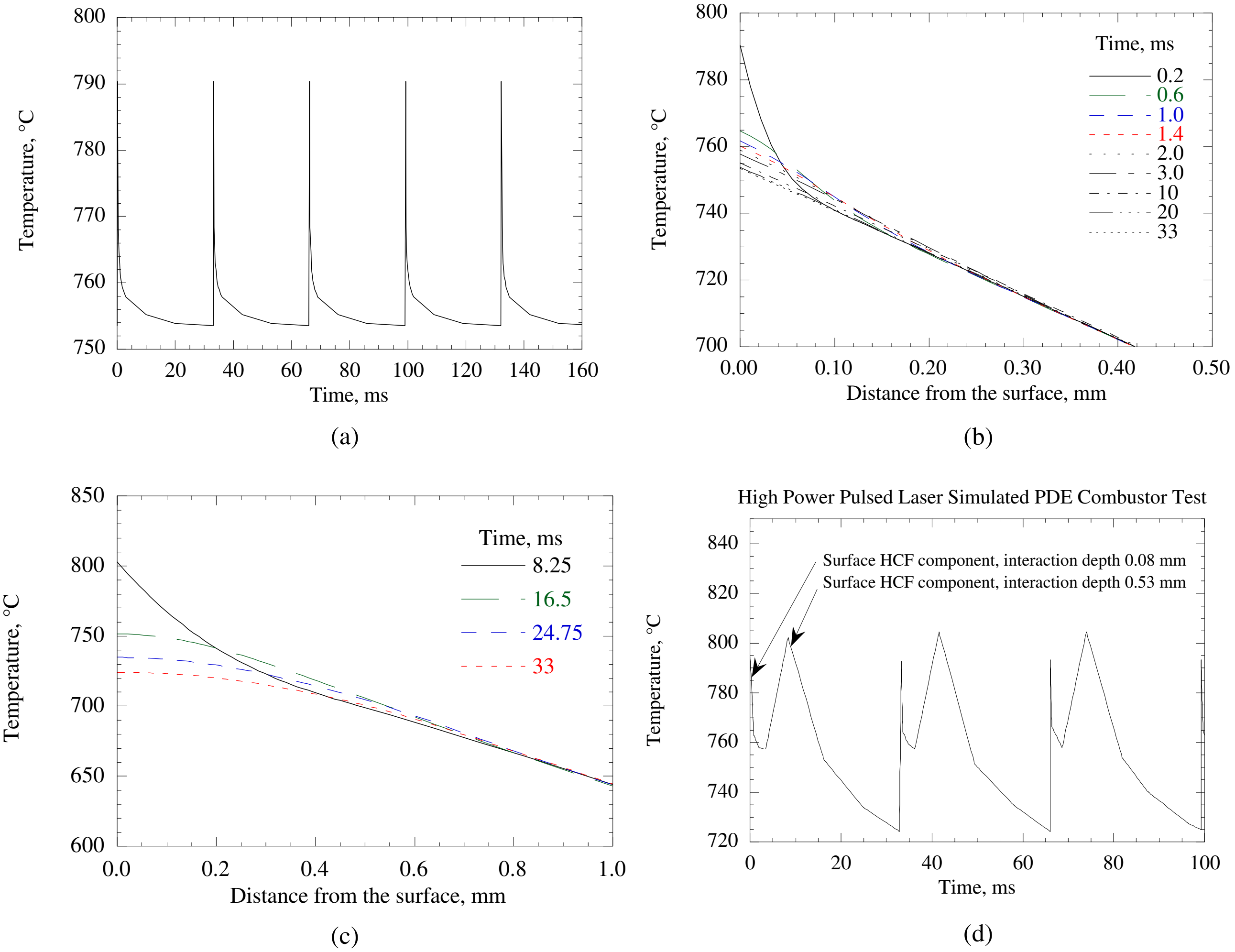
(c)

Fig. 1. A high power CO_2 laser rig developed for testing PDE combustor materials and components under the simulated engine temperature and stress conditions. (a) Schematic diagram showing a laser test rig, and the measured laser pulse waveform from the pulse signal of a 1.5kW CO_2 laser under the enhanced pulse mode using an oscilloscope. The laser pulse width is 8 ms, and a maximum laser power 7.5kW can be achieved over about 0.2 ms duration at the pulse enhancement mode; (b) and (c) Tubular and flat specimen configurations adopted for the simulated PDE engine test, and combined (four point bend) mechanical fatigue and laser surface impulsive thermal fatigue conditions, respectively.

In this study, pulse laser high cycle thermal fatigue behavior has been investigated on flat Haynes 188 alloy specimen (dimension 50x50x1 mm), under the test condition of 30 Hz cycle frequency (33 ms pulse period, and 10 ms pulse width including 0.2 ms pulse spike) [4]. In the test, a gaussian laser beam (with a radius of 16 mm and the above mentioned pulse characteristics) was used to provide the specimen heating and room temperature air was used for specimen backside cooling. Specimen temperatures were measured by two-color pyrometers. The specimens were tested under the high frequency laser pulses at an average surface temperature of 800°C and the back temperature of 650°C. Besides the laser high cycle fatigue (HCF) testing, the specimens were also thermally cycled between the test temperatures and room temperature using 30 min hot cycles with 3 min cooling (low cycle fatigue or LCF), simply by turning on and off the laser power to the specimen surface. The laser induced impulsive temperature profiles and creep response in the test specimens are modeled to help understand the thermal fatigue behavior of the materials system under the laser enhanced HCF and LCF test conditions. The material failure mechanisms under the laser simulated PDE conditions are also presented in this paper.

RESULTS

Figure 2 shows the temperature response and distributions calculated using one-dimensional finite difference models for the Haynes 188 alloy specimen under the enhanced laser pulse thermal fatigue test conditions. The numerical calculations show that that the enhanced 0.2 ms laser pulse spikes, which are used to simulate the PDE temperature and shockwave pulses, can cause a rapid cyclic temperature swing on the specimen surface, as shown in Fig. 2 (a). In addition, an additional 40ºC temperature fluctuation with an interaction depth of 0.08 mm near the specimen surface region will be generated due to the enhanced 0.2 ms laser pulse spikes, as shown in the temperature distribution plot of Fig. 2 (b). This enhanced pulsed temperature swing will be superimposed onto the temperature swing of 80ºC that is induced by the 10 ms regular laser pulse near the 0.53 mm deep surface interaction region (Fig. 2 (c) and Fig. 2 (d)).

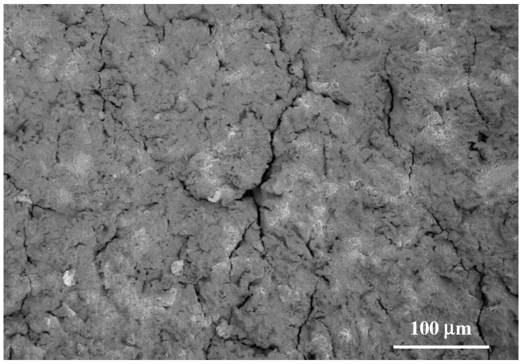


(a) (b) (c) (d)

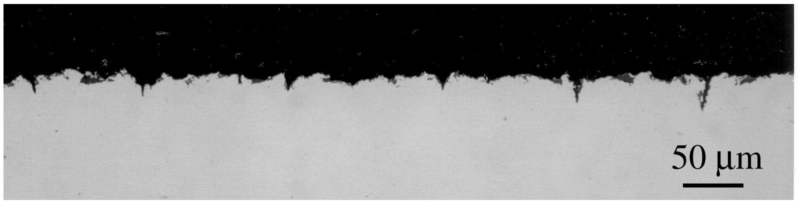
Fig. 2. One-dimensional finite difference modeling results showing the temperature swings on a Haynes 188 specimen under the enhanced pulse condition (33ms pulse period, 10 ms pulse width including 0.2 ms pulse spike). (a) Temperature pulses induced by the high energy laser pulse spike. (b) Temperature swings due to the enhanced, 0.2 ms laser pulse spike. (c) Temperature fluctuations due to the regular 10 ms laser pulse. (d) Superimposed temperature profiles during the enhanced pulse laser testing at the specimen surface.

Specimen failure modes were investigated after the laser thermal fatigue testing. As shown in Fig. 3, extensive surface cracking with the crack depths of approximately 30 μm was observed on the tested specimens under the enhanced laser pulses and thermal cycling. The surface crack morphologies of the specimen are further shown in Fig. 4. As can be seen from Fig. 4, under the oxidizing environments, oxide scales (typically Cr_2O_3 and Ni,Cr spinel oxides) were formed on the Haynes 188 specimen surfaces. Significant alloy creep and fatigue, as indicated by the deformation, cracking and various length scale fatigue striations in the substrate near the oxide/alloy interfaces were observed under the laser test conditions that were involved with large thermal gradients and surface temperature swings. The stresses originated from the large thermal gradients across the specimen, as well as the thermal expansion mismatch between the oxide scales and substrate under the laser HCF and LCF test conditions, resulted in the alloy creep deformation and later the surface cracking due to the oxidation-creep interaction under the complex cyclic stresses.

As shown in Fig. 5, the large induced creep strains, which accumulated at temperature under the thermal and stress gradients, can lead to a large tensile stress state at the surface upon cooling. The specimen surface cracking can be initiated when the creep strain is high enough, and especially when the surface layer is greatly weakened by the presence of the oxidation scales, oxide inclusions, and grain boundary oxide decorations. The cracks initiated can be further propagated under the enhanced laser thermal impulsive fatigue conditions because of the thermal expansion mismatch and thermal stress induced creep-oxidation interactions. The test results suggest that oxidation and creep enhanced fatigue can be an important mechanism for materials surface crack initiation and propagation under the simulated impulsive thermal cyclic conditions.

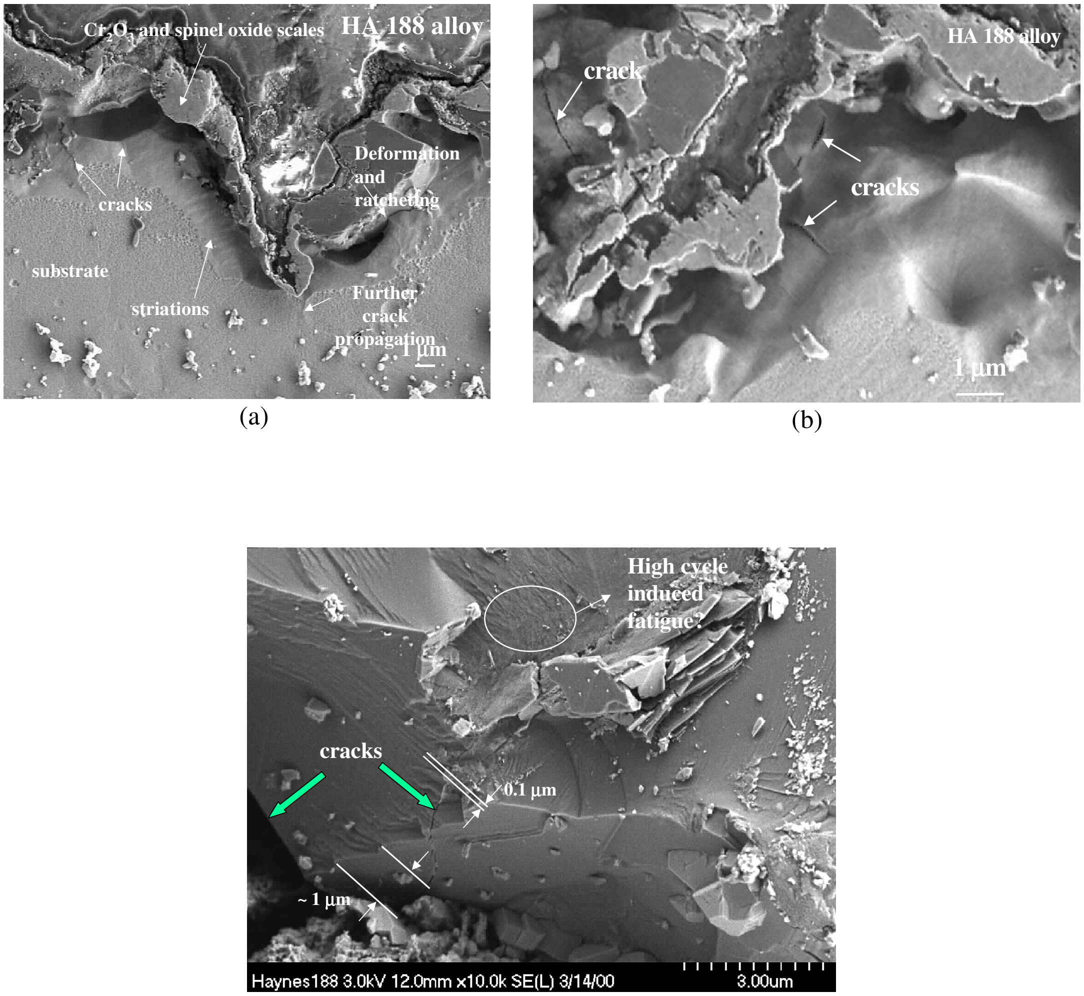


(a)



(b)

Fig. 3. Surface cracking patterns of the Haynes 188 superalloy after the enhanced laser pulses and thermal cycling (10.8 million 30 Hz high cycle fatigue cycles, and 200 30 min-heating-cooling cycles). (b) Cross-section of tested specimen showing surface cracking penetration into the alloy.



(a)

(b)

(c)

Fig. 4. Micrographs showing significant specimen oxidation, creep deformation and fatigue in the alloy substrate near the oxide scale/alloy interfaces after the laser thermal cyclic testing. Oxide scale initial and further growth is detrimental to the materials fatigue resistance due to the thermal expansion mismatch stress induced creep-oxidation interactions.

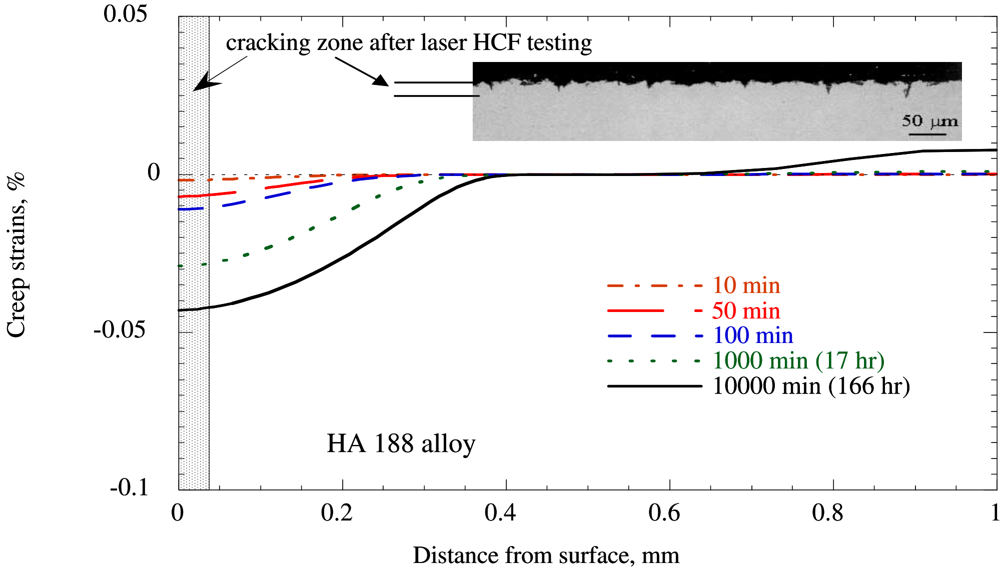


Fig. 5 Modeled creep strain distributions accumulated at temperature as a function of time under the laser thermal gradient testing. Also shown is the surface cracking morphology after the laser testing. Large compressive creep strains will occur at the specimen surface, which can lead to a large tensile stress state upon cooling. The specimen surface cracking can be initiated under high creep strains combined with the surface weakening due to oxidation.

CONCLUSIONS

A high cycle-enhanced pulse CO_2 laser thermal fatigue rig was developed for evaluating candidate PDE combustor materials under simulated PDE conditions. The thermal gradient and temperature swings can result in significant thermal cyclic stresses in the material system, and thus can induce surface cracking under surface oxidation, creep and the thermal cycling conditions. The oxidation- and creep-enhanced fatigue cracking was demonstrated experimentally. Fatigue striations of various sizes were observed at the cracked surfaces and oxide scale/alloy interfaces. The test results indicated that oxidation and creep enhanced fatigue at the oxide scale/alloy interface was an important mechanism for the surface crack initiation and propagation under the laser induced surface impulsive fatigue conditions.

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