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Impact resistance of environmental barrier coated SiC/SiC composites

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Abstract

Impact performance of 2D woven SiC/SiC composites coated with 225 and 525 μm thick environmental barrier coating (EBC) was investigated. The composites were fabricated by melt infiltration and the EBC was deposited by plasma spray. Impact tests were conducted at room temperature and at 1316 °C in air using 1.59 mm diameter steel-balls at projectile velocities ranging from 110 to 375 m/s. Both microscopy and non-destructive evaluation (NDE) methods were used to determine the extent of damage in the substrate and coating with increasing projectile velocity. The impacted specimens were tensile tested at room temperature to determine their residual mechanical properties. At projectile velocities less than 125 m/s, no detectable internal damage was noticed in the MI SiC/SiC composites coated with 525 μm EBC. With increase in projectile velocity beyond this value, spallation of EBC layers, delamination of fiber plies, and fiber fracture were detected. At a fixed projectile velocity, the composites coated with 525 μm EBC showed less damage than those coated with 225 μm EBC. Both types of coated composites retained a large fraction of the baseline properties of the as-fabricated composites and exhibited non-brittle failure after impact testing. Furnace exposure of impacted specimens in a moisture environment at 1316 °C for 500 h indicated that the through-the-thickness cracks in the coating and delamination cracks in the substrate generated after impact testing acted as conduits for internal oxidation.

Keywords: Impact; EBC coatings; SiC/SiC composites; Mechanical properties; NDE

1. Introduction

SiC fiber reinforced SiC matrix composites (SiC/SiC) are candidate materials for next generation aerospace, power, and nuclear applications because of their high temperature strength, high creep resistance, and high thermal conductivity. Currently these composites are fabricated by three processing approaches: melt infiltration (MI), chemical vapor infiltration (CVI), or polymer infiltration and pyrolysis (PIP). To date the SiC/SiC composites fabricated by MI and by CVI are the most investigated [1]. Studies have shown that all three types of SiC/SiC composites are stable up to 1300 °C in air or in oxidizing environments after extended exposure times, predominantly due to growth of an adherent protective silica scale on the external surfaces [2,3]. In contrast, in a combustion environment containing moisture, these composites exhibit recession due to simultaneous formation and volatilization of silica at temperatures greater than 1100 °C [4,5]. To protect these composites from surface recession environmental barrier coatings (EBCs) have been developed. The key examples are multilayered coatings having a barium strontium aluminum silicate (BSAS) or rare earth silicate top coat [6,7]. The BSAS and rare earth silicate based EBCs have upper temperature capabilities of ∼1316 °C [7] and ∼1482 °C [8], respectively for applications over thousands of hours. Flat coupons and sub-elements of MI SiC/SiC composites coated with a BSAS based EBC have been investigated under engine exposure conditions for strength and microstructural stability at temperatures to 1300 °C [9,10]. Also, durability of a MI SiC/SiC composite combustor liner coated with the BSAS based EBC has been demonstrated in an industrial scale engine at ∼1200 °C for

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up to 14,000 h [11]. However, long term durability of EBC on MI SiC/SiC composite components such as nozzle vanes and blades, in the flow path of the combustion gas, has not been fully investigated. In the flow path of a typical turbine, the combustions gas is traveling at velocities as high as 600 m/s [12]. Any objects that enter the turbine inlet are carried by the combustion gas and impact the components. A wide variety of particles and objects can be ingested into the turbine engines depending on the operating conditions. In commercial aero-derivative engines, small objects such as rivets, solder, spalled coatings, ice particles and coke clinkers and large objects such as ice slabs and birds commonly enter into the gas stream. In addition to the above objects, sand and salt are commonly ingested in military engines. Single small object impact can cause local damage to the EBC and substrate, whereas single large object impact can lead to failure of the component. In contrast, multiple small particle impacts that occur from sand erode the coatings as well as substrate of the components.

In current engines, the metal components are coated with a thermal barrier coating (TBC) to keep the substrate temperature below the design allowable. The TBC serves as an insulating layer between the substrate and the hot gases, reducing the substrate temperature substantially, and increasing life of the components. However, the design life of the components is based on life of the uncoated metal under the operating conditions of the engines. In other words the component substrate is prime reliant, not the TBC. Under the operating conditions of the engines, the TBC may get embedded into the substrate due to impact or locally spall off due to thermal cycling, causing hot spots [13,14]. Effects of hot spots on the long term durability are accounted for in the design allowable. In addition, the impact of small hard objects on components causes local damage but not complete failure because of the compliant nature of the substrate material. Oxygen in the combustion environment oxidizes the metallic components resulting in growth of oxide scale on their external surfaces. The influence of moisture in the combustion environment on the oxide scale growth has been fully documented. Also there is no evidence of adverse effects of oxide scale growth on the aero performance, life and thermo-mechanical properties of the components. On the other hand, creep, sand erosion and corrosion due to deposition of salt and siliceous material are major life limiting issues in the current engines.

In contrast, SiC/SiC composites are not as compliant as metals and require a reliable EBC at operating temperatures greater than 1100 °C. Without an EBC the substrate material does not have adequate life. Therefore, for successful use of SiC/SiC composites in hot sections of future turbines, the EBC should be prime reliant. This coating should not only protect the component/substrate against surface recession in a moisture environment, but also provide adequate impact, corrosion, and erosion resistance. It should also retain the design strength of the components under the operating and maintenance cycles of the engine.

Various studies indicate that EBCs developed for the state-of-the art SiC/SiC composites have adequate cyclic oxidative stability against moisture and do not affect in-plane properties of the composites upon deposition [7–9]. On the other hand, corrosion, erosion and impact resistance of EBC coated SiC/SiC composites are not well understood.

Impact damage in coated fiber reinforced ceramic matrix composites is very complex and is influenced by variety of factors such as composite constituents, fiber architecture, EBC properties and morphology, projectile properties, test conditions, and specimen thickness. In spite of this complexity, for a given fiber architecture of the composite, coating microstructure, and testing conditions, general trends in the impact damage mechanisms and consequences of impact damage on composite performance can be determined. With this information, optimum fiber architecture and coating microstructure can be developed to improve impact resistance.

The current study was conducted to understand the basic mechanisms of impact damage, and to determine the influence of impact damage on thermo-mechanical properties and oxidative stability of environmental barrier coated MI SiC/SiC composites. In this study, the influence of EBC layer thickness on single particle impact resistance of coated 2D woven MI SiC/SiC composites has been investigated at room temperature and at 1316 °C. Damage evolution in the EBC and within the substrate with increasing projectile velocity was monitored with optical microscopy, scanning electron microscopy (SEM), pulsed thermography, and computed tomography. Effects of impact damage on in-plane tensile properties of the composite specimens were measured at room temperature and 1316 °C. Some of the impact damaged specimens were also exposed to a mixture of 90% H_2O + 10% O_2 at 0.1 MPa and 1316 °C for 500 h to assess extent of recession by oxidation. Wherever possible, the impact resistance and damage evolution of coated and uncoated MI SiC/SiC composites are compared. Impact resistance of uncoated 2D woven MI SiC/SiC composites is discussed in a companion paper.

2. Experimental procedure

2.1. Material

The MI SiC/SiC composite panels, ∼230 mm (*L*) by 150 mm (*W*) by 2.3 mm (*T*), were purchased from GE Composite Ceramic Products (GECCP), Newark, Delaware. The composites were fabricated by infiltrating SiC particle slurry into a porous SiC/SiC preform and then filling the remaining porosity with molten silicon. The processing details can be found in [15]. The composite consists of eight layers of 2D woven 5HS Sylramic-iBN SiC fiber cloth in a complex SiC matrix that is a mixture of chemically vapor deposited SiC matrix, SiC particles and silicon metal. The as-fabricated SiC/SiC composites contained ∼34 vol% SiC fibers, ∼5 vol% BN coating, and ∼58 vol% SiC coating, SiC particles and silicon, and ∼3 vol% porosity. As indicated above, the purchased composite panel showed batch-to-batch variation in thickness between 2.2 and 2.4 mm. The reasons for thickness variation are manual lay up of fiber mats within the fixture and other processing steps in the early stages of composite fabrication.