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Impact resistance of uncoated SiC/SiC composites

Ramakrishna T. Bhatt [a,*], Sung R. Choi [b], Laura M. Cosgriff [c], Dennis S. Fox [d], Kang N. Lee [e]

[a] U.S. Army Vehicle Technology Directorate, NASA Glenn Research Center, Cleveland, OH 44135, United States
[b] Naval Air Systems Command, Patuxent River, MD 20670, United States
[c] Cleveland State University, Cleveland, OH 44115, United States
[d] NASA Glenn Research Center, Cleveland, OH 44135, United States
[e] Rolls-Royce Corporation, Indianapolis, IN 46206, United States

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Abstract

Two-dimensional woven SiC/SiC composites fabricated by melt infiltration method were impact tested at room temperature and at 1316 °C in air using 1.59-mm diameter steel-ball projectiles at velocities ranging from 115 to 400 m/s. The extent of substrate damage with increasing projectile velocity was imaged and analyzed using optical and scanning electron microscopy, and non-destructive evaluation (NDE) methods such as pulsed thermography, and computed tomography. The impacted specimens were tensile tested at room temperature to determine their residual mechanical properties. Results indicate that at 115 m/s projectile velocity, the composite showed no noticeable surface or internal damage and retained its as-fabricated mechanical properties. As the projectile velocity increased above this value, the internal damage increased and mechanical properties degraded. At velocities >300 m/s, the projectile penetrated through the composite, but the composite retained ~50% of the ultimate tensile strength of the as-fabricated composite and exhibited non-brittle failure. Predominant internal damages are delamination of fiber plies, fiber fracture and matrix shearing.

Keywords: Impact; SiC/SiC composite; NDE; Mechanical properties

1. Introduction

The realization of improved efficiency for engines used for aero and space propulsion as well as for land-based power generation will depend strongly on advancements made in the upper use temperature and life capability of the structural materials used for the engine hot-section components. Components with improved thermal capability and longer life between maintenance cycles will allow improved system performance by reducing cooling requirements and life-cycle costs. This in turn is expected to reduce fuel consumption, and NO_x and CO_2 emissions, for commercial aircraft; to allow improved thrust-to-weight and performance for space and military aircraft; and to reduce emissions and power costs for the electrical power industry.

The aforementioned benefits can be achieved by replacing metallic components with fiber-reinforced ceramic matrix composites (CMC) in general and fiber-reinforced silicon-carbide (SiC) matrix composites in particular [1]. These materials are not only lighter and capable of higher use temperatures than state-of-the-art metallic alloys and oxide matrix composites (~1100 °C), but also are capable of providing significantly better static and dynamic toughness than un-reinforced silicon-based monolithic ceramics. However, for successful application in advanced engine systems, the SiC matrix composites should be able to withstand the component service stresses and temperatures for the desired component lifetime. In an oxidizing environment, CMC display excellent oxidation resistance at temperatures to 1300 °C, but in combustion environment containing moisture, they are unstable due to volatilization of protective silica which results in surface recession [2,3]. To avoid surface recession, environmental barrier coatings have been developed [4–6].

From an operational point of view, the materials used for turbine blade and vane applications should not only have high mechanical properties and oxidation resistance, but also should

* Corresponding author. Tel.: +1 216 433 5513; fax: +1 216 433 5544.
E-mail address: Ramakrishna.T.Bhatt@nasa.gov (R.T. Bhatt).

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have adequate erosion, corrosion, and foreign object damage (FOD) resistance. The FOD problem is more frequent in the compressors than in the turbines. Most of the FOD data on ceramic and composite materials are usually related to multiple erosion and strength degradation by spherical indentation. However single particle/object damage can also be a very serious problem in some components. In current engines, the average velocity of combustion gas in the turbine could reach ∼600 m/s and the average tip speed of the turbine rotor blade can reach 700 m/s [7]. Therefore any object that enters the gas flow path can also travel at a velocity as high as that of the gas stream. Depending on the projectile mass and impact on the turbine nozzle vanes or blades, it can cause damage to the coating and the substrate, and under extreme conditions fracture the components [8]. In general, the FOD spectrum includes both small and large-bodies whose size range from sub-micron to several centimeters in diameter. Damage created by objects such as sand, rocks, rivets, coke clinkers, and ice balls is generally referred to as small body damage. FOD created by ice slabs and birds is referred to as large body damage. Impact damage can occur under several failure modes such as chipping, bending, shearing, Hertzian fracture, depending on where the object strikes the components [9]. Sometimes the secondary damage may be much greater than the primary damage. For example, the major damage in the blade is not due to initial impact but due to damage created by intensity of the shock wave propagating back and forth from the impact site to the root of the blade, causing it to buckle. The extent of impact damage can vary depending on substrate parameters such as substrate hardness, thickness, support, coating, fiber architecture, stiffness, and temperature, and those related to projectiles parameters such as size, hardness, shape, velocity, and angle of incidence relative to the substrate. Currently no ASTM standard test has been developed to generate baseline impact data that can be scaled to design a component. However, gas gun impact tests help in identifying basic damage mechanisms and qualitatively ranking impact resistance of different materials tested in similar conditions.

In current engines, the component materials are prime reliant and their design life is based on the life of the uncoated substrate at the operating conditions. Addition of a thermal barrier coating (TBC) may extend the life of the components. The local hot spots created due to loss of TBC from impact are factored in the design life of the components. Knowing the trajectory of the gas stream, the mass and momentum of the projectiles, and material properties of the substrates, engine designers were able to study component response under impact conditions using DYNA 3D code developed at the Lawrence Livermore National Laboratory, Livermore, California. By changing the component shape and size, the designers were able to reduce or avoid structural damage due to impact in the current metallic components. However, particle erosion and corrosion are still major issues.

Although the advanced fiber reinforced ceramic composites have a high strength-to-density ratio and temperature capabilities 200–300 °C higher than metallic materials, they also show limited strain capability compared to metals and require an environmental barrier coating (EBC) coating to survive in the combustion environment. Under small body impact conditions, CMC components may experience damage to the EBC as well as substrate. The damage can lead to internal oxidation, recession, and loss of mechanical properties.

The current study was conducted to understand basic impact damage mechanisms and the role played by fiber architecture and constituents on impact damage of uncoated and coated SiC/SiC composites. The portion of the study discussed in this paper had three objectives: first, to determine impact behavior of MI SiC/SiC composites at room temperature and 1316 °C in air; second to categorize and quantify the damage using NDE methods; third to determine influence of impact damage on tensile properties. Impact resistance of EBC coated composites and influence of local coating spalling on durability of the composite will be discussed in a separate paper.

2. Experimental procedure

2.1. Material and specimen preparation

The Sylramic-iBN SiC fiber-reinforced SiC matrix composite panels used for impact testing were purchased from GE Composite Ceramic Products (GECCP), Newark, Delaware. The composites were fabricated by a combination of slurry casting and melt infiltration method similar to that reported in reference [10]. For fabrication, the SiC fiber tows (Sylramic^{TM}) from Dow Corning, Midland, MI, were woven into 0/90, 5-harness satin fabric at Albany International Techniweave, Rochester, NH. The woven cloth was treated at the NASA Glenn Research Center by a proprietary process to convert Sylramic fibers into Sylramic-iBN fibers [11]. To describe the composite processing method briefly, the Sylramic-iBN fabric was cut into 230 mm × 150 mm pieces. Eight pieces of fabric were stacked and squeezed in a graphite fixture, and then chemically vapor infiltrated (CVI) with a thin layer of BN-based interphase coating, followed by a layer of SiC matrix over-coating to produce fiber preforms which contained open porosity ranging from 20 to 40 vol.%. In the final stage, the preforms were infiltrated with SiC particles by slurry casting to fill the open porosity. Any remaining open porosity was infiltrated with molten silicon near 1400 °C. For brevity, the Sylramic-iBN fiber-reinforced SiC/SiC composites are henceforth referred to as MI SiC/SiC composites.

The nominal dimensions of as-fabricated composite panels were ∼230-mm (*L*) × 150-mm (*W*) × 2.3-mm (*T*). The panels were machined into tensile dog-boned specimens of dimensions 152-mm (*L*), 13-mm (*W*), and 2.3-mm (*T*) with a reduced gage section. On three tensile bars, a 1.59-mm hole was drilled at the center of gage section to simulate a through-the-thickness hole created by impact tests.

2.2. Impact testing and damage characterization methods

A gas propelled impact gun unit similar to that described in [12] was used for impact testing. Fig. 1 shows a schematic diagram of the gas gun facility and the specimen support system. The target specimen was mounted in a test fixture that was placed in front of and at a distance ∼25–30 cm away from the impact gun. The top and bottom ends of the specimen were held