Composites: Part B 56 (2014) 142–148

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Damage mechanism of a carbon fiber ceramic composite during the step-loading indentation and its effect on the mechanical properties

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ARTICLE INFO

Article history:
Received 12 March 2013
Accepted 12 August 2013
Available online 21 August 2013

Keywords:
A. Ceramic matrix composites
B. Damage tolerance
B. Impact behavior
D. Mechanical testing

ABSTRACT

Indentation damage to a carbon fiber silicon carbide composite (C/SiC) was introduced and then investigated using a step-loading method to understand the impact mechanism. Damages at different indentation energies were characterized by thermography, computed tomography, and microscopy. The indentation energy effects on the residual compressive and tensile strengths were compared. The indentation process indicates that below 0.96 J, the linear elastic behavior and the extensively cracking in the SiC matrix mainly take place in the C/SiC composite, above which it turns into the load-bearing, debonding, breaking and pulling out of the fibers. The C/SiC composites thus have dual damage resistances to the indentation loading, which are mean 1544.5 N from the matrix and 1839.8 N from the fibers respectively. It is evaluated that the fibers mainly absorbed more than 70% of the indentation energy, and the matrix, approximately 30%. Visible indentation damage is identified to initiate from around 0.48 J, behaving as the compressive shear failure of the matrix in the front side, and the tensile breaking of the fibers in the back side. Delaminlation occurs always along the interfaces of the compressive and tensile stress states, resulting accordingly in much larger real damage areas than the apparent ones. With increasing indentation energies, the decreasing rate of the compressive strength is nearly four times higher than that of the tensile ones, revealing that the former is more sensitive to the indentation damage than the latter. The indentation-failed composites still retain 77% residual compressive strength (212.5 MPa) and 89% residual tensile strength (169.5 MPa), respectively.

1. Introduction

Since the fiber composites have applied to aircraft and space shuttle structures, impact damage is always one of key points for designers and airplane users, and focus of new materials' development. Fiber reinforced ceramic matrix composites (CMCs), especially fiber reinforced SiC matrix composites (e.g., C/SiCs, SiC/SiCs), have an increasingly important application prospect in aeronautic and astronautic fields [1–5]. From the view of utilization, the CMCs for engine hot-section parts and space vehicle thermal protection systems (TPS) need have not only good mechanical properties and oxidation resistance, but also excellent capacity resistant to foreign object's impact (FOI) [6–9]. The loss of the space shuttle Columbia highlighted the unprecedented concerns about the fabrication-induced defects and environmental/mechanical damage of the CMC parts, which include the TPS and control surfaces of the shuttle [10]. The composites' capacities resistant to the impact included damage resistance and damage tolerance: the former was the resistance of the materials to the impact events and the latter was effect of the damaged structures on the mechanical properties.

Much previous research on the impact response behavior has been devoted to the fiber reinforced polymers with increasing applications for various aircraft structures [11,12]. The CMCs, however, receive relatively limited attention, mainly focusing on the high velocity impact (>100 m/s) behavior of the SiC/SiC composites with [13] and without [14–16] environmental barrier coating (EBC) coatings by using a projectile steel ball system. Effects of the impact velocity, coating thickness, preform structures, thermally exposed environments were concerned and discussed. The residual mechanical properties were then related to the damaged area, impact energy and microstructures [17]. It is exciting that at velocities >300 m/s the completely penetrated-through SiC/SiC composites retain ∼50% of the ultimate tensile strength with non-brittle failure mode.

However, low velocity impact (LVI) is considered as a very important issue for laminated CMC plates because such kinds of composites can be induced into an internal non-visual damage reducing remarkably the strength. This type of contact damage is usually caused by the dropped tools, removed shuttle tiles, or even small hit during the transportation. This inconspicuous damage,

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http://dx.doi.org/10.1016/j.compositesb.2013.08.058

however, is possibly fatal and can easily result in the ceramic matrix cracking, through which the high temperature applied environmental gas oxidizes the reinforcing fiber or the carbonaceous interface leading to the catastrophic failure of the crafts. A quasi-static indentation (QSI) method (i.e., indentation tests) is widely accepted to understand the LVI damage process in the fiber composites due to their similar principle [7]. Recently, Herb et al. [6,7] reported both the static indentation and LVI investigation on a three dimensional (3D) SiC/SiC thin plate. The results indicate that the damage zone remains localized beneath the indenter/impactor because the 3D fiber architectures in the composites effectively prevent delamination, accordingly retaining good residual tensile strength with insensitivity to the impacted zone. But for 2D laminates, the invisible delamination readily propagates after the LVI and especially decreases the in-plane compressive strength parallel to the interlayer direction. So far, few LVI damage data involving the 2D CMCs is reported [17,18] and the corresponding damage process/mechanism is not yet understood although this preform is simple and commonly-used for many applications such as exhaust nozzle flaps, TPS tiles etc.

This article dealt with explanation of the LVI damage process and mechanism of a thin 2D C/SiC composite plate using a step-loading indentation method. The damage absorbed with different indentation energies was observed by thermography, X-ray computed tomography (CT), and microscopy. Residual mechanical properties were related to the increasing damage size/energies and then the sensitivities of the damage to compressive and tensile strengths were compared.

2. Experiments and methods

2.1. Materials

T300™ carbon fiber [0°/90°] fabric (Toray industries Inc., Tokyo, Japan) was used to prepare 2D preform by laminating layer by layer. Pyrolytic carbon (PyC) interface was deposited on the fibers inside the 2D preform by chemical vapor deposition (CVD) method at around 900 °C, and then SiC matrix was infiltrated into the preform by chemical vapor infiltration (CVI) method at around 1000 °C. The detailed CVD and CVI conditions and parameters were described elsewhere [1,2]. In order to investigate the effects of the indentation damage on tensile and compressive properties, the C/SiC specimens were cut from the as-fabricated composite plates into dimensions of 200 mm (length) × 50 mm (width) × 3 mm (thickness) for tension, and into dimensions of 150 mm × 50 mm × 3 mm for compression after the same QSI tests. The densities of the as-received composite specimens were 2.0 g/cm^3 in average and the volume fraction of carbon fiber was around 40%.

2.2. QSI tests

For understanding the impact damage procedure and mechanism, a step-loading indentation test was used to introduce the indentation damage with an electric universal testing machine (Model CSS-44100, CRITM, Changchun, China). Fig. 1 shows the indentation experimental setup with configuration of the sample, indenter, and centrally-hollow supporter. Indenter is 45# steel hemisphere in 12.7 mm diameter according to ASTM standard. The supporter is designed as a hollow square for indentation loading at the center and the tested sample can be supported only along its four sides. Maximum load of the tester is 10 ton. The QSI test was carried out to realize step-loading in displacement controlled mode with a loading rate of 0.3 mm/min. When the displacements reached at d = 0.5, 1, 1.5, 2 and 2.5 mm, the QSI tests were automatically interrupted to measure the QSI damage size and residual mechanical properties. The depth of the QSI damage was measured by a laser distance meter (Keyence LK-G30 type), and then the damage radius could be calculated by,

$$r_{QSI} = \sqrt{R_I^2 - (R_I - h)^2} \quad (1)$$

where r_{QSI} is the damage radius, R_I is the indenter radius and h, the damage depth.

The residual tensile and compressive properties after the QSI tests were measured on a servo-hydraulic universal testing machine (Model 8801, Instron Ltd., High Wycombe, England) with the damaged C/SiC samples at different indentation d of 0.5, 1, 1.5, 2 and 2.5 mm. The mechanical tests were carried out in a displacement controlled mode with a loading rate of 0.2 mm/min, and both ends of the sample were bonded with Aluminum tab in order to prevent the sample end from grip crush. The plate sample number of each condition is two to guarantee data efficiency. Microstructures and morphologies of the C/SiC samples were observed by scanning electron microscopy (SEM, Hitach S-2700, Tokyo, Japan).

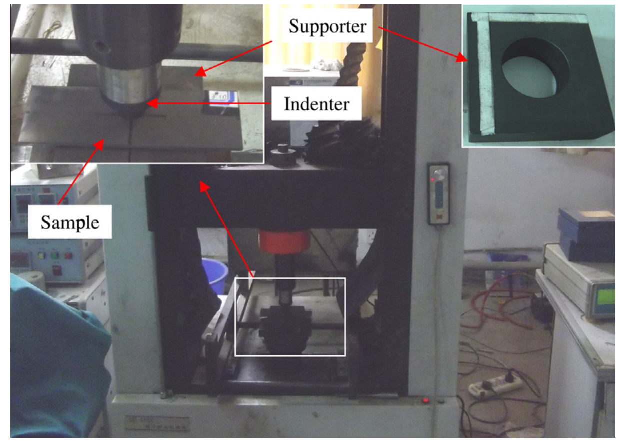

Fig. 1. Photo showing the indentation experimental setup with configuration of sample, indenter, and centrally-hollow supporter.

2.3. Nondestructive tests

An infrared (IR) thermography system (EchoTherm®, Thermal Wave Imaging Inc., USA) was used to examine the QSI damage. The IR imager is a commercial radiometer with a cooled 240H × 320 V-element GaAs focal plane array detector. The expanded field-of-view of this lens is 20° horizontally and 15° vertically. Heat application is achieved by directing the output of two 2.4 kJ xenon flash lamps contained within a hood assembly that helps to focus the energy onto the inspection surface. The front (indentation tested) sides of the C/SiC plate samples were irradiated with the flash of light momentarily. After the flash, the surface radiates energy much like reflection of light. The irradiated surface also conducts heat into the sub-surface. With time, we first get the IR image of the surface and subsequently the images of the sample at deeper thickness as the heat is conducted.

An X-ray computed tomography (CT, BT500, Indintro Co. Ltd., Moscow Russia) was provided to examine the QSI damage of the C/SiC composites. Basic principle of the CT inspection method is described in detail in the previous work [8,9]. The CT system allowed 450 kV tube voltages with a spatial resolution of up to 2 lp/mm and single slice thickness of 0.5 mm for detecting changes in density as well as defect.