An investigation of dynamic failure progress and properties of 2D C/SiC composite from 173K to 1273K by SHTB

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Abstract: Our work studies the dynamic properties of coated and uncoated 2D C/SiC composite material from 173K to 1273K by means of Split Hopkinson Tensile Bar. Examination of the failure process of the specimen by SIM D8 ultra high-speed camera and damage analysis help define the three phases of crack propagation, namely: the elastic pre-damaged phase, the yielding phase or the crack-initiating phase, and the failure phase or the phase of fast-spreading cracks. Experimental results also reveal that the dynamic tensile strength of both coated and uncoated composites decreases with the increase of temperature and decreases more conspicuously at higher temperature. An SEM is employed to examine the fracture surface and damage of C/SiC composites at different temperatures are determined by calculation. Finally, k was introduced according to the Cowper-Symonds fitting model to describe the temperature dependency. This implies a greater significance of SiC coating on the properties of the composite with the increase of temperature. Thus, it is believed that coated composite within the temperature range of 173K to 1273K displays a superior impact property compared with uncoated composite, and is a better structural thermal protection material.

Key words: C/SiC composite; SHTB; dynamic tensile deformation; damage process; SEM; Cowper-Symonds fitting model

1. Introduction

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With the increasing passion for the unknown, aerospace vehicles are continually pushing the limits of technology and subjected to more complex service conditions and wider-ranging working temperatures. For example, the aerospace vehicles could be working at a temperature of 90K in the outer space, while the thermal-protection materials used in hyper-sonic aircraft or combustion chamber, turbine blades or jet nozzle could be servicing at temperatures as high as 2700K[1-4]. In this context, two dimensional C fibers reinforced silicon carbide matrix (2D-C/SiC) composites have been rightly considered as one of the cornerstone materials applied in various aerospace structures subjected to severe circumstances, due to their high temperature sustainability, low density, high specific strength, corrosion and oxidization resistance[5-7].

C/SiC composite has also been inevitably subjected to impact loading and much research has been carried out to study its mechanical properties under static loading [8-15]. However, the working conditions of composite materials imply frequent dynamic or impact loading, such as the launching and landing moments when the structure or material receives discrete or space debris impact with a very short duration of action and high deformation rate. In this regard, ever since the 80's last century, the mechanical properties of composite materials under impact loading have been studied by researchers. Harding and Welsh [16, 17] researched into the dynamic experiments on C fibers reinforced polymer (CFRP) under strain rates of 10^{-4} - 10^3 /s with a conclusion that the material is not rate-sensitive. Todo et al. [18] carried out experiments with a strain rate between 10^{-2} -40/s and concluded that the strength, modulus and the strain of the tested C fibers increase with the increase of strain rate. Camus et al. [19] investigated the damage mechanism and associated mechanical response of 2D C/SiC composite subjected to uniaxial tensile and compressive loadings at room temperature from which an extended non-linear stress/strain response was evidenced. Zhang et al. [20] investigated experimentally and numerically quasi-static and high strain rate compressive behaviors of basalt/vinyl ester 3D orthogonal woven composites along three perpendicular yarn directions.

At the same time, it is worth noting that impact loading of materials also comes with various complex environmental factors like temperature and oxidization, which individually or in a coupled way have certain bearings on the impact properties of composite materials and thus need to be taken into consideration in related studies. Engesser[21] carried out a monotonic tensile test performed at 823K and compared with a room temperature monotonic test. The study showed that elevated temperature had little effect on the ultimate tensile strength of C/SiC. Rio et al. [22] studied the dynamic tensile behavior of CFRPs at temperature of 293K and 213K by SHPB. Results showed little influence of temperature and strain rate on the tensile strength when loaded in the fiber direction while the strength increases appreciably in the transverse direction at low temperature and high strain rate. Yuan et al. [23] studied into the dynamic compressive fracture behavior of C/C composites using a modified split Hopkinson pressure bar under out-plane loading. The results showed that the compressive strength and stiffness were increased at high strain rate and fiber failure under dynamic compressive loading was characterized by multiple splitting without extensive debonding. Labrugere [24, 25] et al studied the dynamic tensile properties of the material at 1100-1300□ which turned out to be supreme. Li et al [26-28] systematically investigated into the dynamic compressive properties of C/SiC material at strain rates ranging from quasi-static to $10^3/s$ and temperatures ranging from room temperature to 1273K. The results showed that the material is strain-rate sensitive with the dynamic compressive strength decreased with the increase of rise of temperature.

As a key material in aerospace structural design, the mechanical properties of C/SiC composite in coupling environment of dynamic loading and high/low temperature have been understudied. Our work studies the dynamic properties of coated and uncoated 2D C/SiC composite material from 173K to 1273K by means of Split Hopkinson Tensile Bar (SHTB), as well as its crack growth and failure process by SIM D8 ultra high-speed camera produced by Specialized Imaging Ltd. An SEM is also employed to examine the fracture surface and damage of C/SiC composites at different temperatures are determined by calculation. The failure mechanism is

analyzed by combining the micro-observation and theoretical computation. The Cowper-Symonds fitting is also carried out on both coated and uncoated 2D C/SiC composite at different temperatures.

2. Experimental procedure

2.1 Material

The 2D-C/SiC composite employed in our work was supplied by the State Key Laboratory of Solidification Processing in Northwestern Polytechnical University, People's Republic of China. The 2D C/SiC composite material mainly comprises of C fibers, SiC matrix, pyrolytic C interface and pore. The constituent properties of 2D C/SiC composite is shown in table 1[29]. The T300-1K C fiber was provided by Nippon Toray Corporation. The composites tested in the present investigation were prepared by chemical vapor infiltration of SiC into 2D fabricated preform consisting of stacks of C fibers woven fabrics laminated in plane direction, with each layer oriented at 90° with the adjacent cloth. The average thickness of the woven fabrics was 0.16 mm. Before infiltration, the C fibers was deposited with pyrolytic C interfacial layer with the average thickness of 100-200nm. In this way, the resultant composite had a fiber volume fraction of approximately 45% and a porosity of 5-8%.

The composite material was machined into flat dog bone shaped specimens, and some were coated with SiC oxidation resistance layer with a thickness of 0.1-0.2mm. The density of coated and uncoated specimens was 2.05 and 1.8g/cm³ respectively. The geometry of the 2D-C/SiC composite specimens prior to dynamic testing is indicated in Fig. 1, the testing section of the specimen has a dimension of 10mm×6mm×2mm. It can be seen clearly from fig 1 (b) the cross-woven transverse and vertical fiber as well as the pores in between. The SiC oxidation protective coating and the cracks caused by residual thermal stress incurred by the mismatch in thermal expansion coefficients between C fibers and SiC coating can be seen in fig 1 (c)..

2.2 SHTB setup for temperatures

The dynamic tensile properties of the C/SiC composites were determined using the SHTB system as indicated in Fig. 2. The SHTB system consisted of a steel big bar,

a steel incident bar, an aluminum alloy transmitted bar, and a steel striker tube. The flat specimen was sandwiched by the epoxy between the incident and the transmitted bar. The longitudinal direction of the specimen was aligned with the tensile loading direction. The gas released from the gas chamber propelled the striker tube that impinged on the free end of the yoke, generating a compressive pulse in the yoke by the impact of the striker tube. The compressive pulse was then converted to a tensile pulse on the free surface of yoke. The tensile pulse propagated along the big bar, and then the incident bar. Some of the incident pulse was reflected back into the incident bar from the input bar-specimen interface and the other part of it was transmitted through the specimen into the transmitted bar. Strain gauges with a resistance of 1000.5 ± 1.0 OHMS and gauge factor of $2.09 \pm 1\%$ mounted on the incident (see Fig. 2) and transmitted bar measured the incident, reflected and transmitted pulses.

The SHTB setup at elevated temperature in this study is an adaptation to the traditional SHTB setup, as shown in Fig.2. It comprises of a heating and cooling system. The main aim is to insulate and cool down the connecting parts between the elastic bars and specimen at the same time of heating the specimen. The heating system was designed to heat the specimen to the target temperature; the cooling system refrigerates the connecting part between the specimen and the bars, so that the temperature of elastic bars be kept well below their quenching temperatures (The incident steel bar has a quenching temperature of 673K, and the transmitted aluminum bar 473K, and the heat-resistant temperature of the adhesive is 523K) [30]. Besides, a heat insulating layer was employed to minimize the heat exchange between the electro-thermo furnace and the cooling chamber.

The experiment at low temperature is also an adaptation to the traditional Hopkinson tensile bar by adding a cooling system comprised of liquid nitrogen vessel, cooling chamber and temperature controller. The specimen is bonded to the two loading bars and a heat-insulating layer is applied to the end region of the loading bars considering the possible effect of low temperature on the adhesive and loading bars. The cooling nitrogen evaporation is channeled to the cooling chamber to refrigerate the specimen and the thermocouple on the specimen tells the temperature variation.

The coated and uncoated 2D-C/SiC composites were tested at temperatures of 173K-1273K under dynamic tensile loading. One-dimensional elastic wave equation was then used to obtain stress, strain and strain rate of the sample [31], Experimental strain rate of the specimen is 350/s.

$$\begin{cases} \sigma_s = E_b \left(\frac{A_b}{A_s} \right) \varepsilon_t \\ \dot{\varepsilon} = - \left(\frac{2C}{l} \right) \varepsilon_r \\ \varepsilon = - \left(\frac{2C}{l} \right) \int \varepsilon_r dt \end{cases} \quad (1)$$

where σ_s, ε stand for the stress and strain of the specimen, $\varepsilon_r, \varepsilon_t$ the reflected and transmitted strain, C the longitudinal wave speed of the bar, A_b, E_b the cross-sectional area and elastic modulus of the bar, l, A_s the length and the cross-sectional area of the specimen, respectively.

3 Dynamic deformations

3.1 failure process

To better understand the dynamic properties and crack propagation of C/SiC composite, SIM D8 ultra high-speed camera produced by Specialized Imaging Ltd is employed to record the failure process of the specimen under dynamic loading, as shown in Fig.3. The ultra high-speed camera has nanometer scale exposure time and very high resolution, and is capable of continuous shooting 8 separate full-amplitude images. It has great significance in the scientific research and engineering applications of instantaneous process of penetrating, blasting, striking and dynamic fracture [32]. The ultra high-speed camera and the flash light are controlled by the triggering signal on the external data collector and the captured images are transmitted to the computer control unit.

By corresponding the images and the experimental data collected from SHTB setup, the dynamic failure process, crack formation and propagation can be correlated on the time scale with the macro-mechanical response of the material. As can be seen

from the oscilloscope and the corresponding capturing time in Fig. 4 that aside from the incident, reflected and transmitted signals, “monitor” is a single that the camera feed back to the oscilloscope. With each voltage jump indicating one photo shot, there are 8 voltage jumps and thus 8 images captured by the camera.

The camera is triggered by the incident pulse from the strain gauge on the incident bar. A time lag of approximately $80\text{-}100\mu\text{s}$ from the triggering to the stabilization of the light source makes a delay between the actual loading time of the specimen and the capturing time of the camera. In order to record the whole process of specimen failure, the time delay Δt between the capturing time t_3 and the time when the incident wave reaches the specimen (or the loading time of the specimen) t_2 has to be worked out and kept below microsecond level to ensure that the camera takes pictures properly.

Moreover, a pulse shaper is employed to ensure stress equilibrium of brittle C/SiC composite material in the process of loading, making the determination of Δt even more difficult and critical.

At least two specimens are needed in this step: first, set the trigger time of the camera t_0 , and locate the corresponding time on the reflected wave t_1 ; second, calculate the loading time on the specimen t_2 with $t_2=(t_0+t_1)/2$; third, work out the time delay between the loading time and capturing time Δt with $\Delta t = t_3 - t_2$. The capturing time of the camera is thus readjusted to fully record the whole deformation process, crack initiation and propagation of the specimen in the next experiment.

The 8 images show the deformation process of the C/SiC composite material under impact tensile loading as can be seen in Fig. 5. Correspondingly, 8 points (a-h) can be located on the time-stress curve as shown in Fig. 6 (a), and the stress and strain value of the 8 points can also be found on the stress strain curve as shown in Fig. 6 (b). The specimen is loaded horizontally from right to left, and the interval between neighboring images is $11\mu\text{s}$.

In the first photo (a), the specimen is unloaded, undamaged and the corresponding stress value is 0MPa ; the second photo (b) presents the initial stage of the specimen, where no obvious yielding or damage can be observed and the stress value is 12MPa .

However, in the third photo (c), though the longitudinal and transverse fibers are full of tension, there is still no sign of yielding or damage. And the stress value is 43MPa; In photo (d), a very small crack is formed on the specimen surface, around which certain amount of yielding take place on the longitudinal and transverse fiber, with a corresponding stress value of 90MPa; The crack begins to grow in the photo (e) with increasing surrounding area of yielding and a small amount of fiber pull-out or fiber fracture. The stress value at this time comes to 139MPa; the six photo (f) witnesses noticeable expansion of the length and width of the crack, the direction of which, however, is no longer in parallel with the loading direction but deviate some 30° away from it. There is more noticeable fiber pull-out and fiber fracture, accompanied by increasing yielding area. The stress value then is 197MPa; in the seventh photo (g), the crack stops growing and changing directions but increases in its width, indicating matrix cracking within the material. Large amount of fiber are pulled out and fractured, and the stress value then is 248MPa; the eighth photo (h) doesn't see obvious increase of damaging area compared with the seventh photo (g). The stress strain curve in Fig. 6 also indicates that the specimen has already yielded with a corresponding stress value of 90MPa.

3.2 Impact Damage

To better describe the dynamic tensile properties of the material, damage D is developed. Fig. 7 shows a typical tensile strength/strain curve tested at 293K, displaying a typical non-linear fractured behavior. The curve can be divided into three segments. Basically, the first segment is linear-elastic up to 85MPa; In the second segment from 85MPa to about 185MPa, the composite presents a non-linear feature due to the initiation of cracks and fiber yielding. In the third segment, the stress-strain curve develops to the ultimate tensile strength in a linear-elastic manner until the specimen breaks.

In this study, parameter D is illustrated on the tensile strength/strain curve in Fig. 7 to understand damage evolution associated with the tensile fractured process [33].

$$D = \left(1 - \frac{(d\sigma_c/d\varepsilon_c)_i}{(d\sigma_c/d\varepsilon_c)_0} \right) \left(\frac{U_{p,i}}{U_p} \right) \quad (2)$$

where $(d\sigma_c/d\varepsilon_c)_i$ is the tangent modulus at *i*th point in the UTS/strain curve (stress σ_i and strain ε_i), $(d\sigma_c/d\varepsilon_c)_0$ the tangent modulus in the linear region of the tensile stress–strain curve in which $(d\sigma_c/d\varepsilon_c)_0$ is nearly the same as the Young's modulus E_0 , and $U_{p,i}$ inelastic energy absorption at σ_i , respectively

$$U_{p,i} = \int_0^{\varepsilon_i} \sigma_c d\varepsilon_c - \frac{1}{2} \sigma_i \varepsilon_i \quad (3)$$

where U_p is the inelastic portion of the total energy absorption during the tensile test loaded up to the ultimate tensile strength (UTS), σ_m ,

$$U_p = \int_0^{\varepsilon_m} \sigma_c d\varepsilon_c - \frac{1}{2} \sigma_m \varepsilon_m \quad (4)$$

where ε_m is the maximum strain at the fracture UTS σ_m [34].

According to the damage equation and the images of fracture process of the specimen under dynamic tensile loading captured in 3.1, a figure of crack propagation and damage can be obtained to facilitate the understanding of the relationship between energy consumption and crack propagation in the process of dynamic fracture. Fig.8 shows the Damage-dynamic tensile strength curves of specimens loaded up to UTS.

From which it can be seen that D basically equals zero when the stress is less than 80MPa and the composite is in the first segment of elasticity, thus no damage can be observed from the figure 5 (a)-(c); later when the stress value increases from 80MPa to 150MPa and enters the second stage of yielding, the composite is being damaged with a very small damage (D less than 0.1), thus small cracks and regional fiber yielding can be observed on the surface of the specimen ((d) and (e)). When the stress value surpass 150MPa, the composite enters the third stage of fracture when the slope of D curve and the value of D noticeably increases, taking the form of fast-expanding cracks and crack deviation to some degree (see (f) and (g)) and drastic

spreading of damage area. The SiC matrix begins to undergo severe fracture accompanied by large amount of fiber pull-out and breaking, implying the most severe damage to the specimen in this stage until the ultimate failure. Thus it can be concluded that the nucleation and propagation of cracks within the composite is the macro representation of its mechanical properties. In other words, the damage accumulates in the first stage, the crack initiates in the second stage, and spread fast in the third stage.

Fig. 9 is the transverse fracture morphology and fiber pull-out length of the specimen after failure. It can be seen that the fracture is jagged, featuring obvious delamination and fiber pull-out in 9 (a). In 9 (b) is presented the microscopic photo of failed SiC matrix together with regional fiber pull-out, where the voids in the matrix that existed since the preparation of the specimen will serve as initial micro cracks and grow when the specimen is damaged. Besides, the fibers are pulled out in bundles with almost consistent pull-out fiber bundle length of $249.1\mu\text{m}$. However, within each bundle, the fibers are uneven, enhancing the reinforcing effect of the fiber in the composite.

4 Results and discussion

4.1 Experiment results

Fig. 10 is the dynamic tensile stress-strain curve of uncoated and coated 2D C/SiC composite from 173K to 1273K. To ensure the validity of the experimental results, three to five repeated experiments are carried out with an average strain rate of 350/s. It can be seen that both coated and uncoated 2D C/SiC composite exhibit non-linear characteristic under different temperatures in its stress/strain curve, and the feature is most conspicuous at 173K and 293K, then 1073K and least at 1273K.

To better analyze the dynamic tensile properties of C/SiC composites at elevated temperature, Fig.11 presents the correlation between average tensile strength and strain with the change of temperature, where the specimen witnesses a decrease of dynamic tensile strength when the temperature increases from 173K to 1273K, and reaches the lowest in strength and strain at 1273K, coated or uncoated. It can also be

noted that the mechanical property of the composite degrades most severely at 1273K due to the influence of temperature elevation on the dynamic tensile property of 2D C/SiC composites [27]. At 173K, the tensile strength reaches maximum value of 335MPa and 307MPa for coated and uncoated specimen, up by 18% and 15% than that of 293K, and slightly lower in failure strain than that of 293K.

Some researchers point out that as the media of tensile loading between fiber and matrix, the interface plays an important role in the mechanical properties of composite materials [9, 10, and 33]. A comparison of experimental results between coated and uncoated composites at different conditions reveals that the former exhibits a superior tensile strength and strain than the latter in equal experimental conditions.

4.2 Microscopic analysis

To better understand the dynamic fracture characteristics of coated and uncoated 2D C/SiC composites from 173K to 1273K, both microscopic analysis and theoretical computation are employed. By combining SEM description of the fracture morphology of the specimen and the damage at different temperatures description of the specimen, the failure mechanism can be obtained.

Fig. 12 presents the damage-dynamic tensile strength curves loaded to UTS of uncoated and coated 2D C/SiC composites from 173K to 1273K as well as their fracture morphology, where it can be observed that not only is the failure strength decreased, but the slope of damage is also increased with the rising temperature for both coated and uncoated specimen. With the same stress, the damage value increases with the increase of temperature, indicating that the material is more prone to damage at elevated temperature and the more severe it is damaged, the faster the damage escalates. A close observation of the fracture morphology under different temperatures in (a)-(h) also evidences the above conclusion.

At 173K, as shown in 12(a) and (e), the interface between the fiber and matrix, in-bundle fiber and fiber all presents a sound cohesion with no sign of in-bundle debonding, this shows the reinforced fiber-matrix and fiber-fiber interfacial friction, effecting in inner interface reconstruction [33], calling for even more fracture energy for composite damage until failure, thus enhancing the UTS of the material. However,

the relatively short fiber pull-out and even fracture surface have reduced the toughness of the material at low temperature, suppressing the reinforcing mechanism of the fiber and thus decreasing the fracture strain of the composite.

At 293K, as shown in 12(b) and (f), the fibers are pulled out in whole bundles without severe delamination within the bundle, implying a sound in-bundle interfacial reinforcement and a suppressed in-bundle debonding. Since the final failure of C/SiC composite under dynamic tensile loading is effected by the breaking of fibers and fiber pull-out is the main energy- absorbing and reinforcing mechanism, the more and longer fibers are pulled, the better reinforcing effect of the composite material. Thus, the material witnesses the highest failure strain and fracture strength at 293K.

At 1073K, the marginal area of the fracture surface is chosen to observe the oxidization failure morphology of the specimen, as shown in 12(c) and (g). For uncoated specimen, most fibers have been obviously oxidized, leaving the SiC shell and only a small part is oxidized to a cone-shape. For coated specimen, there is no sign of fibers being oxidized and the fiber pull-out is uneven. This indicated that due to the lack of SiC coat protection, the pores produced during the weaving of the material are exposed to high temperature and become the best channel for oxidizing gas. Since oxidization mainly takes place between C and oxygen [26], the C including C fibers and pyrolytic C nearest to the gate of the channel are the first to be oxidized. Given the limited time of loading under dynamic loading condition, (from 6(a), it takes only 76 μ s from 0 to UTS), the spreading of oxidizing gas within the material is also limited, and the oxidization in further areas is not severe, thus the damage is not as severe as that of the marginal areas, retaining to some degree the dynamic tensile properties of the composite. On the other hand, the 0.1-0.2mm-thick SiC coating on the coated composite effectively obstructs the diffusion of oxidizing gas, greatly reducing the oxidization of C within the composite. Thus, the damage caused by oxidization is much less than that of uncoated composite, with its dynamic tensile strength decreased by a mere 11% than that of the room temperature, maintaining the dynamic tensile properties of the composite.

At 1273K, the marginal area of the fracture surface is also taken to observe the

oxidization fracture morphology as shown in 12(d) and (h). for uncoated composite, C fibers undergo severe oxidization leaving the SiC shell, while for coated composite, although the fibers also undergo obvious oxidization, only a small amount of them are totally oxidized while most are oxidized to a cone shape. This indicated that due to the lack of SiC coat protection, the oxidization and its damage at elevated temperatures of 1273K are extremely severe, and oxidizing gas travels along the pores and cracks towards the middle area of the composite severely degrades the dynamic tensile strength of the specimen.

For coated composite, despite of the protection of anti-oxidizing SiC coating, the mismatch of thermal coefficient between the C fibers radial direction and SiC matrix leads to the residual stress between the two during preparation as well as the formation of initial micro-cracks of the composite[35], which can be seen on the SiC coating in fig.1(c). These initial micro-cracks are gap of the anti-oxidization coverage, facilitating the diffusion of high-temperature oxidizing gas and causing the partial oxidization of the fibers. However, considering the limited diffusion room and oxidizing duration, as well as the SiO₂ protective film caused by the oxidization of SiC at 1273K [36], the oxygen has a very low permeability, thus protecting the C phase around the area, and maintains the stability within the structure. In this sense, the oxidization is only limited to the marginal area of the composite without penetrating to further areas in the middle, thereby effectively reduces the area and degree of damage, retaining to some extent the dynamic tensile properties of the composite.

From the above microscopic observation and analysis of the fracture surface of coated and uncoated 2D C/SiC composite under different temperatures, it is believed that the amount, length, and the way the fibers are broken are the main mechanisms of energy-absorption and reinforcement of the composite.

From Fig.12, the elevation of temperature from 173K-1273K not only changes the fiber pull-out and breaking mode at 173K and 293K, but also aggravates the oxidization of the fiber at 1073K and 1273K, which all contribute to the reduced reinforcing mechanism of the fiber and the toughness of the composite. This, in

reverse, is consolidated from the macro scope: the higher the temperature, the greater the slope, the more prone to damage, and the greater the damage value of the composite.

4.3 Cowper-Symonds model

To better describe the influence of SiC coating on the strength of the composites within the range of 173K to 1273K, strength influence factor k is introduced to describe the temperature dependency of the composite [37]. The ratio of coated and uncoated composite at 173K is used as a reference value. K at certain temperature is written as $k=\sigma_{\text{coated}}/\sigma_{\text{uncoated}}$, in which σ_{coated} stands for the strength of coated composite, σ_{uncoated} that of uncoated composite, and k the temperature function.

According to the Cowper-Symonds model [38, 39], the k can be written as

$$k=1+(T/D)^{1/q} \quad (5)$$

where D , q are the two parameters of the model, and T the temperature, respectively.

After the fitting of experimental data, k can be expressed as:

$$k=1+(T/1082)^{1/0.15} \quad (6)$$

Fig. 13 illustrates k as a function of the temperature in dynamic tension of coated and uncoated composites within the temperature range of 173K to 1273K. A close comparison of the fitting curve and experimental data suggests that the k faithfully depicts the variation of the strength ratio of coated and uncoated composites in relation to that of the temperature. It can be seen from figure 13 that the value of k increases with the increase of temperature and the higher the experimental temperature, the more noticeable k increases. This implies a greater significance of SiC coating on the properties of the composite with the increase of temperature. Thus, it is believed that coated composite within the temperature range of 173K-1273K displays a superior impact property compared with uncoated composite, and is a better structural thermal protection material.

5. Conclusion

In this work, a study of the dynamic properties of coated and uncoated 2D C/SiC

composite material from 173K to 1273K by means of Split Hopkinson Tensile Bar (SHTB) has been carried out. Examination of the failure process of the specimen by SIM D8 ultra high-speed camera and damage analysis help define the three phases of crack propagation, namely: the elastic pre-damaged phase, the yielding phase or the crack-initiating phase, and the failure phase or the phase of fast-spreading cracks. Experimental results also reveal that the dynamic tensile strength of both coated and uncoated composites decreases with the increase of temperature and decreases more conspicuously at higher temperature. An SEM is employed to examine the fracture surface and damage of C/SiC composites at different temperatures are determined by calculation. It was found that the higher the temperature, the greater damage of the fiber, and the greater value of the damage of the composite. Finally, k was introduced according to the Cowper-Symonds fitting model to describe the temperature dependency and the value of k was found to increase with the increase of temperature and the higher the experimental temperature, the more noticeable k increases. This implies a greater significance of SiC coating on the properties of the composite with the increase of temperature. It is thus concluded that coated composite within the temperature range of 173K to 1273K displays a superior impact property compared with uncoated composite, and is a more desirable structural thermal protection material.

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Table 1 constituent properties of 2D C/SiC composite [28]

Basic performance	T-300fiber	CVI-SiC	Py C
Tensile strength(MPa)	3530	294	-
Axial tensile strength(MPa)	230	430	30
Diametral tensile strength(MPa)	22	430	11
Density(g/cm ³)	1.76	3.2	-
Poission's ratio	0.3	0.2	-
Axial thermal expansion coefficient(10 ⁻⁶ /K)	-0.1-1	4.8	3
Diametral Axial thermal expansion coefficient (10 ⁻⁶ /K)	7-10	4.8	26-28

Fig.1 Coated and uncoated 2D C/SiC composite specimen: (a) Geometry of specimens; (b) Macrostructure morphologies of C fiber and void; (c) Macrostructure morphologies of sic coating and crack.

Fig. 2 The SHTB setup experiment system. (a) geometry of pulse shaper; (b) The connection between the specimen and the bars; (c) SHTB setup; (d) Experiments at elevated temperature.

Fig. 3 SIM D8 high speed camera system

Fig.4 The oscilloscope and corresponding capturing time in which t_0 is the trigger time of the camera, t_1 the time of reflected wave corresponding to t_0 , t_2 the loading time of the specimen where $t_2 = (t_0 + t_1)/2$, t_3 the capturing time of the camera and Δt the time delay between t_3 and t_2 where $\Delta t = t_3 - t_2$, respectively.

Fig.5 The deformation process of 2D-C/SiC composites captured by high speed camera

Fig. 6 (a) The deformation process of specimen captured by high speed camera; (b) The stress-time curve of 2D-C/SiC composite, in which the 8 points correspond with the high speed photo

Fig.7. Typical stress-strain curve and calculation of the damage

Fig. 8 Crack propagation and damage

Fig. 9 The transverse fracture morphology and fiber pull-out length of the specimen after failure.

Fig. 10 Dynamic tensile stress-strain curve of uncoated and coated 2D C/SiC composite from 173K to 1273K

Fig.11 The correlation between the average tensile strength and strain with the change of temperature

(a) Uncoated composites

(b) Coated composites

Fig. 12 The damage–dynamic tensile stress curves of coated and uncoated composites from 173k to 1273k.

Fig. 13 Strength influence factor k of SiC coating on coated and uncoated composite within the temperature range of 173K to 1273K.

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