Effects of oxygen content on the ablation/erosion behavior of 4D carbon/carbon composite material

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Abstract

A self-designed oxygen-kerosene ablation system was employed to test the four-directional braided carbon/carbon (4D C/C) composite material for studying the ablation performance under different oxygen-rich conditions, that is, −5%, 0% and 5%. The morphology of post-test specimens was analyzed via a scanning electron microscope (SEM), and the ablation rates were calculated. The influence principle of oxygen content on the ablation behavior of carbon/carbon composite material was studied, and the mechanism of ablation was also analyzed. Experimental results showed that the oxygen content will mainly affect the thermo-chemical ablation. The maximum mass ablation rate was 0.161 g·s⁻¹ when the oxygen content was 5%, while the minimum was 0.146 g·s⁻¹ when the oxygen content was 0. Within the range, the interstice between the axial fiber bundle and matrix became larger with the increase of oxygen content. In the two-phase flow test, the effect of particle erosion on material damage was much stronger than the change of oxygen content; on the other hand, fiber bundles were broken particles to form fine particles attaching to fracture fibers, which increased the contact area of the oxidation reaction and indirect accelerated thermochemical ablation process, the number of small carbon particles attaching to the surface gradually decreased with the increased of oxygen content.

The multi-directional braided carbon/carbon (C/C) composite material is a kind of excellent ablative thermal structure material, which has excellent mechanical properties, good thermophysical properties, high-temperature ablation resistance, low density and other excellent characteristics. At present, it is mostly used in the nozzle throat of solid rocket motor (SRM) [1−5]. When the engine works, the ablation thermal environment of the throat structure is very adverse, which will be destroyed by complex thermochemical ablation, airflow erosion and particle erosion. The research on the ablation behavior of C/C composites in a complex thermal environment has been a hot issue in the field of materials.

At present, many scholars have studied the ablation behavior and properties of C/C composites employing oxygen-acetylene ablation test, plasma ablation test and ablation engine test. Wang et al studied the ablation morphology and properties of C/C composites in particle direct impact mode. The results show that small pits appeared in the erosion area after particle direct impact. The micro-morphology of the non-eroded area is consistent with the throat morphology after the ablation test [6]. Liu and Hui et al employed a lab-scale solid rocket motor to examine the ablation behavior of a 4D C/C, focusing on the failure mechanism from the perspective of particle erosion [7, 8]. Wu et al carried out ground ignition tests based on the C/C composite throat braided by the shaft bar method. It was found that the ablation performance of the material was stable and consistent, and the ablated surface was smooth. The material is suitable for high working pressure and high flow rate engine nozzles [9]. Shameel Farhan et al used an oxygen-acetylene flame to study the effect of density and fiber orientation on the ablation performance of C/C composites. The results show that the higher the density, the better the ablation performance of C/C composites. The fibers parallel to the jet direction are burned into tip shape and finally blunted by the jet-flow [10].

Due to the limitation of experimental means, the research on the ablation behavior of C/C composites is mostly focused on particle erosion and the physical and chemical properties of the material. There are little
research and analysis on ablation conditions, especially on the effect of oxygen enrichment of gas on the ablation performance of materials. The test data needed for material development are insufficient.

In this paper, a self-developed Oxygen-Kerosene simulation ablation test system \[11\] was employed to carry out ablation tests of four-directional braided C/C composites under different oxygen enrichment conditions. The relationship between the ablation rate and oxygen enrichment degree of gas was analyzed. From two aspects of mesoscopic-scale (fiber and intra-bundle matrix) and microscopic-scale (fiber bundle and inter-bundle matrix), it was further studied that the influence mechanism of C/C composites on oxygen enrichment degree.

1. Ablation test

1.1. Test system
Aviation kerosene and oxygen are respectively as fuel and combustion supporting agent for the ablation test system, controlled by the operator console stably transporting to the ablation test motor. After atomization the fuel mixes with oxygen in the combustion chamber to form a combustible mixed gas, then it is ignited by high-energy spark plug forming high temperature and high-pressure gas that is accelerated by Laval nozzle to become a stable ablation gas jet-flow. At the same time, the powders are injected into the gas through the powder feeding port in the cavity wall of the ablation motor. After mixing, heating and acceleration, the specific gas-solid two-phase flow ablation thermal environment required for the test is formed. Finally, the spurt of gas comes from the outlet of the ablation engine to the specimen surface for the ablation test \[11\]. The system principle is shown in figure 1.

1.2. Test parameters and schemes
Oxygen enrichment $\beta$ is the mass fraction of oxygen in gas, which is used to characterize the degree of oxygen enrichment in gas. According to the actual work of the test system, its calculation formula is simplified as follows:

$$\beta = \frac{K - K_0}{K + 1}$$

The theoretical mixing ratio of $K_0$ is 3.3 in the simulated ablation test, which satisfies the ratio between combustion aids and fuel when the fuel is fully burned. $K$ is the oxygen/fuel ratio, namely the actual mixture ratio.

The material used is four-directional high-density C/C composites carbon, whose preform shown in figure 2(a) is obtained by soft and hard mixing knitting technology to fiber bundle and axial carbon rod \[2\]. The distance between the rods with a 1.5 mm diameter was fixed to be 3.2 mm. The fiber bundles whose diameter was controlled to be 1.5 mm were preformed into hexagonal shapes with three directions: W, X and Y, which were aligned along the same plane at 60°. After a series of densification cycles including high-pressure impregnation, carbonization and graphitization, the ultimate density of the braided preform reaches 1.990 g·cm$^{-3}$. Figure 2(b) gives the specimen appearance after wire-electrode cutting, whose thickness is 10.4 mm with a 50 mm × 50 mm ablation surface that is fixed perpendicularly to the Z-direction.

In the experiment, the oxygen flow rate is set at a fixed value of 308 L·min$^{-1}$, kerosene flow rate is adjusted to obtain different oxygen enrichment environment, ablation distance (distance between the center of the specimen and nozzle outlet) is set at 50 mm. Thermodynamic calculation and simulation analysis of free jet
show that the jet center total temperature at the ablation position under this condition is about 3200 K with a velocity of approximate 1400 m · s⁻¹ and a static temperature of 2424.8 K, which is shown in figure 3. With an ablation angle of 90° for the specimen, the stagnation temperature is close to the total temperature in SRM [12–14].

In the jet-flow, Al₂O₃ powder showing spherical in shape is chosen as the erosion particle for two-phase flow with a centralized particle diameter of 5 ~ 15 μm. The micro-morphology of the powder is shown in figure 4.

Finally, the initial test conditions are determined and set according to the parameters listed in table 1.

The material loss caused by erosion effect far exceeds that caused by ablation effect. For C/C materials used in the throat of SRM, the key of equivalent simulation is the construction of particle erosion environment.
SRM, the erosion result of particle swarm can be considered as a simple superposition of the erosion result of single particle. Erosion rate of target material correlation analysis reveals a method for equivalent simulating erosion with a formula as follows:

\[
S_{te} = \frac{1.02(1 - 2\sigma_0)\rho_{pp}}{2\sigma_0\rho_d}\left(\rho_{pp}v_p^3\right)
\]

where \(\sigma_0\) is the characteristic stress of failure, \(\rho_{pp}\) represents the particle density with \(\rho_d\) indicating target material density, \(\rho_{pp}\) is the particle content (volume concentration) in incoming stream, and \(v_p\) is the incident velocity of particle.

The physical parameters of particles and target materials are the same as those in the combustor, which means the first term on the right of equation (2) is equal. The second term on the right \((\rho_{pp}v_p^3)\) is kinetic energy flux, which can be written as the product of mass flow rate per unit area \((\rho_{pp}v_p)\) and kinetic energy \((v_p^2)\).

To capture the flight speed of particle, particle Image Velocimetry (PIV, Dentec FlowSense EO) is applied to calibrate the characteristic of free flow field under ablation test condition. The PIV result of the free jet, shown in figure 5, reveals the particle velocity of about 1100 m \(\cdot\) s\(^{-1}\) at the ablation position. The high-speed images captured via PIV show that the particles flow has a 5 degree dilated half angle after flying out of the ablation engine.

Based on simulated test parameter shown in tables 1 and 2, The erosion rate \(S_{te}\) is close to that of real SRM internal throat whose parameters under typical operating situations refer to literatures [12–14, 16].

According to the actual oxygen-enriched environment in the SRM and the property and situation of the system, three typical oxygen enrichment conditions, i.e. –5%, 0% and 5%, are finally determined to be tested [17]. In the experiment, three groups of specimens were selected to simulate two-phase flow environment by adding particles into the jet-flow, and the other three groups were used as controlled experiments without particles. To prevent the erosion of the specimen from affecting the measurement of the ablation rate, the ablation time of the added particle group is finally set at 3 s, while that of the pure gas jet is set at 20 s. The specific test scheme is shown in table 2.
2. Results and discussions

2.1. Ablation rate analysis

Before and after the test, the overall mass and the thickness of the ablation center were measured by electronic balance (resolution: 1 mg) and depth gauge (resolution: 0.01 mm), respectively for calculating the mass ablation rate and linear ablation rate of the specimen [18, 19]. The following formula gives the calculation of the mass ablation rate.

\[ R_m = \frac{m_0 - m_1}{t} \]  

\( R_m \) is the mass ablation rate, \( m_0 \) is the mass of virgin material, \( m_1 \) is the mass of material after ablating, and \( t \) is the ablation time.

Because the initial thickness of the specimen is small, the surface morphology is irregular after a long time of high temperature and high-speed jet, and the carbonization layer on the outer surface is brittle, so it is difficult to measure directly with the depth caliper. To accurately measure the recession of the nadir of the specimen surface after ablation, the base measurement method is designed according to the actual situation of the specimen. In the middle of the base, move the depth gauge to find the appropriate measurement position, and then carry out multiple measurements after the measurement position is determined. The depth measurement schematic diagram is shown in figure 6.

The linear ablation rate calculation formula is as follows:

\[ R_l = \frac{d_1 - (d_0 - d_2)}{t} \]  

\( R_l \) is the linear ablation rate, \( d_1 \) is the central thickness of virgin material, \( d_0 \) is the height of the base platform, \( d_2 \) is the depth gauge reading of specimen after ablating as shown in figure 6, and \( t \) is the ablation time.

It’s found that under the condition of pure gas jet ablation, the overall morphology of the specimen changes slightly. It is difficult to accurately measure the thickness decrement of the ablation center via a depth gauge, which will lead to a large error in calculating the linear ablation rate. Therefore, the first three groups show the mass ablation rates without linear ablation rates in table 3.

From table 3, it can be concluded that the influence of oxygen content on the mass ablation rate is complex within the range tested. The effect of particle erosion will mask the partial ablation phenomenon, which will interfere with the analysis of the influence of oxygen enrichment on the material, so this section focuses on the analysis of the first three groups of macro ablation rate data. The mass ablation rate reached the maximum of 0.161 g · s\(^{-1}\) at 5% oxygen enrichment. With the change of oxygen enrichment, the temperature, velocity and
oxygen content of the jet-flow will change accordingly, influencing the ablation behavior of the specimen. After the simulation calculation of the test parameters of the ablation engine, a conclusion can be drawn that when oxygen enrichment decreases, the outlet temperature and velocity of the jet-flow increase, while the oxygen content decreases. The two have opposite effects on the ablation: the increase of temperature and velocity will aggravate the destructive ability of ablation flame and accelerate the ablation process; and the decrease of oxygen content will restrain the oxidation reaction of specimens to a certain extent. When oxygen enrichment changes, it is difficult to determine the dominant factors, which leads to the complexity of the law between oxygen enrichment and mass ablation rate.

An in-depth analysis of the data in table 3 shows that the maximum change of mass ablation rate caused by oxygen enrichment is 0.015 g s⁻¹ without particles, neglecting the slight change of particle concentration. The maximum value is only 0.054 g s⁻¹ with particles. Under the same oxygen enrichment condition, the minimum change of mass ablation rate with particles is 0.279 g s⁻¹, which is 5 times of the maximum value of the non-particles group whose maximum value has reached 0.324 g s⁻¹. It can be concluded that the effect of oxygen enrichment on ablation rate of specimen mass is much less than that of particle action.

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Due to the lack of linear ablation rate of the first three groups of specimens, qualitative analysis is carried out based on the overall ablation morphology of the ablated specimens that are shown in figure 7. The ablation pits in the ablation areas of specimen 1 and 2 are shallow, the change of oxygen content has little effect on the ablation morphology. And the central thickness of the two ablated specimens is almost the same. Because of particle erosion, the surface of specimen 4 was severely damaged. the ablation center moved back obviously. From table 3, the minimum linear ablation rate of specimen reached 1.854 mm s⁻¹ after adding particles at the same oxygen enrichment. Therefore, the effect of oxygen enrichment on the linear ablation rate is much less than that caused by particle erosion.
2.2. Ablation morphology analysis

For further analyzing the ablation mechanism of oxygen enrichment on the matrix, axial and radial fibers, the micro-morphology of the specimens’ key ablation area was observed via scanning electron microscopy (SEM).

2.2.1. Effect of oxygen enrichment on matrix

After graphitization, the matrix of C/C material presents a lamellar structure similar to that of graphite. Through SEM observation on the matrix, it is found that lamellar structure mainly exists two distribution forms as shown in figure 8.

According to the layout direction of the lamellar structural plane, it can be divided into two types: the plane parallel to the ablation surface and perpendicular to the ablation surface. The structure, shown in figure 8(a), is referred to as the parallel layer matrix as well as the vertical layer matrix for what shown in figure 8(b). Obviously, the two structures reflect the high degree of anisotropy of graphite. It can be seen from figure 8 that there are holes and cracks on the matrix layer due to the defects of the processing technology, which will greatly restrict the ablation resistance of the matrix and become the weak area for ablation.

In the experiment, due to the difference of the spatial relationship between the jet direction and the two kinds of matrix layers, the ablation mechanism of the two kinds of matrixes is also different under the same conditions, which is mainly manifested in different leading factors causing the material ablation.

For the parallel layer matrix, the layer is perpendicular to the jet direction and resists the impact of the jet in the front, results in the intense thermochemical ablation of the layer matrix carbon. This process involves oxidation and sublimation of surface carbon at high temperature [20]. In thermochemical ablation, the main factors affecting the rate of carbon oxidation reaction include dynamic control mechanism and diffusion control mechanism. On the other hand, the weak ablation regions such as cracks and holes in the matrix structure will cause a large temperature gradient which is easy to generate thermal stress concentration. When the coupling stress exceeds the strength of the material, flake peeling will be caused. This is another ablation mechanism of C/C composite material, which is called mechanical denudation [21]. There are generally two forms of mechanical denudation. The other is described in section 2.2.2.

For the vertical layer matrix, even with a high graphitization degree, there are gaps or cracks between layers inevitably, which will continuously grow and expand under the thermochemical ablation as shown in figure 9. When the defect develops to a certain stage, the thermal stress concentration in the layer will produce a force on the layer, causing it to deform and form a twisted strip structure in space. The deformation of the layer accelerates the spalling. Due to the complexity of matrix spatial, the growth and expansion of defects can easily lead to the intersection of cracks and then cause the fracture and peeling of the layer.

Through the analysis of the ablation mechanism of the above two kinds of structure matrix, it can be seen that the ablation performance of the parallel layer matrix is better than that of the vertical layer matrix under the same conditions with ignoring the influence of defects. This is because the ablation plane is parallel to the plane.
Figure 8. Structural diagram of virgin matrix carbon.

Figure 9. Ablation morphology of vertical layer matrix.
of the parallel layer matrix, and its surface is relatively closely arranged, which is not conducive to oxygen diffusion to the interior of the matrix. Due to the existence of certain gaps between the layers of the vertical layer matrix, and these gaps exposed to the jet directly will continuously expand with the thermo-chemical ablation so that oxygen is easy to diffuse to the interior of the matrix. Moreover, the layers are relatively independent in space and not closely arranged, so that they are easy to be scourd by the jet. Based on the above description, the ablation difference between the two types of substrates is finally represented by surface gradient as shown in Figure 10. In the square region, there is a parallel layer matrix, while in the elliptic region, there is a vertical layer matrix. The ablation depth of the latter is larger than that of the former, which shows that the ablation performance of the parallel layer matrix is better than that of the vertical layer matrix. Because of the depth of the field between the two regions, the image is partially blurred.

It is found that there was no significant difference in the morphology of the matrix at different oxygen enrichment. The main reasons are as follows: firstly, the change in jet parameters caused by oxygen enrichment is small. According to the simulation results, when oxygen enrichment increases from $-5\%$ to $5\%$, the exit temperature of the jet decrease by $0.48\%$, the exit velocity of the jet decreases by $2.96\%$, and the jet-flow reaching the surface of the specimen has no difference after the decay of 50 mm ablation distance. Secondly, the lamellar structure of the matrix material has repeatability in space, and the difference between layers can not be observed by SEM alone. Thirdly, the erosion of Al$_2$O$_3$ powder particles will seriously destroy the morphology of the matrix, which conceals the effect of oxygen enrichment on ablation behavior.

2.2.2. Effect of oxygen enrichment on axial fiber

Similar to the matrix, there are cracks between the axial fiber bundles and the matrix as well as axial fiber bundles, which is more conducive to the diffusion of airflow and accelerates the thermochemical ablation process. At the same time, stress concentration is easy to occur at the cracks, and these places are often areas with relatively weak material strength, which are more prone to mechanical denudation.

In addition, to crack, the density diversity between the axial fiber bundle and matrix is also an important factor affecting ablation. Under the same conditions, the ablation rate is different with different density, which leads to the ablation asynchrony. The axial fiber bundles are closely arranged and the density is higher than that of the matrix. With the progress of thermochemical ablation, the axial fiber bundles gradually protrude. Under the action of shear force and eddy resistance, the protruding part appears granular exfoliation, which is another form of mechanical denudation [21]. On the other hand, ablation asynchrony will lead to an increase in surface roughness, which in turn will further aggravate thermochemical ablation.

Because the interface between matrix and axial fiber bundle is often not tight enough as shown in Figure 11 that gives the overall ablation morphology of the first three groups of specimens, it becomes a weak area for ablation. The defects in this region will preferentially undergo thermochemical ablation [22]. The burning of the interface leads to the loss of support between the axial fiber bundle and the matrix, and the expansion of the clearance is prone to stress concentration. The tangential force generated will have a certain scouring effect on the fibers at the clearance and then the fibers will be broken.
Figure 12 can reflect the ablative process of the axial fiber bundle. The center part is an axial fiber bundle, the oblique line area on both sides is the surrounding matrix carbon, and the black part is the gap between the two. Figure 12(a) shows the virgin morphology. Figure 12(b) shows the initial stage of ablation. The fiber head is ablated, and the gap between the fiber and the matrix carbon increases. Figure 12(c) shows the further ablation stage, the fiber head is burned sharper, and the carbon gap is further enlarged forming an inverted trapezoid. Figure 12(d) shows the fiber bundles exposed after the matrix carbon spalling. Figure 12(e) is the fiber breaking stage, in which the fiber exposed is broken. Since the breaking point may be higher than, parallel to or lower than the matrix. Therefore, three forms are shown in figure 12(e). The above fiber ablation process (a)–(e) recurs repeatedly in the interior of the material.

Without particles, the morphology of the axial fiber bundles varies significantly with oxygen enrichment as shown in figure 11. Without considering the obvious crack expansion at the interface between the axial fiber bundle and the matrix due to the defects of the material itself and mechanical denudation, the gap between the axial fiber bundle and the matrix increases gradually with the increase of oxygen enrichment. The increase of oxygen enrichment will directly lead to the widening of the gap between the fiber bundle and the matrix due to the thermochemical ablation at the interface. Compared with other regions, this one is more conducive to the diffusion of gas flow. With the diffusion control mechanism, the thermal chemical ablation rate of specimens is significantly enhanced [23]. The larger the oxygen enrichment is, the stronger the oxidizing atmosphere of the jet-flow is. On the premise of strong diffusion control, the more intense the thermochemical ablation is at the interface, which leads to the wider gap between the axial fiber bundles and the matrix. On the other hand, the larger the gap between the bundles, the easier the accumulation of particles. In conclusion, without particles, oxygen enrichment mainly affects the overall ablation behavior of the axial fiber bundles.
After adding particles, the erosion effect is dominant, and the overall morphology of the specimen will be seriously damaged. After ablation, the gap between the axial fiber bundles and the matrix is small, and the effect of the oxygen-enriched environment on ablation behavior is not obvious under this amplification factor [24]. Therefore, the amplification factor was further increased to study the axial fiber. Figure 13 shows the micro-morphology of the axial fiber under different oxygen-enriched conditions after magnifying 5000 times. It can be seen from the graph that with the decrease of oxygen enrichment, the morphology of the fibers themselves does not differ greatly. They are all round-like structures, which are caused by the mechanical damage of the particles. The brittle fibers bundles are directly broken under the strong impact force of the particles. Simultaneously, with oxygen enrichment increasing, the small carbon particles on the surface of the fiber decrease obviously. Under the oxygen enrichment environment, most of the small carbon particles are consumed by an oxidation reaction with a small amount of the remaining particles adhering to the fiber surface; Under an oxygen-poor condition, the small carbon particles tend to deposit and accumulate at the fracture of the axial fiber.

2.2.3. Effect of oxygen-rich degree on radial fiber

Although the raw materials of radial fiber and axial fiber are T300CF-3K, the jet scouring fibers directly along the direction perpendicular to the fiber axis causes the fibers to burn out easily. This is determined by the anisotropy of the carbon fiber itself. Although the shear strength of radial fiber bundles cannot be directly measured, it can be indirectly characterized by the macroscopic mechanical properties of C/C composites whose shear strength is far less than the tensile and the compression strength.

For radial fibers, figure 14 can reflect the ablation process. The four side-by-side rectangles represent radial fibers, and the diagonal represents the matrix carbon surrounding the fiber. Figure 14(a) shows the fibers are closely arranged and the matrix carbon encapsulates the fibers well before ablation; figure 14(b) is the initial stage of ablation. Since the matrix carbon first comes into contact with the jet, the ablation and spalling of the matrix carbon occur first; In figure 14(c), the fibers become thin and pointed, and the matrix is further peeled off; The fibers are burned out as shown in figure 14(d); In figure 14(e), the fibers are burned pointed because of the difference in oxygen concentration diffusion between the fibers. In figure 14(f), the fibers are burned short. Because the six processes are repeated in the material, any of the morphologies can be observed after ablation. However, it was observed that the microstructure of the burned fibers was mainly ‘bamboo shoots shape’ as shown in figures 14(e) and (f).

Figure 15 shows the typical ablation morphology of the radial fiber after ablation, which is similar to the ‘bamboo shoot shape’ as shown in figures 14(e) and (f) [20]. Besides, it can be seen from the figure that the matrix carbon between the fibers is consumed, because there are cracks and interface delamination defects between the fibers and matrix which are conducive to the internal diffusion of oxidizing components, resulting in the so-called interface ablation [2]. Interfacial ablation isolates the fiber from the carbon matrix that more easily ablated by mechanical denudation. Figure 15 shows that the thermochemistry ablation and mechanical denudation resistance ability of the carbon matrix in this region was weaker than that of fibers [25].

Figure 16 is a partial enlargement detail of the radial fibers after different oxygen enrichment test. It can be seen from the diagram that the ablation morphology and the distance between fibers have no significant

![Figure 13. SEM images of the axial fiber tested with particles.](image-url)
difference by different oxygen enrichment under non-particles. With the oxygen enrichment increasing, the small carbon particles adhering to the radial fibers decrease gradually.

The micro-ablation morphology of the fibers without particles shows that oxygen enrichment has little effect on the ablation behavior of the radial fibers in the range. In this jet environment, the ablation of radial fibers is mainly thermochemical ablation and mechanical denudation of airflow. With oxygen enrichment increasing, the oxygen content in the jet increases, while the temperature and velocity decrease. Two of them have the opposite effect on the ablation of the specimens. The combined effect has little effect on the micro-ablation morphology of the radial fibers. The radial fibers observed by SEM show finer and are burned out [21]. Meanwhile, the relative variation of jet parameters is limited due to the small range of oxygen enrichment, and the final ablation thermal environment does not change significantly. Therefore, without particles the influence of oxygen enrichment on the ablation behavior of the radial fibers is limited.

After adding particles, the ablation mechanism of the material transfers to the comprehensive effect of erosion of particles, thermochemical ablation and mechanical denudation of airflow all affecting the ablation process. From (b), (d) and (f) of figure 16, the fracture of carbon fibers can be observed, which is caused by the violent impact of high-speed particles on the fibers [26]. When oxygen enrichment is $-5\%$, the surface of the fibers is covered with small particles of carbon, but with the oxygen enrichment increasing, the small particles of carbon adhering to the surface of the radial fibers decrease. For radial fibers, when adding particles, the bundles of fibers are smashed into particulates, which increases the reaction area of thermochemical reaction and

![Figure 14. Schematic diagram of radial fiber ablation process.](image1)

Figure 14. Schematic diagram of radial fiber ablation process.

![Figure 15. Typical ablation morphology of radial fiber.](image2)

Figure 15. Typical ablation morphology of radial fiber.
strengthens the effect of oxygen enrichment on the thermal chemical ablation. The higher the oxygen enrichment of jet-flow, the faster the rate of particulate carbon consumed by thermal chemical ablation. This is the process of indirect acceleration of oxidation reaction by particle erosion.

3. Conclusion

(1) Within the range of oxygen enrichment, the change of oxygen enrichment will cause the corresponding changes of jet temperature, velocity and oxygen content. The mechanism of the three factors on specimen ablation is different, which leads to the complexity of the law between oxygen enrichment and mass ablation rate. Moreover, the effect of oxygen enrichment on mass ablation rate and linear ablation rate is much less than that of particle erosion effect.

(2) Without particles, the change of oxygen enrichment mainly affects the ablation morphology of the axial fiber bundle. With the oxygen enrichment increasing, the gap between the axial fiber bundle and the matrix caused by thermal chemical ablation widens gradually. Meanwhile, the oxidizing atmosphere of the jet-flow becomes stronger and stronger, and the small carbon particles attached to the axial fiber section decrease gradually due to the enhancement of the oxidation reaction.

(3) For radial fibers, oxygen enrichment has little effect on their ablation behavior under non-particles ablation test; after adding particles, the influence of oxygen degree on their ablation behavior increases sharply. Fiber bundles are broken by particles to form granular particles attaching to the fracture fibers, which greatly increases the area of the oxidation reaction. Particle erosion indirectly accelerates the thermochemical ablation process. Under the condition of low oxygen enrichment, the morphology of radial fibers becomes blurred due to the large number of carbon particles attaching to the surface.

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