ZrC ceramic modified C/C composite is prepared by a quick and low-cost reactive melt infiltration process with a Zr-Si8.8 alloy. Reaction kinetics and mechanism of pyrolytic carbon with the infiltrated Zr-Si8.8 alloy are investigated. A continuous ZrC layer is found to be formed around pyrolytic carbon due to the in situ reaction and its thickness parabolically increases with an increase in reaction time period. Zr concentration in the alloyed melts decreases due to the reaction between Zr and pyrolytic carbon and Zr2Si phase precipitates from the residual alloyed melts. A model for the growth of ZrC layer is established to describe the reaction kinetics of pyrolytic carbon with Zr-Si8.8 alloy. The calculated thickness of the reaction-formed ZrC layer is in good agreement with the experimental data. Based on the Arrhenius equation, the activation energy of the reaction between carbon and Zr-Si8.8 alloy is 313.2 KJ/mol, smaller than that of the reaction between carbon and pure zirconium. The microstructure of the reactive melt-infiltrated ZrC-modified C/C composite is characterized by optical microscope, SEM, EDS, XRD, and TEM. The mechanism of the reaction between pyrolytic carbon and Zr-Si8.8 alloy is discussed on the basis of the characterization results and phase diagram. A schematic is proposed to understand the reaction mechanism between pyrolytic carbon and Zr-Si8.8 alloy and microstructure development of the ZrC-modified C/C composite.

I. Introduction

Carbon/carbon (C/C) composite has many merits such as low density, high strength-to-weight ratio, high specific module, high thermal shock resistance, good ablation resistance, and chemical stability. It is an attractive candidate for highly demanding engineering applications such as nozzle throats of rocket engines, airplane brakes, etc.1–3 However, carbon begins to oxidize over 773 K and experiences rapid oxidation under high temperature and pressure, which seriously limits the widespread application of C/C composite.4, 5 Introduction of ultra-high-temperature ceramics (UHTCs) such as refractory carbides and borides into the matrix of C/C composite has been considered as an effective approach to improve the ablation and oxidation resistance of C/C composite at higher temperatures.6,7 In the family of UHTCs, ZrC has received considerable attention due to its high melting temperature, relatively low density, and ablation-resistant oxide scale formed during the ablation process.8,9 Many attempts have been made to introduce ZrC into C/C composite and the investigations10–14 indicate that the ablation resistance of C/C composite is significantly improved by ZrC addition into C/C composite matrix.

Different approaches such as reactive melt infiltration (RMI) and polymer infiltration and pyrolysis have been reported to introduce ZrC into C/C composite. Among these methods, RMI with the advantages of much shorter processing time and applicability to thick sections and complex geometries has been demonstrated as a fast and economical process for ZrC-modified C/C composite.13,14 During RMI, liquid zirconium or zirconium-based alloys infiltrate into a low-density C/C composite under the driving force of capillary. The infiltrated melts expand to fill the pores and react with the carbon in the C/C composite, which ultimately result in a dense matrix with residual carbon and reaction-formed ZrC. It should be mentioned that the reaction of carbon with the infiltrated melts is extremely important for the RMI of ZrC-modified C/C composite. Insufficient reaction may result in some residual metal and excessive reaction may lead to the damage of carbon fibers, which causes a negative effect on the mechanical properties of the ZrC-modified C/C composite.

In the published literature, Zou et al.15 investigated the microstructure development of liquid zirconium-infiltrated C/ZrC composite. Wang et al.10 and Chen et al16 studied the mechanical properties and ablation resistance of the zirconium infiltrated C/C-ZrC composite. Zeng et al17 infiltrated the C/C composite with a Zr-Ti alloy and evaluated the ablation resistance of the modified composite. To decrease the RMI temperature, Zhu et al18 and Wang et al19 used a low-temperature Zr–Cu alloy to infiltrate the porous C/C composite. These previous investigations mainly focus on the microstructure and performance of the RMI ZrC-modified C/C composite. To our knowledge, no publication has yet reported the reaction between carbon and the infiltrated alloy during RMI. The reaction kinetics and mechanism of pyrolytic carbon with the infiltrated alloy during RMI of ZrC-modified C/C composite are still not clear up till now. In our previous work,18 ZrC-modified C/C was prepared by RMI with a Zr-Si8.8 alloy. It is demonstrated that the RMI C/C-ZrC composite has high mechanical strength and presents much better ablation resistance than C/C composite. The aim of the present work is to investigate the reaction kinetics and mechanism of pyrolytic carbon with the Zr-Si8.8 alloy during RMI of ZrC-modified C/C composite.

II. Experimental Procedure

1 Material Preparation

Carbon fiber needled felts were used as preforms. The carbon fiber was Polyacrylonitrile based (T300; Toray, Tokyo, Japan). The needled felts were prepared by a three-dimensional needling technique, starting with repeatedly overlapping the layers of 0° nonwoven fiber cloth, shortcut fiber
web, and 90° nonwoven fiber cloth with needle-punching step by step. Pyrolytic carbon was deposited on the carbon fibers to prepare a porous C/C composite preform by chemical vapor infiltration process. The porous C/C preform was cut, polished, ultrasonically cleaned with ethanol, and dried at 100°C for 4 h. The Zr–Si alloy (Zr: 91.2 at.%, Si: 8.8 at.%) with a melting point of 1570°C prepared by an arc melting technique was placed on the porous C/C preform. It was then heated to 1800°C at a speed of 10°C/min and kept for 30 min in an Ar atmosphere. The Zr–Si alloy melted and infiltrated into the porous C/C composite preform and reacted with pyrolytic carbon, resulting in a ZrC-modified C/C composite.

To avoid the effect of alloyed melts infiltration during RMI on the reaction of pyrolytic carbon with Zr–Si8.8 alloy, high-density polycrystalline graphite was chosen to investigate the reaction kinetics of carbon with Zr–Si8.8 alloyed melts. The graphite had very few pores and the reaction of carbon with Zr–Si8.8 alloy was thought to occur on the contacted surface of the graphite. Before carrying out the experiments, the graphite samples were cleaned by ultrason in alcohol and annealed at 1800°C for 30 min for degassing. Zr–Si8.8 alloy was placed on the surface of the graphite, which was then heated to the designed temperature 1800°C–1950°C and kept for 30–240 min in an Ar atmosphere. After cooling, the specimens were cut perpendicularly to the interface. The first half was embedded in resin and polished for optical and scanning electron microscope (SEM) observations. The thickness of the reaction-formed layer was measured at eight different points and the thickness of the layer was determined by the average value.

(2) Characterization
The morphologies of the composites were observed by a Hitachi-S4800 (Tokyo, Japan) SEM and JEM-3010 (JEOL Ltd, Tokyo, Japan) transmission electron microscopy (TEM). The chemical composition was examined by energy dispersive spectroscopy (EDS). The phases were identified by X-ray diffraction (XRD, Rigaku D/Max 2500VB–C, Tokyo, Japan) using a Ni-filtered CuKα radiation at a scanning rate of 5°/min and scanning from 15° to 80° of 2θ.

III. Results and Discussion

(1) Reaction Kinetics
Figure 1 shows the cross-section microstructure of the interface between the Zr–Si8.8 alloy and polycrystalline graphite after reaction at 1800°C for different time periods. As can be seen, a continuous interfacial layer, which is ZrC as demonstrated by EDS, is formed by the reaction of the polycrystalline graphite with Zr–Si8.8 alloy. The thickness of the ZrC layer formed for different reaction time periods is uniform and it increases with the extension of the reaction time. Thus, the thickness of the ZrC layer formed in different reaction conditions is measured to characterize the reaction kinetics between carbon and Zr–Si8.8 alloy. Figure 2 shows the thickness of ZrC layer formed by the reaction between carbon and Zr–Si8.8 alloy after reaction at 1800°C for different time.

According to the Arrhenius equation, K can be expressed as

\[ K = K_0 e^{-\frac{E_a}{RT}} \]  

(2)

where \( K_0 \) is the preexponential factor, \( E_a \) the activation energy, \( T \) the temperature, and \( R \) the universal gas constant.

To determine the reaction kinetics equation of carbon with Zr–Si8.8 alloy, the reaction experiments at different temperatures were carried out. The thickness of the ZrC layer formed at different temperatures is shown in Fig. 3. The thickness of the ZrC layer rapidly increases with the increase in reaction temperature. \( K \) values for different reaction temperatures are calculated using Eq. (1). The relationship between ln \( K \) and inverse temperature \( 1/T \) is shown in Fig. 4. In \( K \) increases linearly with the increase in \( 1/T \). On the basis of Eq. (2), the activation energy for the reaction between carbon and Zr–Si8.8 alloy can be calculated from the slope of Fig. 4, which is found to be 313.2 KJ/mol. The activation energy of the reaction between carbon and pure zirconium is 354.1 KJ/mol,\(^{19}\) which demonstrates that the addition of silicon into zirconium could decrease the activation energy of the C–Zr reaction and facilitate the reaction between zirconium and carbon.

(2) Reaction Kinetics Model
The reaction of carbon with pure silicon\(^{19}\) and zirconium\(^{18,21}\) indicated that a continuous SiC and ZrC layer instantly formed between the solid carbon and the liquid metal melts (normally less than 1 min). The reaction between carbon and Zr–Si8.8 is considered to have something in common with the Zr–C reaction and a ZrC layer is expected to be formed between carbon and Zr–Si8.8 alloy in a very short time period. To confirm the rapid reaction formation of the ZrC layer, a porous C/C composite preform was infiltrated with Zr–Si8.8 alloy melts for just 1 min to investigate the reaction between carbon and Zr–Si8.8 alloy in a very short time period. The cross section of the composite prepared for 1 min RMI is shown in Fig. 5. A nearly continuous interfacial layer, which is ZrC determined by EDS, is clearly formed between carbon and the residual alloy. Fig. 5 also shows the XRD analysis of the composite. The strong ZrC diffraction peaks indicate that ZrC phase is formed by the reaction between pyrolytic carbon and infiltrated Zr–Si8.8 alloy. The XRD analysis result is consistent with the EDS analysis result and further confirms the reaction formation of ZrC layer in a very short time period (less than 1 min). Once the ZrC layer is formed by the reaction of carbon with Zr–Si8.8 alloy, the solid carbon and Zr–Si8.8 alloyed melts are separated and they do not contact directly. Further growth of the ZrC layer depends on the diffusivity of carbon and zirconium through the ZrC layer and subsequent reaction at the contacted surface. According to Adelsberg et al study,\(^{19}\) the diffusion speed of carbon in ZrC is much higher than that of zirconium in ZrC. Thus, the ZrC layer growth mainly proceeds by the migration of carbon through ZrC layer and the consequent reaction at the ZrC/Zr interface. With the increasing reaction time, the ZrC layer thickens. According to Fick’s diffusion law, the diffusion flux of carbon through the ZrC layer can be expressed as

\[ J = \frac{D}{\delta} (C_i - C_l) \] 

(3)

where \( D \) is the diffusion coefficient of carbon through ZrC layer, \( C_i \) the concentration of carbon at ZrC/Zr interface (kg/m\(^3\)), \( C_l \) the concentration of carbon at ZrC/Zr interface, \( \delta \) the thickness of the ZrC layer (m).

The mass of the ZrC layer formed during time \( t \) can be calculated by
\[ m = \delta \rho S \]  
\[ \frac{dm}{dt} = \rho S \frac{d\delta}{dt} \]  
\[ \frac{d}{dt} \frac{d\delta}{dt} = \rho S \frac{d\delta}{dt} = S \frac{D}{\delta} (C_i - C_0) \]  
\[ \frac{\delta}{dt} \frac{d\delta}{dt} = D \frac{C_i - C_0}{\rho} \]  
\[ \frac{d}{dt} \frac{d\delta}{dt} = \frac{2D}{\rho} (C_i - C_0) \]  

where \( S \) is the interfacial area between molten \( \text{Zr-Si8.8} \) alloy and carbon (\( m^2 \)), \( \rho \) the density of \( \text{ZrC} \) (\( \text{kg/m}^3 \)), \( m \) the mass of \( \text{ZrC} \) layer (\( \text{kg} \)).

Making use of Eqs. (3) and (5), we have

\[ \frac{d}{dt} \frac{d\delta}{dt} = S \frac{D}{\delta} (C_i - C_0) \]  
\[ \frac{\delta}{dt} \frac{d\delta}{dt} = D \frac{C_i - C_0}{\rho} \]

The reaction speed between carbon and \( \text{Zr-Si8.8} \) alloy is very high at high temperatures. Thus \( C_i \) can be considered close to zero. Thus, by integrating Eq. (7) with respect to \( t \), we have

\[ \frac{d^2 \delta}{dt^2} = \frac{2D}{\rho} C_i \cdot t + H \]  
\[ \frac{d^2 \delta}{dt^2} = \frac{2D}{\rho} C_i \cdot t \]

where \( H \) is a constant.

When the reaction time is zero, the thickness of the reaction-formed \( \text{ZrC} \) layer is also zero. Considering this condition, \( H \) is zero. Equation (8) can be reduced to

\[ \frac{d^2 \delta}{dt^2} = \frac{2D}{\rho} C_i \cdot t \]

Equation (9) can be used to calculate the thickness of the reaction-formed \( \text{ZrC} \) layer for different reaction time periods. As indicated by Eq. (9), the thickness of the \( \text{ZrC} \) layer parabolically increases with the extension of reaction time, which agrees with experiment results (Fig. 2). To further validate the accuracy of Eq. (9), the thickness of the \( \text{ZrC} \) layer formed at \( 1800 \degree \text{C} \) for different time periods is calculated and listed in Fig. 2. The diffusion coefficient of carbon through \( \text{ZrC} \) layer is \( 4.3 \times 10^{-9} \text{ cm}^2/\text{s} \). As can be seen from Fig. 2,
the calculated ZrC layer thickness is in good agreement with the experimentally measured thickness of ZrC layer, indicating that the calculation model is effective and accurate for calculating the ZrC layer thickness for different reaction conditions. In other words, the calculation model is effective to describe the reaction kinetics of carbon with Zr–Si8.8 alloy at high temperatures.

(3) Microstructure Morphologies of the Reaction Areas and ZrC-Modified C/C Composite

To characterize the morphologies of reaction areas and phase transformation during reaction, a specific experiment shown in Fig. 6 is performed to prepare a ZrC-modified C/C composite by RMI with the same parameters described in Section II(1) and investigate the reaction between carbon and Zr–Si8.8 alloy. Excessive Zr–Si8.8 alloy is used to infiltrate the porous C/C composite preform and the residual alloy is solidified outside the C/C composite preform after RMI.

Figures 7(a) and (b) shows the cross-section morphologies of the ZrC-modified C/C composite. As can be seen, a nearly continuous interfacial layer, which is ZrC determined by EDS, is formed between pyrolytic carbon and the infiltrated alloy. Four different phases are formed due to the reaction between pyrolytic carbon and the infiltrated alloy, which are marked as a (the needle-shaped phase), b (the lath-shaped phase), c (the spherical phase), and d (the continuous matrix), respectively in Fig. 7(b). EDS analysis indicates that the needle-shaped phase a and the lath-shaped phase b are Zr2Si with atom compositions of Zr:Si = 68:32 and Zr:Si = 66:34. The spherical phase c is composed of Zr and C, which is believed to be the ZrC phase formed by the reaction between pyrolytic carbon and Zr. The continuous matrix d is Zr phase with just Zr peaks in the EDS patterns. The
alternate distribution of the needle phase Zr$_2$Si and continuous Zr matrix is the same as the microstructure morphologies of the eutectic Zr–Si8.8 alloy (Fig. 8), which is believed to be the unreached eutectic Zr–Si8.8 alloy.

The cross-section morphologies of the residual alloy in Fig. 6 are shown in Figs. 7(c) and (d). A continuous ZrC layer, which is the same as the ZrC layer in Fig. 7(b), is formed between pyrolytic carbon and the external residual Zr–Si8.8 alloy. The microstructure of the residual Zr–Si8.8 alloy is little different from that of the eutectic Zr–Si8.8 alloy (Fig. 8). Besides the typical eutectic microstructure of Zr–Si8.8 alloy, some lath-shaped Zr$_2$Si phases and spherical ZrC phase, the same as that in Figs. 7(a) and (b), are formed in the residual Zr–Si8.8 alloy.

To further determine the phase composition of the ZrC-modified C/C composite prepared by the Zr–Si8.8 alloy melt infiltration, a high-density C/C composite preform with relatively few pores is infiltrated with accordingly small amount of eutectic Zr–Si8.8 alloy at 1800°C for 60 min (a longer time to react completely). The cross section of the as-produced ZrC-modified C/C composite with XRD analysis is shown in Fig. 9. Due to the fewer pores and longer reaction time, the infiltrated Zr–Si8.8 alloy and pyrolytic carbon react completely. XRD analysis indicates that the composite is composed of carbon, ZrC, and Zr$_2$Si phases. No Zr peaks are found in the XRD patterns, demonstrating that pyrolytic carbon reacts with the infiltrated Zr–Si8.8 alloy completely. The Zr$_2$Si phase determined by the XRD analysis is consistent with the EDS analysis results. As seen in Fig. 9(a), a continuous ZrC layer is formed along pyrolytic carbon. Some spherical ZrC particles and a Zr$_2$Si phase matrix are formed in the middle area of the pores surrounded by the continuous ZrC layer. To further characterize the ZrC layer and the interface between pyrolytic carbon and the ZrC layer, TEM analysis is carried out. The TEM morphologies with selected-area electron-diffraction (SAED) patterns of the interfacial zone and the ZrC layer of the ZrC-modified C/C composite are shown in Fig. 10. Pyrolytic carbon has a turbostratic graphite structure and shows an amorphous ring in the SAED patterns. The reaction-formed ZrC layer shows a polycrystalline structure. The ZrC grains with diameter about 100–250 nm bond tightly to pyrolytic carbon. The SAED
patterns demonstrate that the reaction-formed layer directly adheres to pyrolytic carbon is ZrC without other phases.

(4) Reaction Mechanism
Reaction between carbon and zirconium\textsuperscript{[19,21]} indicates that once the solid carbon contacts with the liquid zirconium, carbon atoms begin to dissolve into the liquid zirconium. Due to the very limited solubility, carbon dissolution becomes saturated in a very short period. ZrC precipitates from the saturated liquid zirconium and a continuous ZrC layer is formed around the solid carbon, separating the remaining molten Zr from the pyrolytic carbon. Any subsequent reactions occur at the metal-carbide interface by carbon diffusion through the ZrC layer, that is, the rate-determining step of the reaction. Many spherical ZrC particles are also found in the residual zirconium. They are thought to precipitate from the carbon saturated liquid zirconium during cooling of the sample.

Zr–Si8.8 alloy has only 8.8 at.% silicon and its reaction mechanism with carbon is believed to have much in common with the reaction between pure zirconium and carbon. At the very beginning of RMI, Zr–Si8.8 alloyed melts infiltrates into the porous C/C composite preform under the driving force of capillary. When the infiltrated alloy melts contacts with pyrolytic carbon in the C/C composite preform, carbon begins to dissolve into the liquid alloy. The carbon concentration in the alloy melts at 1800°C is about 0.5%, much less than that in the liquid zirconium, about 1% at 1860°C.\textsuperscript{15} Thus, the dissolution of carbon into the alloy melts becomes saturated in a very short period. In the C–Zr binary system, ZrC precipitates from the saturated liquid zirconium by the reaction between carbon and zirconium. However, silicon in the Zr–Si8.8 alloy can also react with carbon to form SiC in the carbon saturated Zr–Si8.8 alloy melts. The situation between
carbon and Zr-Si8.8 is remarkably different from that between carbon and pure zirconium. To determine which element reacts first with carbon, the reaction abilities of silicon–carbon and zirconium–carbon are evaluated based on the Gibbs free energy of the reaction. The Gibbs free energy change in the zirconium–carbon reaction is \(-180.1\) kJ/mol, which is much more negative than that of the silicon–carbon reaction \(-55.9\) kJ/mol, indicating that the reaction between zirconium and carbon is more favorable in thermodynamics.

EDS analysis indicates that a continuous ZrC layer is formed along pyrolytic carbon and no silicon is found in the ZrC layer. The further TEM observation of the interface between pyrolytic carbon and the reaction-formed layer demonstrates that the reaction-formed carbide layer is single ZrC phase and it directly contacts with pyrolytic carbon. EDS and TEM analysis are in agreement with the thermodynamic analysis. Thus, when the dissolution of carbon into the Zr–Si8.8 alloy melts becomes saturated, ZrC preferentially precipitates from the saturated alloyed melts by the reaction between carbon and zirconium. A continuous ZrC layer is formed around pyrolytic carbon in a very short period (Fig. 5), which separates the direct contact between the alloy melts and pyrolytic carbon. The subsequent reaction between zirconium and pyrolytic carbon proceeds by diffusion of carbon and zirconium through the ZrC layer and the subsequent interfacial reaction. According to Adelsberg et al investigation, the diffusion speed of carbon in ZrC is much higher than that of zirconium in ZrC. Thus, the ZrC layer growth proceeds by the migration of carbon through the ZrC layer and the consequent reaction at the interface of the ZrC layer and the alloy melt. As the reaction between zirconium and carbon proceeds, the ZrC layer grows and the concentration of zirconium in the infiltrated alloy melts decreases. Known from the phase diagram of Zr–Si binary system (Fig. 12), Zr3Si phase may firstly begin to precipitate from the alloy melts due to the decrease in zirconium concentration. However, Zr3Si is not definitively shown in the phase diagram and no Zr3Si phase was found in the EDS and XRD analysis of the reactive melt infiltrated composite and the Zr–Si8.8 alloy. Thus, Zr3Si phase should not appear in the reaction process of pyrolytic carbon and Zr–Si8.8 alloy melts. With that in mind, Zr3Si phase is believed to precipitate from the alloy melts due to the decrease in zirconium content. With the proceeding of the reaction between pyrolytic carbon and the infiltrated alloy melts, more and more zirconium in the alloyed melts is consumed and Zr3Si phase precipitates continuously from the infiltrated alloyed melts.
until all the infiltrated melts completely changes to Zr$_2$Si phase.

To further understand the reaction mechanism between pyrolytic carbon and Zr–Si alloy melts and the microstructure formation of the ZrC-modified C/C composite prepared by RMI, the reaction process and microstructure development of the composite are illustrated by the schematic in Fig. 13. At the beginning of RMI, the Zr–Si8.8 alloy is melted and the liquid alloy melts infiltrates into the porous C/C composite preform under the driving of capillary force [Fig. 13(b)]. When pyrolytic carbon contacts with the infiltrated alloy melts, carbon atoms begin to dissolve into the alloy melts. Because of the very limited carbon solubility in the alloy melts, the carbon dissolution becomes saturated in a very short time period [Fig. 13(c)]. Due to the stronger reactivity between carbon and zirconium, zirconium in the melts prefers to react with pyrolytic carbon and a continuous ZrC layer is formed around the pyrolytic carbon [Fig. 13(d)].

The infiltrated alloy melts and pyrolytic carbon are separated by the ZrC layer and the subsequent reaction between zirconium and pyrolytic carbon proceeds mainly by diffusion of carbon through the ZrC layer and the reaction at the ZrC/alloy melts interface. As the reaction between zirconium and carbon proceeds, the ZrC layer grows and the concentration of zirconium in the melts decreases continuously due to the reaction between pyrolytic carbon and alloy melts. Zr$_2$Si phase is formed by the reaction of silicon with zirconium and begins to precipitate from the alloy melts due to the consumption of zirconium [Figs. 13(e) and (f)]. If the reaction continues for a long time period and the amount of the infiltrated alloy melts is small, a significant amount of zirconium will be consumed by the reaction between pyrolytic carbon and zirconium and the residual alloy melts will completely change to Zr$_2$Si phase. Zr$_2$Si, with the melting point of 1925°C, is in solid state during the RMI process. Atoms in the solid Zr$_2$Si diffuse slowly and the formation of ZrC goes along at a rather low speed. Consequently, ZrC and Zr$_2$Si are formed in the as-received ZrC-modified C/C composite after RMI process (1800°C, 30 min) [Fig. 13(h)]. ZrC distributes around the pyrolytic carbon and Zr$_2$Si locates in the middle of pores surrounded by the ZrC layer. On the contrary, if the reaction maintains in a short time period and the amount of infiltrated alloy melts is large, the consumption of zirconium will be very small. The residual alloy melts do not completely change to Zr$_2$Si phase. A certain amount of residual eutectic Zr–Si8.8 alloy will still exist in the resulting ZrC-modified C/C composite, appearing as a eutectic microstructure, which is the same as the Zr–Si8.8 alloy [Fig. 13(i)].
IV. Conclusion

Reaction kinetics and mechanism of pyrolytic carbon with Zr–Si8.8 alloy are investigated. A continuous ZrC layer is observed to be formed along pyrolytic carbon in a very short time period and the thickness of the ZrC layer increases parabolically with extension of the reaction time. A model is established to describe the reaction kinetics of pyrolytic carbon with Zr–Si8.8 alloy. The calculated thickness of the ZrC layer is in good agreement with the experimental data. The microstructure and phase composition of the reactive melt-infiltrated ZrC-modified C/C composite is characterized and a reaction mechanism based on the characterization results and phase diagram is proposed.

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