



Review paper

Review on thermal conductivity of SiC_f/SiC composites for nuclear applications

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Abstract

Continuous silicon carbide fibre toughened silicon carbide composites (SiC_f/SiC) are highly promising materials for nuclear reactor applications due to their low chemical activity, low density, low coefficient of thermal expansion, high energy conversion rate and good high temperature strength. However, the thermal conductivity requirements of nuclear reactors are difficult to meet in conventional SiC_f/SiC composites. To improve the thermal conductivity of SiC_f/SiC composites, many approaches to enhance the thermal conductivity of SiC_f/SiC composites under nuclear reactor applications were firstly introduced. Further, the worldwide research process in this field has been reviewed. Finally, further development of the thermal conductivity research was discussed and prospected.

Keywords: SiC_f/SiC composites, fabrication, thermal conductivity, nuclear reactor applications

I. Introduction

Environmentally sustainable, reliable and economically competitive energy is essential for the world economy [1]. Nuclear energy is recognized as a major energy source of the future due to its unparalleled high output of heat, low energy consumption, long-term use and almost no emission of greenhouse gases [2]. Nuclear fusion reactor is the key to obtain fusion energy, which will eventually lead to large-scale controlled fusion reactions. Fusion reactor mainly includes cladding, shielding, magnet, auxiliary system and other components. The main role of cladding is to convert fusion energy into thermal energy, which is subjected to serious conditions such as high temperature, high radiation intensity and high stress [3]. Therefore, the choice of cladding material is crucial for fusion reactor. SiC_f/SiC composites have low neutron activation (radioactivity under neutron action), low shutdown waste heat, low gas permeability (especially for nitrogen) and excellent high temperature mechanical properties, making them very promising candidates for fusion reactor cladding. The American ARIES series of fusion power plant designs,

the Japanese DREAM and A-SSTR2 reactor designs and the European TAURO and nitrogen-cooled spherical bed cladding designs all use SiC_f/SiC composites as cladding first wall candidates [4–6].

In reactors, the core temperature can reach 800–1100 °C, which is much higher than operating temperature of metal materials for nuclear applications, such as stainless steel and vanadium alloys. With SiC_f/SiC composites for nuclear applications, research has focused on improving the thermal conductivity of SiC_f/SiC composites, because this performance can greatly affect the fuel temperature and the stress state of the SiC_f/SiC composites under normal operating conditions. The higher the thermal conductivity of nuclear SiC_f/SiC composites, the more favourable it is, which results in lower fuel temperatures and correspondingly less fission gas release and fuel swelling [7]. In addition, a high thermal conductivity will also reduce the through-thickness temperature gradient of the SiC_f/SiC composites and thus reduce the internal stresses in the SiC_f/SiC composites [8]. Therefore, the thermal conductivity plays an important role in the nuclear applications of SiC_f/SiC composites [9–11]. SiC_f/SiC composites are composed of SiC matrix, SiC fibre, fibre-matrix interface coating and pores. The influencing factors of

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thermal conductivity mainly include the impurity content, crystallization degree, lattice defects density, average grain size of the matrix; the number, thickness, structure and composition of the interface between fibre and matrix; the number, distribution, shape, size, alignment orientation, connectivity and atmosphere of pores; fibre composition, structure, degree of crystallization, orientation and volume content, etc. Therefore, this paper reviews the research methods and progress in improving the thermal conductivity of SiC_f/SiC composites in the background of nuclear applications through manufacturing process, fibre, preforms structure, interface and high thermal conductivity media, and provides an outlook on the future of this research area.

II. Thermal conductivity mechanism of SiC_f/SiC

Where there is a temperature gradient, the transfer of heat from high temperature to low temperature occurs, which is called heat transfer. There are three main ways of heat transfer: heat convection, heat conduction and heat radiation. For SiC_f/SiC composites for nuclear applications, heat conduction is the main way of heat transfer [12]. The carriers of heat conduction include molecules, electrons, phonons, photons and so on. In most non-metallic crystals, heat transfer is mainly generated through lattice waves through lattice vibrations, i.e. interactions and collisions between phonons. Compared to the ordered structure of crystals, the inorganic non-crystalline structure presents long-range disorder and short-range order, which can be approximately regarded as crystals composed of extremely fine grains, and thermal conductivity analysis is also carried out based on phonon transport theory [13]. Therefore, in SiC_f/SiC composites, phonons are the main carriers of heat and the effective collisions between phonons are mainly affected by the mean free path and the collision rate (mainly limited by phonon scattering). This is temperature dependent mechanism derived from inelastic collisions between phonons and scattering caused by object boundaries, interfaces, defects and impurities [14].

The heat transfer capacity of SiC_f/SiC composites is usually characterized by thermal conductivity, which refers to the heat passing through a unit area in a unit time under a unit temperature gradient. In SiC_f/SiC composites, the thermal conductivity is affected by manufacturing process, fibre type, preform structure, matrix interface and other factors.

III. Manufacturing process

In SiC_f/SiC composite materials, there are many pores with high volume fraction, and the heat transfer efficiency of pores is much lower than that of solids, which can lead to a substantial decrease in the thermal conductivity of the composites [15,16]. Therefore, in order to improve the thermal conductivity of SiC_f/SiC composites for nuclear application it is important to im-

prove the density of matrix and reduce its porosity.

The main factor that determines the density of the composite materials is the preparation process. The traditional preparation processes of SiC_f/SiC composites mainly include chemical vapour infiltration (CVI) [17–18], precursor infiltration and pyrolysis (PIP) [19], CVI-PIP, hot pressing (HP) [20] and direct conversion methods such as molten silicon infiltration (MI) [21,22]. In order to improve the thermal conductivity of SiC_f/SiC composites, on one hand, researchers are committed to match and improve the original process. On the other hand, they have developed many new preparation processes, such as reaction sintering (RS) [23] and nano-infiltration and transient eutectic phase (NITE) [24], etc.

The SiC_f/SiC composite used in nuclear reactor should have the matrix with near stoichiometric ratio, high purity and complete crystallization, because the secondary phase in the ordinary matrix is unstable under irradiation. CVI method is an advanced basic process for the preparation of SiC_f/SiC [25]. The prepared SiC matrix is pure crystalline and less defective β-SiC, which has a good resistance to irradiation, so CVI is one of the best processes for the preparation of SiC_f/SiC composites for nuclear reactor applications. However, the SiC_f/SiC composites prepared by this process still have some disadvantages, such as long cycle time, insufficient thermal conductivity and high porosity (10–15%) [26–29]. Katoh *et al.* [30] predicted by modelling that the thermal conductivity of 3D CVI SiC_f/SiC composites in the thickness direction was 10–15 W/(m·K) after irradiation at 800–1000 °C, while for 2D SiC_f/SiC composites, their thermal conductivity was below 5 W/(m·K) after irradiation below 800 °C.

PIP method can be used to prepare SiC_f/SiC for large complex parts with low preparation temperature and low damage to fibres, and a denser SiC matrix can be obtained after several cycles. However, it is not suitable for the preparation of high-size precise components, and there are problems such as high residual carbon content, low crystallinity of SiC and low thermal conductivity [31]. This is the reason why the PIP process does not attract much attention in nuclear applications, which is closely related to the development of the ceramic technology of polycarbosilane precursor [32,33]. With the continuous development of precursor materials with near stoichiometric conversion characteristics, PIP SiC_f/SiC composites with cost and performance advantages may gradually approach the application requirements for nuclear structural materials [34].

CVI combined with PIP method can combine the advantages of CVI and PIP, which means better control the matrix densification and part shape [35]. However, the thermal conductivity of the prepared composites in general tends to be lower than that of CVI SiC_f/SiC. Yamada *et al.* [36] prepared 3D CVI Tyranno SA SiC_f/SiC and PIP-CVI Tyranno SA SiC_f/SiC with thermal conductivity of 40–50 and 35–40 W/(m·K) at room temperature and 24 and 18 W/(m·K) at 1000 °C, respectively.

In addition, CVI + PIP method also has the problems of introducing Si–C–O amorphous phase with low thermal conductivity and poor irradiation performance and poor crystallinity of SiC matrix obtained by precursor cracking.

There is always a lot of residual silicon in the composites prepared by MI [37,38], RS [39–41] and HP [42] processes, which affects the stability of the composites under high temperature and irradiation, so the application in nuclear reactor technology is greatly limited. Thus, these processes have been basically abandoned at present.

In recent years, the NITE process has been rapidly developed and is considered to be an ideal process for the preparation of SiC_f/SiC structural composites with potential nuclear applications. This method was developed from the transient liquid-phase sintering (LPS) process. LPS process is a method for producing dense SiC ceramics under a certain pressure. In recent years, scholars have gradually developed NITE process by adding a small amount of oxide additives during the LPS process [43,44]. The SiC_f/SiC prepared by this process has the characteristics of high density, low porosity and high thermal conductivity [45]. Lee *et al.* [46] prepared SiC_f/SiC composites by NITE process, which had a bulk density of more than 95 %TD and a thermal conductivity of 65 W/(m·K) at room temperature, which was higher than the thermal conductivity of the SiC_f/SiC composites prepared by conventional processes. In conclusion, the advantages of NITE SiC_f/SiC are high density and robustness, low porosity, high crystallinity of near stoichiometric ratio matrix, high thermal conductivity, good chemical stability, low cost, etc. Therefore, many researchers believe that NITE will be an alternative method to CVI. However, the NITE method also has some unavoidable problems: sintering aids must be used in the sintering densification, and the aids can affect the overall irradiation properties of the composite, especially under high-dose irradiation conditions, which can deteriorate the stability of the composite, and the high preparation temperature of the process (generally greater than 2000 °C) have adverse impact on the fibre properties [47,48].

In order to solve the problems of long process cycle time and high residual porosity between/within fibre bundles when CVI and PIP are used, Novak *et al.* [49–51] focused on a more flexible, simple and effective electrophoretic deposition (EPD) method. EPD method has been widely used in the preparation of coatings and bulk ceramics. Novak *et al.* [52] combined EPD with the NITE method to form the slip infiltration and transient eutectoid (SITE) method. In this method, SiC particles are uniformly dispersed into suspension, then deposited on the SiC fibre preform by EPD method, and then densified and sintered by NITE method. SITE method combines the advantages of EPD and NITE to obtain denser SiC_f/SiC composites with higher thermal conductivity. This process utilising the combination of EPD and NITE methods is called SITE-A. However, it still has problems such as high preparation temperature and the need for sintering aids. Subsequently, Novak *et al.* [53] developed the SITE-P process on this basis. This process is a combination of EPD and PIP method where the final densification of SiC_f/SiC composites uses PIP method. With the increase of PIP times in the later stage, SITE-P process can obtain SiC_f/SiC composites with high density and high thermal conductivity (Fig. 1) without sintering aids. The density of SiC_f/SiC composites obtained by Novak *et al.* [53] using the SITE-P process was 2.8 g/cm³, which was 86.5% of the theoretical density. The strength was 400 MPa, the modulus of elasticity was 250–300 GPa and the thermal conductivity was about 60 W/(m·K) at room temperature and 30 W/(m·K) at 1000 °C. However, SITE-P still has the problems of introducing the Si–C–O amorphous phase with poor irradiation performance as the PIP process and the need for high-temperature cracking to improve the crystallinity of the SiC matrix.

IV. Fibres

Fibre is the load-bearing unit of SiC_f/SiC composites, which has an important effect on the thermal conductivity, high temperature stability, irradiation resistance and other properties of SiC_f/SiC composites. Therefore, the effect of SiC fibre on thermal conductivity of SiC_f/SiC

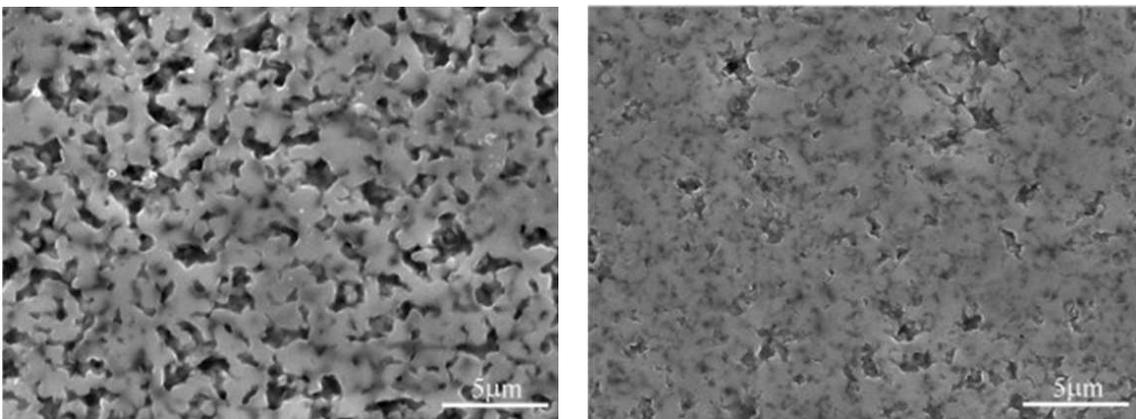


Figure 1. Microstructure of SITE-P SiC collected after different number of PIP cycles: a) 1 and b) 6 times [53]

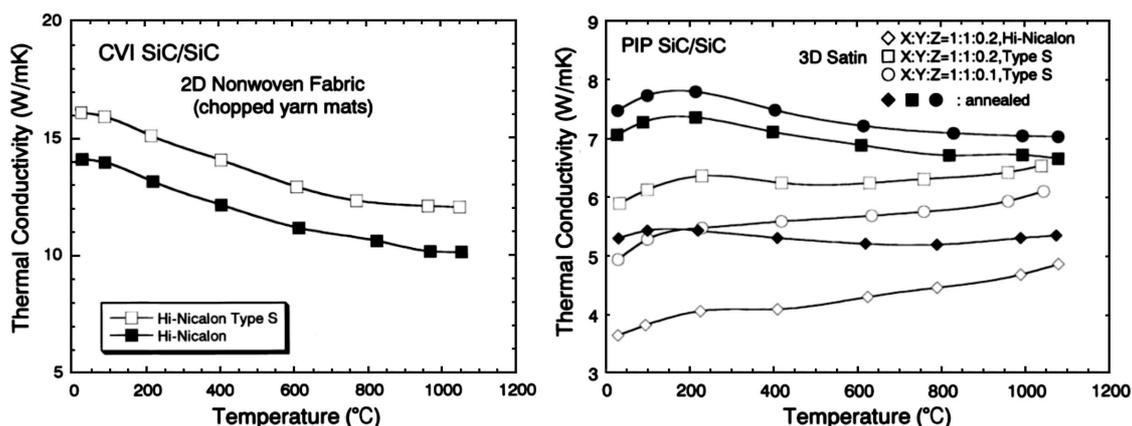


Figure 2. Comparison of thermal conductivity of: a) 2D non-woven fabric CVI SiC_f/SiC composites when Hi-Nicalon fibre and Hi-Nicalon Type S fibre were used and b) 3D satin woven PIP SiC_f/SiC composites when Hi-Nicalon and Hi-Nicalon Type S were used (the annealing conditions were 10 h at 1400 °C in vacuum) [63]

composites has attracted much attention. SiC fibre with high thermal conductivity should be pure and highly crystalline, so the ideal SiC fibre in the conditions of nuclear reactor is oxygen-free, having ideal stoichiometric ratio and crystalline structure and even large grain size. Many researchers around the world are also working to develop more desirable SiC fibres.

Professor Yajima of Tohoku University, Japan, pioneered the precursor conversion method to prepare SiC fibres in 1975. Subsequently, Nippon Carbon Corporation obtained the patent implementation rights for SiC fibres and further developed it into a commercial product named Nicalon in 1979 [54,55]. After that, the company successfully commercialized the production of Hi-Nicalon fibres with low oxygen content using e-book radiation cross-linking technology based on the preparation process of Nicalon fibre [56]. These two kinds of SiC fibres contain a large amount of surplus free carbon, the C/Si ratio of Nicalon is 1.31 and that of Hi-Nicalon is 1.39. Therefore, the thermal conductivity of SiC_f/SiC composites prepared by CVI and PIP processes using traditional SiC fibres (e.g. Nicalon) is not high, about 10 W/(m·K) [57]. Additionally, the presence of large amounts of free oxygen and carbon in Nicalon fibres can lead to poor thermal and irradiation stability, and the presence of excess carbon and silicon in Hi-Nicalon fibres can lead to obvious size shrinkage when the irradiation dose is high [58,59].

Subsequently, Hi-Nicalon S-type [60], TyrannoTM-SA type [61] and Sylramic type [62] SiC fibres with near stoichiometric ratio were successfully developed. Among them, Hi-Nicalon S fibre raw filaments are cross-linked by anhydrous and oxygen-free electron beam, which has the properties of lower oxygen content, higher thermal conductivity, better high-temperature stability, and higher modulus. Yamada *et al.* [63] used three-dimensional satin-woven fabrics and two-dimensional non-woven fabrics of S-type and Hi-Nicalon SiC fibres to prepare composites by CVI or PIP process. The results showed that both CVI and PIP SiC_f/SiC composites prepared from S-type fibres with

higher thermal conductivity had higher thermal conductivity in the thickness direction than that of CVI and PIP SiC_f/SiC composites prepared from Hi-Nicalon fibres only (Fig. 2). From Fig. 2, it can be seen that the thermal conductivity of composites increases when the content of S-fibres in the z-direction increases. In addition, the thermal conductivity of 3D PIP SiC_f/SiC composites increased after vacuum annealing at 1400 °C. This is because their cracking temperature is lower than the annealing temperature, which causes the internal grains to grow.

Tyranno fibre (w(C) : w(Si) = 1.0) is a Ti-containing SiC fibre prepared by UBE Kogyo after introducing Ti into the synthesis of a precursor polycarbonylsilane (PCS), and a production line with a monthly capacity of 1 ton was built in the late 1990s. Itatani *et al.* [64] prepared HP SiC_f/SiC composites with fibre content of 0–50% using Tyranno SA short-cut fibres with an average length of 394 μm, hot-pressed at 1800 °C, 31 MPa and 30 min. The thermal conductivity of the monomer SiC sample was 32.1 W/(m·K), while the thermal conductivity of the composite with 50% fibre content was 56.3 W/(m·K). Yamada *et al.* [36] prepared 3D CVI Tyranno SA/SiC and CVI S-type Hi-Nicalon/SiC composites with thermal conductivities of 40–50 W/(m·K) and 36 W/(m·K) at room temperature and 24 W/(m·K) and 20 W/(m·K) at 1000 °C, respectively, which are much higher than those of SiC_f/SiC composites prepared with conventional SiC fibres. Similarly, Katoh *et al.* [65] prepared unidirectional NITE SiC_f/SiC composites by using TyrannoTM-SA3 grade polycrystalline SiC fibres and obtained composites with thermal conductivity of 29 and 18 W/(m·K) at room temperature and 1200 °C, respectively, which are higher than those of SiC monolithic ceramics cracked under the same conditions (the thermal conductivity at room temperature and 1200 °C are 25 and 17 W/(m·K), respectively). These higher thermal conductivities are attributed to the use of fibre with near stoichiometric ratio.

Sylramic (w(C) : w(Si) = 1.0) is a boron-containing polycrystalline SiC fibre obtained by Dow Corning from

PCS precursor in 1988. Sylramic fibre has high thermal conductivity, strength and modulus and good heat resistance, but the fibre contains 2 wt.% B and 0.4 wt.% N. B and N elements undergo transmutation in the radiation environment and produce long-lived isotopes, so Sylramic BN is not suitable for use in nuclear reactors.

V. Preforms structure

SiC_f/SiC composites are prepared by firstly braiding SiC fibres into preforms to make the reinforcement of SiC_f/SiC composites. The braiding method of SiC fibres determines the volume fraction of SiC fibres in the braid and the fraction of SiC fibres in each direction, which can have a large effect on the thermal conductivity of SiC_f/SiC composites. At present, 2D and 3D SiC fibre preforms could be used for nuclear reactors.

Recently, 2D preform structures are mostly used and researched. 2D woven preform can be divided into five-harness satin and plain weave according to different weaving methods. Katoh *et al.* [35] studied the effect of different weaving methods on the thermal conductivity of SiC_f/SiC composites. The results showed that there was no significant difference in the thermal conductivity of the plain and five-harness satin SiC_f/SiC composites prepared by CVI.

The 3D preforms can significantly increase the volume fraction of SiC fibres in SiC_f/SiC composites, especially the volume fraction of fibres in the z-direction, which can theoretically improve the thermal conductivity of the composite along the thickness direction and increase its interlaminar shear strength. Yamada *et al.* [36] studied the effect of z-directional fibre content on the overall thermal conductivity of 3D CVI SiC_f/SiC composites with Tyranno SA as the reinforcing fibre and studied the z-directional thermal conductivity of the composites with x, y, and z-directional fibre ratios of 1 : 1 : 0.09, 1 : 1 : 0.2, and 1 : 1 : 1.23, respectively. The results showed that the z-directional thermal conductivity of the composites increased with the increase of fibre content in this direction. Katoh *et al.* [35] prepared CVI SiC-based unidirectional 2D and 3D composites using near stoichiometric SiC fibres and SiC/graphite hybrid fabrics. The experimental data and model analy-

sis showed that the thermal conductivity of 3D SiC_f/SiC composites ($x : y : z = 1 : 1 : 4$) was better than that of other structural composites. Nannetti *et al.* [66] also demonstrated that composites with 3D structure can obtain better thermal conductivity.

VI. Interface

Since the fibre/matrix interface is often amorphous, layered and has phonon scattering, it can act as a thermal resistance between crystal phases and also has a non-trivial effect on the thermal conductivity of the composites [67]. The material, thickness and coating method of the interfacial coating all have an effect on heat conduction, but there is no systematic studies in this area.

Carbon coating is widely used in the CVI SiC/Nicalon system [68], and Taguchi *et al.* [69] prepared RS SiC_f/SiC composites with CVD C-SiC double coating. The thermal conductivity of CVD C-SiC double-coated composites was about 32 W/(m·K) at room temperature and 16 W/(m·K) at 1000 °C, which can meet the requirements for fusion reactor structural materials. The preparation and performance characterization of a commercially graded 3D SA3/CVI SiC composite with a PyC single interfacial layer of about 80 nm thickness was carried out in the EU program, and the results showed that the thermal conductivity of the composite in the thickness direction was 18 W/(m·K) at 1000 °C. Itatani *et al.* [64], however, concluded that the effect of a 100 nm thick C coating on the thermal conductivity of the composite is negligible and can be ignored. But more researchers believe that the optimal thickness of PyC coating is 0.17–1 μm [70]. In addition to this, many researchers have investigated the replacement of conventional PyC interfaces with (PyC/SiC)_n multilayer interfaces [71–73] and porous SiC interfaces [74]. Nashain *et al.* [75] showed that the (PyC/SiC)_n interface has better irradiation stability and post-irradiation fracture strength than the porous SiC interface. At present, the mechanical test results of non-irradiation and low-dose irradiation have confirmed the application of PyC and (PyC/SiC)_n interface layers. However, PyC undergoes large dimensional changes under neutron irradiation, so it is likely to be an unac-

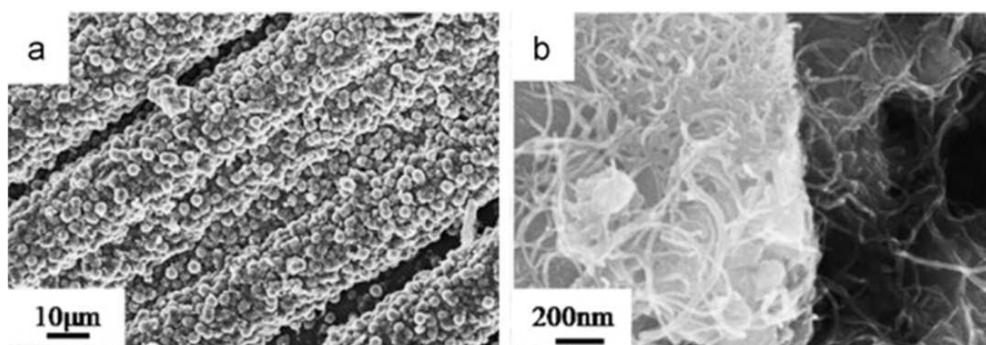


Figure 3. Surface morphologies of SiC fabric after depositing a thin SiC layer and CNTs layer: a) the low magnification surface morphology and b) the CNTs deposited on SiC fabric [78]

ceptable interface for SiC_f/SiC composites subjected to high dose irradiation. However, little work has been done to directly investigate the effects of high-dose irradiation on the commonly used PyC interfacial layer.

In addition, the interface of carbon nanotubes (CNTs) prepared by EPD has also attracted the attention of researchers [76]. König *et al.* [77] deposited CNT on the surface of SiC fibre for the first time using the EPD method, forming an effective carbon nanotube interfacial phase for SiC_f/SiC composite. Feng *et al.* [78] deposited a layer of CNTs on the PyC interface of SiC fibre by EPD (Fig. 3). The thermal conductivity of the CNTs-deposited SiC_f/SiC composites attained 14.3 W/(m·K), which was ~1.74 times higher than that of SiC_f/SiC composites without CNTs. Similarly, Li *et al.* [79] introduced CNTs at the PyC interface by chemical vapour deposition (CVD) in order to improve the thermal conductivity of SiC_f/SiC composites (Fig. 4). The results showed that the thermal conductivity of SiC_f/SiC composites was enhanced by the addition of CNTs, and the deposition of 5.8 vol.% CNTs (corresponding to 20 min CVD deposition) was found to be the best condition to improve the thermal conductivity of SiC_f/SiC. However, for the CVI BN interface, which is another popular application in SiC_f/SiC, it cannot be used as an interfacial structural unit because of its helium production after irradiation.

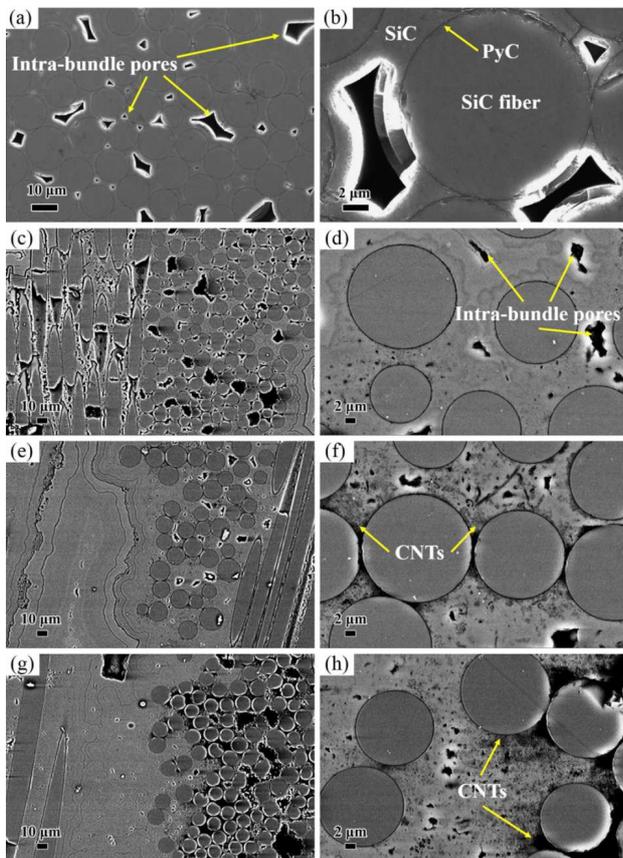


Figure 4. Cross-sectional morphology of different types of SiC_f/SiC composites containing CNTs: (a-b) SS, (c-d) SSC1, (e-f) SSC2 and (g-h) SSC3 [79]

VII. High thermal conductivity medium

In addition to improving the existing components and processes, it is also practical to introduce high thermal conductivity media such as nanomaterials into SiC_f/SiC composites to increase thermal conductivity [80–82].

CNTs have the extraordinary properties, including high rigidity with an elastic modulus of more than 1 TPa and extremely high thermal conductivity (theoretical value ~3000 W/(m·K)) [83–85]. Therefore, the introduction of CNTs is expected to improve the thermal conductivity of SiC_f/SiC composites. Zhao *et al.* [86] introduced CNTs on the surface of SiC fibre by chemical vapour deposition (CVD). Their results showed that the introduction of CNTs helped the thermal conductivity of composites increase from 1.64 to 1.83 W/(m·K) at room temperature. Taguchi *et al.* [87] prepared SiC_f/SiC composites containing 4% CNTs (volume fraction) using the RB process and investigated the effect of CNTs on the thermal conductivity of the composites. The results showed that the thermal conductivity of the SiC_f/SiC composites with CNFs added was doubled compared to the original one, close to 90 W/(m·K) at room temperature, and more than 40 W/(m·K) at the fusion reactor operating temperature of 800 °C, which could meet the conceptual design guidelines of fusion reactor.

However, homogeneous dispersion of CNTs in composites is hard to achieve because of its agglomeration. The agglomeration of CNTs also limits the amount of CNTs introduced into CVI SiC_f/SiC composites. In recent years, EPD method has been considered as an effective method to introduce CNTs into SiC_f/SiC composites, but the amount of CNTs introduced into SiC_f/SiC is usually only about a few volume percentages [88–90], which leads to the inability to improve the thermal conductivity of SiC_f/SiC composites sufficiently. In order to introduce more uniformly dispersed CNTs in SiC_f/SiC composites, Feng *et al.* [91] developed a new method to fabricate SiC-CNTs/SiC composites: vacuum filtration combined with CVI. Compared with previously reported works [92], more CNTs were added into CVI SiC_f/SiC composites, as the amount of the introduced CNTs can be increased from several volume percentages to around 25–30 vol.%. There is almost no agglomeration appearing in CNTs films (Fig. 5). SiC-CNTs/SiC had outstanding thermal conductivity of 23.9 W/(m·K) at room temperature which was 2.9 times higher than traditional SiC_f/SiC composites.

In addition, SiC nanowires (SiC_{NWS}) have also been studied more and more due to their high mechanical strength, excellent oxidation resistance and excellent thermal conductivity [93,94]. The addition of SiC_{NWS} is conducive to the formation of thermal conductivity channels, which can improve the thermal conductivity of composites [95,96]. Cui *et al.* [97], after *in situ* growth of SiC_{NWS} on the surface of PyC interface by CVI process (Fig. 6), found that the addition of SiC_{NWS} could significantly improve the thermal conduc-

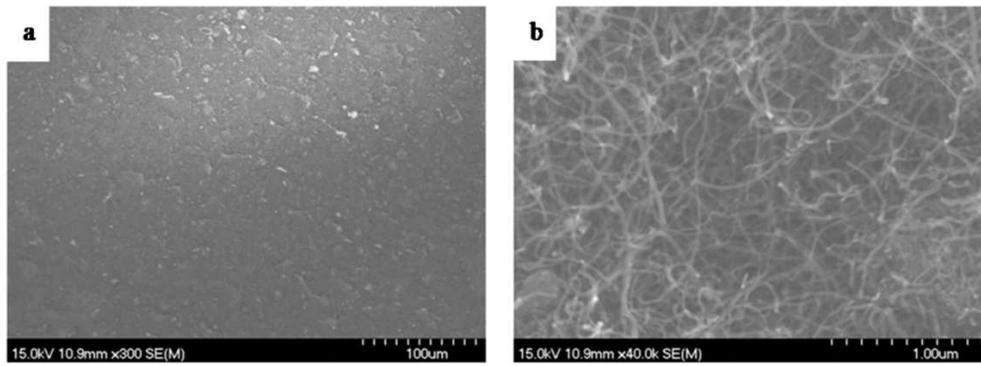


Figure 5. The morphologies of CNTs film: a) low and b) high magnification [92]

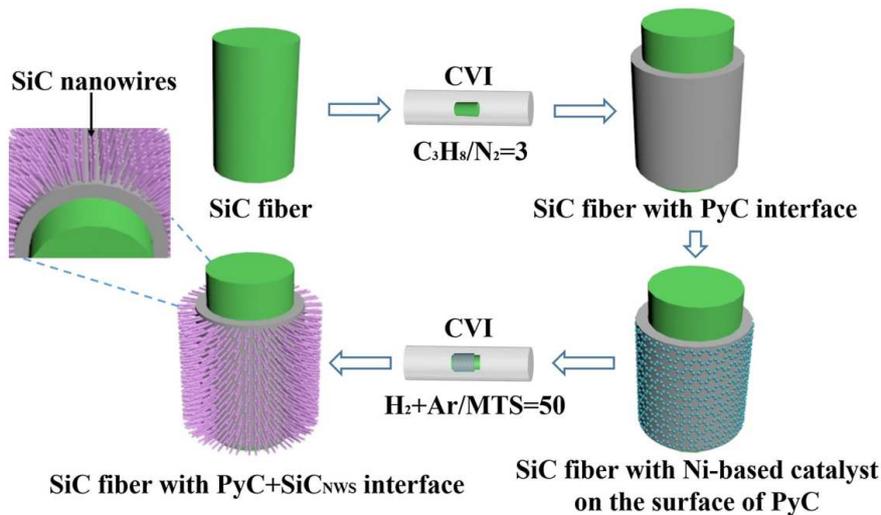


Figure 6. Fabrication process of the SiC fibres with PyC + SiCNWS interface [97]

tivity of 3D SiC_f/SiC composites prepared by PIP process. Compared with traditional SiC/PyC/SiC composites, the thermal conductivity of SiC_f/SiC composites containing SiC_{NWS} was increased by 43% at 1000 °C. Tao *et al.* [98] found that SiC_{NWS} could effectively fill the pores of CVI SiC_f/SiC cladding tube by introducing SiC_{NWS} on graphite rods, and increase the density of CVI SiC_f/SiC cladding tube from 2.63 to 2.78 g/cm³, and its thermal conductivity was also improved with the addition of SiC_{NWS}.

VIII. Conclusions and prospects

SiC_f/SiC composites have great prospect for nuclear reactor applications owing to their various aspects such as high temperature mechanical properties, thermophysical properties and nuclear radiation properties. In conclusion, the thermophysical properties of SiC_f/SiC composites for the nuclear applications have been greatly improved with the efforts of scientists all over the world. The current research status and future prospects of SiC_f/SiC composites as well as current test situation will make them more competitive for future reactor applications. However, there is still a lot of work to be done in the future in terms of the thermal conductivity of SiC_f/SiC composites based on nuclear applications.

First, most of the preparation processes still have their own limitations, such as the large porosity of CVI SiC_f/SiC composites, the poor crystallinity and the need for precursors improvement of PIP SiC_f/SiC composites, as well as the secondary phase stability and microstructure control during the composites production by RS, MI and NITE processes. Therefore, the existing processes should continue to be improved or new preparation processes should be developed to further improve the thermal conductivity of SiC_f/SiC composites. Secondly, after years of development, SiC fibres with near stoichiometric ratio, high temperature resistance and high crystallinity have been developed and introduced, but cost-effective fibres with high comprehensive performance still need to be developed. Third, the current research on the influence of preforms structure on the thermal properties of composites is not deep and systematic enough, and the influence mechanism should be proposed to further improve the thermal conductivity of composites. Fourth, a more systematic study of the effects of the composition, thickness and coating method of the composite interface on the thermal conductivity should be conducted, and the applicability of PyC interfacial coating in SiC_f/SiC composites under high-dose irradiation conditions should be studied in depth. Besides, more types of possible high thermal conductivity

media could be introduced and their introduction mode, content, concentration and effect should be studied to improve the thermal conductivity of advanced SiC_f/SiC composites for applications in nuclear area.

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