Sustainable high emissivity of Si–Zr–C–O fiber felts despite oxide layer formation in oxidative environment

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The effect of oxide layer formation on the emissivity of Si–Zr–C–O fibers was examined in this study. In order to form a uniform oxide layer on each fiber surface, the Si–Zr–C–O fiber felt was exposed to air at a high temperature. The oxide layer consisted of SiO₂ (cristobalite) and dispersed 10–25 nm ZrO₂ particles. Whereas, the fiber core itself exhibited no microstructural changes crystallographically or morphologically despite the exposure. The total emissivity of the exposed fiber felt calculated at 1000°C was $87.6 \pm 4.1\%$ and exhibited a similar value to the initial total emissivity ($89.2 \pm 4.2\%$). These results indicated that the emissivity of the Si–Zr–C–O fiber felt was unchanged irrespective of the formation of the oxide layer when the layer thickness was less than 5–6 μm. Furthermore, the radiation heat transfer performance was theoretically evaluated taking into consideration the diameter degradation of the fiber core itself. This suggests that the decrease in size of the diameter of the fiber core do not have a significant effect on heat transfer in this study range.

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1. Introduction

Silicon carbide fibers have been promising candidates for reinforcement materials for composites in the fields of high-temperature structural materials and also for insulation materials in high temperature furnaces and so on.^{1)–6)} This is because silicon carbide fibers exhibit excellent emissivity, high thermal stability and other properties.^{1),2)} With respect to insulator applications, it has been reported that the energy efficiency of furnace operation was significantly improved by just covering the inner walls of the furnace with a mat of Si–Zr–C–O fiber felt.^{3)–6)} The increasing in energy efficiency was due to not only the fiber's high emissivity but also excellent insulating properties.³⁾ However, when the furnace operation is usually carried out at high temperatures in an atmosphere including oxygen i.e. air, a passive oxidation of the Si–Zr–C–O fiber is unavoidable. Thus, it is important to examine the effect of oxidation layer formation on the emissivity behavior of the fiber.

Generally speaking, SiC material oxidation to form SiO₂ on its surface occurs at high temperatures in atmospheres which include oxygen such as air. This SiC oxidation behavior is called passive oxidation and expressed as followed:

In this passive oxidation behavior, the kinetics is usually controlled by interface at an initial stage and then obeys gas diffusion through SiO₂ layer.^{7),8)} The oxidation of several types of amorphous silicon carbide fibers (e.g. Nicalon, Hi Nicalon, Si–Ti–C–O and Si–Zr–C–O fibers) has been the subject of many studies.^{9)–14)} It was demonstrated that the oxidation behaviors

were followed by a parabolic law at the later stage regardless of the types of the fibers. The Si–Zr–C–O fiber which was developed by Ube Industries, Ltd., exhibited high oxidation resistance as compared to Si–Ti–C–O fiber.^{14)–16)} Besides, the Si–Zr–C–O fiber showed higher heat resistance (i.e. weight loss, SiC crystal grain growth and tensile strength) as compared to the Si–Ti–C–O fiber and exhibited β-SiC grain growth occurred above 1500°C.¹⁶⁾ These might be due to zirconium playing an important role in the improvement of both the oxidation resistance and the heat resistance in the Si–Zr–C–O fibers according to the previous reports.^{14)–16)}

To recap, oxidation of Si–Zr–C–O fibers spontaneously occurs when it was exposed to air at high temperatures, but the fiber exhibited a relatively slow oxidation formation rate and relatively high oxidation resistance. However, the effect of the microstructural change such as an oxide layer formation mainly accompanied with the high temperature exposure on the fiber's emissivity has not been discussed. In this study, therefore, both unexposed and exposed Si–Zr–C–O fiber felts were prepared, and their microstructural characterizations were conducted using SEM-EDS, TEM, XRD and Raman spectroscopy. The emissivity of both types of fiber felts was also evaluated by a reflective method using fourier transform infrared spectroscopy (FT-IR). Furthermore, the effect of the microstructural changes associated with the oxidation layer formation on the emissivity and radiation heat transfer of the fiber felt was discussed.

2. Experimental procedure

2.1 Preparation

Si–Zr–C–O fiber felts were produced by accumulating chopped Si–Zr–C–O short fibers. The chopped short fibers were cut to a certain length from continuous Si–Zr–C–O fibers produced in Ube Industries, Ltd. The detailed process of producing contin-

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Table 1. Representative properties of continuous Si–Zr–C–O fiber⁵⁾

Tensile strength, GPa	Tensile modulus, GPa	Elongation, %	Density, g/cm ³	Specific heat, J/gK	Thermal conductivity, W/mK	Coefficient of thermal expansion, 10 ^{−6} /K
3.4	200	1.7	2.48	0.709	2.52	4.0

uous Si–Zr–C–O fibers has been described in previous papers.^{15),17)} The properties of the continuous Si–Zr–C–O fibers are listed on **Table 1**, and their representative chemical composition is 56 wt.% Si, 34 wt.% C, 9 wt.% O and 1 wt.% Zr.⁵⁾ The average fiber diameter used in this study was about 14 μm . In order to form an oxide layer thick enough (i.e. 5–6 μm in thickness) on the Si–Zr–C–O fibers, the fiber felts were set in a conventional electric furnace (MF-1200, Mizukami Electric Works Co. Ltd., Osaka, Japan), and exposed to 1150°C in air.

2.2 Microstructural characterization

Both the unexposed and the exposed Si–Zr–C–O fiber felts were characterized using scanning electron microscopy (SEM) (JSM-6510 scanning electron microscope, JEOL, Tokyo, Japan) coupled with energy-dispersive spectroscopy (EDS) and transmittance electron microscopy (TEM) (JEM-2100F field emission electron microscope, JEOL, Tokyo, Japan). Both the unexposed and the exposed Si–Zr–C–O fiber felts were embedded into epoxy resin, glued onto a molybdenum ring and Ar-ion milled for the TEM study. The TEM was performed at acceleration energy of 120 kV. The crystalline structures of the Si–Zr–C–O fiber felts were also characterized using a X-ray diffractometer (Rigaku RINT-TTR III) with monochromated Cu-K α radiation, operating at 300 mA and 50 kV. The samples were also pulverized for this evaluation. In addition, a Raman spectroscopy (NRS-3300, JASCO corp., Tokyo, Japan) using 532 nm Nd-YAG laser excitation was conducted at room temperature in air to evaluate carbon structure.

2.3 Emissivity evaluation

The evaluation of emissivity of the Si–Zr–C–O fiber felts was carried out by the reflective method using FT-IR, complying with JIS R 1693-2:2012.¹⁸⁾ At first, its spectral reflectivity (ρ) was measured in a nitrogen atmosphere at room temperature with an internal Au-coated integrating sphere (RSA-PE-200-ID, Lapsphere) coupled with FT-IR (FT-IR: System 2000, Perkin Elmer). This measurement range was from 1.66 to 25 μm (wave number of 400 to 6000 cm^{-1}) and its resolution was 16 cm^{-1} . The spectral emissivity (ε) was then calculated using follow equation:

$$\rho + \tau + \gamma = 1 \quad (2)$$

$$\rho + \tau + \varepsilon = 1 \quad (3)$$

Where ρ was reflectivity, τ was transmissivity, γ was absorptivity and ε was emissivity, respectively. According to Kirchhoff's law,¹⁹⁾ the absorptivity (γ) is assumed to be equal to emissivity (ε). Meanwhile the transmittance (τ) was postulated to be zero when the measuring materials had enough thickness and were not transparent. Thus, the assumption equation, $\varepsilon = \gamma = 1 - \rho$, was utilized to estimate both spectral emissivity (ε) and absorbance (γ) of the materials at room temperature.

Furthermore, a spectral radiant emittance at a high temperature (i.e. 1000°C) was estimated using the spectral emissivity obtained at room temperature and spectral radiant emittance of the black body at this temperature. The black body's spectral radiant emittance can be calculated using Planck's law.²⁰⁾

Fig. 1. XRD results of (a) unexposed and (b) exposed Si–Zr–C–O fibers.

For a preparation of the measurement, both the unexposed and the exposed Si–Zr–C–O fiber felts were very rough-pulverized and then the pulverized samples were packed into a holder having 30 mm width, 30 mm length and 10 mm height.

3. Results and discussion

3.1 Microstructural characterization

3.1.1 XRD

Figure 1 shows X-ray diffraction pattern of the unexposed and exposed Si–Zr–C–O fibers. As can be seen in Fig. 1(a), a broad diffraction pattern of the unexposed Si–Zr–C–O fiber was found and indicated an amorphous structure. On the other hand, a strong peak of SiO₂ (cristobalite) was found in the exposed Si–Zr–C–O fiber in Fig. 1(b). Additionally, slightly weak peaks of ZrO₂ were confirmed. Since oxygen might exist around the environment at Zr in the amorphous Si–Zr–C–O fiber, the oxidation reaction is likely to be expressed in the equation:

3.1.2 Microstructure

Figures 2 and **3** depict representative micrographs of the unexposed and exposed fiber, respectively. The unexposed fiber exhibited smooth surface and uniform microstructure as shown in Fig. 2(a). Figures 2 (b)–2(d) show the bright field and β -SiC 111 images, and SAD pattern recorded near the unexposed fiber surface, respectively. The β -SiC grain was distributed uniformly in the fiber and its size was less than 3 nm. This grain size corresponded to previous report,¹⁴⁾ in which the size (≈ 2 nm) was estimated using Scherrer equation from the results of X-ray diffraction pattern. As aforementioned in Fig. 1(a), the Si–Zr–C–O fiber also had an amorphous structure. Consequently, it seems that the microstructure of Si–Zr–C–O fiber was mainly constituted of amorphous Si–C–O phases and nano-crystallized β -SiC grains.

On the other hand, the exposed fiber formed a 5–6 μm thick layer on the core fiber as can be seen in Fig. 3(a). Some cracks

Fig. 2. Representative micrographs of unexposed Si–Zr–C–O fiber near surface; (a) SEM, (b) TEM bright field, (c) SAD pattern and (d) β -SiC 111 images.

Fig. 3. Representative micrographs of exposed Si–Zr–C–O fiber at the high temperature; (a) cross section near fiber surface, and (b) TEM bright field, (c) SAD pattern and (d) β -SiC 111 images nearby the reaction layer/core interface in the fiber core.

and micro-pores within the oxide layer were also found. The generation of these cracks and micro-pores might be caused by volume contraction contributed by $\alpha \leftrightarrow \beta$ cristobalite phase transition and thermal stress resulted from coefficients of thermal expansion mismatch during cooling. According to Fujiyoshi et al., the $\alpha \leftrightarrow \beta$ cristobalite phase transition occurs at 200–400°C.²¹⁾ Figures 3(b)–3(d) show the bright field and β -SiC 111 images, and SAD pattern recorded in the fiber core nearby the reaction layer/core interface. The β -SiC grain size was less than 3–5 nm. Interestingly, as compared to that of the unexposed fiber [Figs. 2(b) and 2(d)], the SiC grain size and distribution in the

Fig. 4. TEM back scatter images of the exposed Si–Zr–C–O fiber at the high temperature in air; (a) the formed oxide layer and (b) formed ZrO_2 in the oxide layer.

Table 2. EDS analyses results in the core of unexposed and exposed Si–Zr–C–O fibers

	C (at.%)	O (at.%)	Si (at.%)	Zr (at.%)
Unexposed	46.7	9.5	43.8	—
Exposed	48.3	9.5	42.2	—

core were quite similar and stable despite the high temperature exposure without a remarkable grain growth. Thus it indicated that the β -SiC grain in the exposed fiber was almost stable as compared to the unexposed fiber unless the fiber was oxidized.

Additionally, Fig. 4(a) presents a TEM back scatter image of the formed oxidation layer on the core fiber. Approximately 10–25 nm particles (white) dispersed uniformly in the oxide layer. The particles were identified to be crystallized ZrO_2 (tetragonal) from the results of SAD pattern [Fig. 4(b)]. ZrO_2 existence was also confirmed in the XRD results as shown in Fig. 1(b). According to some studies in literatures,^{22),23)} amorphous metal oxide nanoparticles precipitated throughout a Si–Zr–O–C matrix at the temperatures from 800 to 1100°C, and then the formed metal oxide nanoparticles were crystallized above 1100°C in argon atmosphere. The atmosphere in this study was quite different from the literatures although, assumed that oxygen existed around Zr in Si–Zr–C–O fiber, the formation of ZrO_2 might be come from phase separation in the Si–Zr–C–O fiber despite the atmosphere. The formation of the ZrO_2 nanoparticles in the fiber at high temperature will be needed to study further.

In order to evaluate the change in chemical composition in the fiber core after exposure, EDS analyses for both unexposed and exposed fibers were conducted. Table 2 lists the atomic percentage of C, O, Si and Zr elements of both the unexposed and exposed Si–Zr–C–O fibers. The result showed quite similar values of each element. This supported idea that the fiber core was unchanged from the view point of the chemical composition. However, it was difficult to identify Zr peaks and to estimate its concentration due to the small amount of Zr in the fiber core.

3.1.3 Raman spectroscopy

Figure 5 depicts Raman spectra of the core of (a) unexposed and (b) exposed Si–Zr–C–O fibers. The Raman spectra of the fibers showed peaks at around 1350 and 1600 cm^{-1} . These Raman peaks were related to carbon: D-band at around 1350 cm^{-1} and G-band at around 1600 cm^{-1} . The G-band corresponds to the in-plane vibrations of the nearest neighbor atom in the graphite, whereas the disorder-induced D-band depends on the presence of lattice defects. In general, the relative intensity ratio for the D- to G-band, $I(\text{D})/I(\text{G})$, and the broadening of the peak are used for characterization of the disorder and crystalline size

Fig. 5. Raman spectra of the core of (a) unexposed and (b) exposed Si-Zr-C-O fibers.

Fig. 6. Absorbance of (a) unexposed and (b) exposed Si-Zr-C-O fiber felts.

in graphite materials. The intensity ratios for the $I(D)/I(G)$ of the unexposed fiber and the exposed fiber were 1.97 and 1.66, respectively. This indicated that the carbon was very amorphous or disordered crystallite and exhibited similar crystal structure despite the exposure.

3.2 Emissivity

Figure 6 depicts the absorbance of the unexposed and the exposed Si-Zr-C-O fiber felt at room temperature. In the case of the unexposed fiber felt as shown in Fig. 6(a), more than 90% absorbance was found in all measured wavelength ranges. The exposed fiber felt also exhibited high absorbance similar to the unexposed fiber felt in all wavelength range, but the absorbance of the exposed fiber felt slightly dropped at around 9 μm wavelength as can be seen in Fig. 6(b). This slight absorbance dropping wavelength corresponded to the transmittance declining wavelength of SiO_2 (cristobalite), which was around 9 μm .²⁴⁾ It could be hard to clarify the reason for the drop in this study, but this relation will support that the formation of SiO_2 (cristobalite) layer on the fiber has some kind of affect on the absorbance drop.

Since it is assumed that the absorptivity (γ) is equal to emissivity (ε) according to Kirchhoff's law,¹⁹⁾ it can be possible to regard the absorbance as a spectral emissivity. A spectral radiant

Fig. 7. Spectral radiant emittance at 1000°C of (a) unexposed and (b) exposed Si-Zr-C-O fiber felts as compared to (c) black body.

Fig. 8. Relationship between (a) oxide layer thickness and (b) ratio of oxide layer thickness/fiber radius, and the total emissivity and average emissivity at 2–3 μm of the Si-Zr-C-O fiber felts.

emittance at a high temperature (i.e. 1000°C) was estimated from the obtained spectral emissivity. **Figure 7** depicts the spectral radiant emittances of the unexposed and the exposed Si-Zr-C-O fiber felts at 1000°C. The spectra exhibited were quite similar in spite of the exposure and reached a peak at the wavelength of about 2.3 μm , which corresponded to the Wien's displacement law.¹⁹⁾

Figure 8 shows the relationship between total emissivity and average emissivity at 2–3 μm of the Si-Zr-C-O fiber felts and (a) oxide layer thickness and (b) ratio of oxide layer thickness to fiber radius. The total emissivity of the exposed fiber felt having 5–6 μm silica layer was $87.6 \pm 4.1\%$, and the exposed fiber felts

maintained an initial total emissivity ($89.2 \pm 4.2\%$) as shown by the back circles in Fig. 8(a). Since the main formation of SiO_2 from Si–C reacted with O_2 is accompanied with its volume gain, Fig. 8(b) expressed the emissivity as a function of the ratio of oxide layer thickness to fiber radius for a reference. Even though around 60–70 vol.% of the fiber was changed to the oxidation layer, it was found that the total emissivity was sustained. On the other hand, taking into consideration of radiation heat transfer in a practical usage, which is strongly governed by emissivity and an operating temperature conforming to Planck's and Stefan-Boltzman's laws, it is important to focus attention on the emissivity in the range of infrared ray, especially a peak wavelength corresponding to temperature. The peak wavelength is estimated by using Wien displacement law and decreases with increasing temperature. The radiation heat transfer energy also increases with fourth power of increasing in temperature following Stefan-Boltzman's law. Here it was assumed that the temperature range was from around 700 to 1200°C, a peak wavelength of roughly 2–3 μm was estimated. The white square plots in Fig. 8 present the average emissivity at 2–3 μm of the Si–Zr–C–O fiber felts. The average emissivity of the exposed fiber felt having 5–6 μm oxide layer thickness was 92.5%, and quite similar to the value of the unexposed fiber felt (93.6%). As the results, the emissivity of the Si–Zr–C–O fiber felt was independent to the formation of the oxide layer on the fiber core until its thickness was less than 5–6 μm (less than 0.6–0.7 ratio of oxide layer thickness divided by fiber radius).

Furthermore, in order to confirm the effect of the sample preparation such as the rough pulverization, the emissivity of unpulverized fiber felt was evaluated as a reference. The roughly unpulverized fiber felts exhibited high spectral emissivity and total emissivity of $88.5 \pm 4.2\%$, corresponding to the total emissivity of the rough-pulverized fiber felts. Consequently, the pulverization does not seem to have any effect on emissivity in this measurement range.

4. Discussion

4.1 Effect of oxide layer formation on the emissivity

Firstly, the microstructure characterization aforementioned in Chapter 3.1 is summarized. In the case of the fiber core itself, no significant microstructural changes in (1) chemical composition, (2) β -SiC size and distribution or (3) carbon crystal structure were found in spite of the exposure. Thus, it can be concluded that the only significant microstructural change was the formation of the oxidation layer along with the exposure at the high temperature in air. On the other hand, the emissivity of the Si–Zr–C–O fiber felt was almost stable regardless of the thickness of the oxide layer formation as can be seen in Fig. 8. Thus, the results indicated that the emissivity of the Si–Zr–C–O fiber was unchanged irrespective of the formation of the oxide layer on the fiber core until its thickness was less than 5–6 μm .

Let us discuss the reason why there was almost not effect of the oxidation layer on the emissivity from two viewpoints of microstructural features of the formed oxide layer on the fiber core. According to an infrared spectrum database of SiO_2 (cristobalite),²⁴⁾ the transmittance (τ) of the cristobalite was more than 95% in the wavelength range of less than 7 μm . This indicated that an infrared ray at the wavelength of less than 7 μm can almost pass through the cristobalite layer and might not lead to degradation of the emissivity due to the cristobalite phase. Additionally, the uniform dispersion of fine ZrO_2 particles in the SiO_2 (cristobalite) layer existed as presented in Fig. 4. The ZrO_2

particle size (approx. 10–25 nm) was more than one-hundred times shorter than the chief infrared rays' wavelength (about 2–3 μm), which was in agreement with the peak wavelength at the temperatures of 700 to 1200°C by Wien displacement Law.¹⁹⁾ From the viewpoint of Rayleigh scattering, it is well-known that there is a correlation between particle size and transparence, and a particle size of less than one-twentieth wavelength leads to significantly diminish its scattering.²⁵⁾ In this case, the ZrO_2 particle was much smaller than the infrared rays' wavelength, which suggests that the infrared rays will pass through the formed silica layer without decay of the ray's wavelength or degradation of the ray's energy and scattering despite the ZrO_2 particle dispersion.

4.2 Effect of the microstructural changes on a radiation heat transfer

As previously mentioned, it was found that the emissivity was almost unchanged despite the formation of the oxidation layer on the fiber as presented in Fig. 8 when the layer thickness was less than about 5–6 μm . However, it is necessary to confirm the effects of the microstructural changes of the exposed Si–Zr–C–O fiber felt on radiation heat transfer as well because the radiation heat transfer volume, Q , is expected to be related to energy efficiency. The radiation heat transfer volume is expressed as following equation:²⁶⁾

$$Q = \varepsilon_1 \varepsilon_2 \sigma (T_1^4 - T_2^4) A_1 F_{12} \quad (5)$$

where ε_1 and ε_2 are emissivity, σ is the Stefan-Boltzmann constant [$= 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$], T_1 and T_2 are temperature, A_1 is surface area, and F_{12} is view factor. The number in subscript denotes a radiator and a receiver respectively. Here we defined that subscript 1 was Si–Zr–C–O fiber felt and subscript 2 was a receiving material. In order to focus on the effect of the microstructural changes of the felt caused by the exposure at the high temperature, the temperatures of T_1 and T_2 , and the emissivity of ε_2 were presumed to be constant. The ε_1 was found to be almost constant regardless of the oxide layer formation. Thus the Eq. (5) can be simplified as following equation:

$$Q \propto A_1 F_{12} \quad (6)$$

In order to estimate the value of F_{12} , a coaxial parallel disk model²⁶⁾ was used as shown in the following equations:

$$F_{12} = \frac{1}{2} \left\{ S - \left[S^2 - 4 \left(\frac{r_2}{r_1} \right)^2 \right]^{1/2} \right\} \quad (7)$$

$$S = 1 + \frac{1 + R_2^2}{R_1^2} \quad (8)$$

$$R_1 = \frac{r_1}{L} \text{ and } R_2 = \frac{r_2}{L} \quad (9)$$

$$A_1 = \pi r_1^2 \text{ and } A_2 = \pi r_2^2 \quad (10)$$

where r_1 and r_2 are radius of the radiator and the receiver, and L is distance between the radiator and the receiver. According to the Eq. (7), the F_{12} value was controlled by the surface area of the fiber felt, A_1 , as well as the distance, L , when the other function such as a receiver surface area, A_2 , was independent to the microstructural changes of the fiber felt. So, it was found that the value of Q was strongly impacted by the surface area of the fiber felt from these equations. **Figure 9** shows the correlation between a normalized radiation heat transfer volume and a normalized radiation surface area as a function of the distance, L . The normalized radiation surface area was defined the ratio of the surface area of the radiation material (i.e. the Si–Zr–C–O fiber

Fig. 9. Correlation between normalized radiation heat transfer volume and normalized radiating surface area at various distance (L) of 0.1, 0.3, 0.5 and 1.0.

felt) to that of a receiving material. As can be seen in Fig. 9, when the radiating surface area was relatively small, the normalized radiation heat transfer volume decreased with decreasing in the surface area. When the surface area was while relatively large, the radiation heat transfer volume remained a constant. Additionally, it was found that the shorter distance, L , between the radiator and the receiver led to minimize the effect of change of the surface area on the heat transfer volume.

The non-woven Si-Zr-C-O fiber felt used in this study was configured with solely random-oriented short Si-Zr-C-O fibers and exhibited quite low total weight per area ($\approx 250 \text{ g/m}^2$). Another additional feature of the Si-Zr-C-O fiber felt was that it had a significantly large surface area. Given that the Si-Zr-C-O fiber felt and the receiving material plate were the same size and were parallel, the actual surface area of the fiber felt facing the receiver was estimated to about 14.4 times larger than that of the receiver due to the feature configuration. Thus, the normalized area was about 14.4. On the other hand, the fiber core itself of the exposed Si-Zr-C-O fiber with $5\text{--}6 \mu\text{m}$ oxide layer had an average diameter of $6.6 \mu\text{m}$, at which the normalized area was calculated to 6.8. Here it was given a hypothesis that all radiation heat transfer passes through the formed oxide layer without decay as the discussion in chapter 4.1. This case suggests that a significant degradation of the radiation heat transfer volume will not occur at the distance, L , of less than 0.3 to 0.5 as can be seen in Fig. 9. Therefore, it is indicated that the decrease in size of the diameter of the fiber core do not have a significant effect on heat transfer. Note that the sustainability of the radiation heat transfer performance in the long period will be affected by allocations and configurations of the receiving material as well as the Si-Zr-C-O fiber felt performances such as the emissivity, the morphology and so on.

5. Conclusions

In this study, we examined the effect of oxide layer formation on the emissivity of Si-Zr-C-O fibers. Both unexposed and exposed Si-Zr-C-O fiber felts were prepared. The exposed fiber felt was exposed to air at the high temperature in order to form a uniform oxidation layer. Obtained results in this study were summarized as follow;

1. The exposed Si-Zr-C-O fiber had around $5\text{--}6 \mu\text{m}$ thick of oxide layer which consisted SiO_2 (cristobalite) and $10\text{--}25 \text{ nm}$ fine ZrO_2 particles dispersion.
2. In the core fiber itself, no significant microstructural changes in (1) chemical composition, (2) $\beta\text{-SiC}$ size and distribution or (3) carbon crystal structure were found in spite of the exposure at the high temperature, although the oxide layer was formed on the fiber core in the exposed Si-Zr-C-O fiber.
3. The total emissivity of the exposed fiber felt calculated at 1000°C was $87.6 \pm 4.1\%$ and exhibited a quite similar value to the initial total emissivity of $89.2 \pm 4.2\%$. These results indicated that the emissivity of the Si-Zr-C-O fiber was unchanged irrespective of the formation of the oxide layer on the fiber core until its thickness was less than $5\text{--}6 \mu\text{m}$.
4. A radiation heat transfer performance was evaluated taken into consideration the diameter degradation of the fiber core accompanied with the oxidation. This suggests that the decrease in size of the diameter of the fiber core do not have a significant effect on heat transfer in this study range.

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