Complex permittivity control of SiCf/SiC composite through thermal oxidation

Hyun Seok Lee1 and Won Jun Lee1,2,✉
1Weapon Systems Engineering, University of Science and Technology, Daejeon, Republic of Korea
2Agency for Defense Development, Daejeon, Republic of Korea
✉Email: ngwljys@gmail.com

In this letter, we propose a process for fabricating a Silicon Carbide fiber (SiCf)/Silicon Carbide (SiC) composite radar-absorbing structure (RAS); the process can precisely control the complex permittivity of the composite in high-temperature environments. During the manufacturing of the SiCf/SiC composite, sufficient carbon is supplied to the SiC fibre to ensure conductive properties. Thereafter, thermal oxidation is performed to remove carbon, which transformed the conductive property of the composite material into the dielectric property. The duration of thermal oxidation was controlled because of which the complex permittivity of the composite material approached the optimal complex permittivity for impedance matching. A specimen of the SiCf/SiC composite radar-absorbing structure was produced, and the reflection loss of the specimen was measured. The results indicated that the specimen could absorb more than 99% of the incident electromagnetic waves in the frequency range from 9.02 to 9.84 GHz.

Introduction: The radar-absorbing structure (RAS) absorbs or shields incident electromagnetic (EM) waves, which suppresses reflected waves. RASs are used not only to block harmful EM waves for civilian purposes but also in stealth technology for military purposes. In general, the RAS comprises a combination of various lossy materials and can be developed as a paste, patch, or structure for load-bearing [1, 2]. Furthermore, in stealth aircraft for military use, it is necessary to apply RASs to structures exposed to high-temperature environments, such as in the case of aerodynamic heating by high-speed flight or to an engine exhaust port. However, most RASs are made of materials that cannot be used in high-temperature environments [2–5]. Therefore, it is difficult to predict EM wave absorption performance in a high-temperature environment.

Theoretically, it is possible to design an RAS based on a ceramic material that can be used at high temperatures; however, it is not easy to control the permittivity, permeability, or electrical conductivity to impart EM wave absorption characteristics to the material. For example, in the case of a SiCf/SiC composite, it is possible to implement the dielectric property by controlling the carbon content of the SiC fibre [6]. However, it is challenging to precisely control the mechanical and EM properties of the composite during a high-temperature fabrication process that densifies the SiC matrix on the fibre.

The permittivity of the SiC fibre and SiC matrix may change during the high-temperature fabrication process. In addition, the final thickness of the structure may differ from the design thickness attained through the matrix densification process. This is likely to cause a change in permittivity depending on the matrix densification process conditions. Additionally, another disadvantage is that fibre breakage occurs and mechanical properties deteriorate in the conventional process of manufacturing a composite structure because the composite is machined to achieve the desired thickness. Furthermore, carbon is deposited on the SiC fibre surface to reduce the interfacial force between the SiC fibre and the SiC matrix for improving the mechanical properties. This carbon makes the composite highly conductive.

The above reasons make it difficult to precisely control the mechanical and EM properties for fabricating the SiCf/SiC composite through the conventional manufacturing process.

**SiCf/SiC Composite RAS:** The SiCf/SiC composite RAS is made up of ceramic-based materials that can be used in high-temperature environments. It comprises a single-slab SiCf/SiC composite with a specific thickness and a perfect electric conductor that can shield EM waves. A schematic of the SiCf/SiC composite RAS is shown in Figure 1.

**Fig 1.** Schematic of SiCf/SiC composite radar-absorbing structure (RAS)

The SiCf/SiC composite RAS suppresses reflected EM waves through impedance matching, which is used to match the input impedance ($Z_i$) with the characteristic impedance of the free space ($Z_0$) to prevent loss by reflection at the boundary of the structure. Equation (1) is used to calculate the input impedance of a single-slab RAS:

$$Z_i = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh \left[ \frac{2\pi d}{\lambda \sqrt{\varepsilon_r \mu_r}} \right]$$

Because the SiCf/SiC composite is a non-magnetic material, complex permeability ($\mu_r$) is not treated as a design variable. Therefore, the composite is designed by considering three variables: Complex permittivity ($\varepsilon_r$), thickness ($d$), and wavelength of the incident EM wave ($\lambda$).

**Manufacturing technique for SiCf/SiC Composite:** In this letter, we propose a process for fabricating a SiCf/SiC composite that can be used in high-temperature environments and satisfies the target EM wave absorption performance. A flow chart of the process is shown in Figure 2.

First, the variables ($\varepsilon_r$, $d$, $\lambda$) necessary for the design of the composite were determined. To obtain the complex permittivity required for the design of the composite, the SiC fibre was carbonised to impart high loss characteristics. The densification process progressed to impregnate the fibres with the SiC matrix. Next, the thickness and complex permittivity of the fabricated SiCf/SiC composite were measured. In general, after the densification process at high temperature, the complex permittivity and thickness of the manufactured composite changed and showed a difference from the initial design variables. Subsequently, the design variables are redesigned to obtain the EM wave absorption performance based on the measured thickness. If the complex permittivity measured after the densification process is higher than the design complex permittivity, a post-process is started. In the post-process, a large amount of carbon contained in the SiCf/SiC composite is partially removed (decarbonised) through a thermal oxidation process. It is possible to precisely control the complex permittivity for impedance matching to the measured thickness of the SiCf/SiC composite through thermal oxidation.

**Thermal oxidation:** Figure 3 shows the change in the complex permittivity of the SiCf/SiC composite according to the duration of thermal oxidation. The SiCf/SiC composite was produced with carbon, which is a lossy material. The SiCf/SiC composite exhibited conductive properties because the composite contains excessive carbon. Accordingly, the composite completely reflects EM waves. Therefore, thermal oxidation was performed for a specific duration in a high-temperature environment (900°C) to remove excessive carbon, replacing SiC with SiO$_2$. Next, because a certain amount of carbon was removed, the conductive property of the SiCf/SiC composite was transformed into a dielectric property. After the first round of thermal oxidation, the SiCf/SiC composite demonstrated a complex permittivity corresponding to step 1 in
Figure 3. The curve marked with black dots represents the optimal complex permittivity according to the thickness for impedance matching of the single-slab RAS. Thermal oxidation was performed three times, over 166 h, during which the complex permittivity of the SiCf/SiC composite gradually decreased and approached the optimal complex permittivity. The complex permittivity was adjusted by controlling the conditions and duration of thermal oxidation. Consequently, the thickness and complex permittivity of the SiCf/SiC composite for EM wave absorption performance were obtained, and the SiCf/SiC composite RAS was designed.

Reflection loss measurement: A specimen of the SiCf/SiC composite RAS was fabricated, and Figure 4 shows the fabricated specimen. The dimensions of the specimen were 110 × 120 mm with a thickness of 2.3 mm. The reflection loss of the specimen was measured in the X band (8.2–12.4 GHz). The results indicated that the reflection loss of the specimen was lower than −20 dB (99% absorption) in the frequency range from 9.02 to 9.84 GHz. The lowest reflection loss is −27.5 dB at 9.41 GHz. The results are shown in Figure 5.

Conclusion: It is challenging to precisely control the mechanical and EM properties of the SiCf/SiC composite with the conventional ceramic-based composite manufacturing process. Therefore, herein a manufacturing process for ensuring precise EM property control of the SiCf/SiC composite is presented.

The resulting composite has improved mechanical properties and the fabrication is simple because additional machining is not required to obtain the impedance matching thickness. Thus, precise permittivity control of the SiCf/SiC composite was achieved through thermal oxidation.

The specimen of the SiCf/SiC composite RAS was fabricated with a thickness of 2.3 mm, and the reflection loss was measured in the X band. It exhibited excellent absorption performance by absorbing more than 99% of EM waves in the frequency range of 9.02–9.84 GHz.

Therefore, it was demonstrated that ceramic-based RAS for high-temperature environments could be designed. In addition, it is expected that the development of multislab broadband RAS will be possible by determining the correlation between the thermal oxidation process conditions and the complex permittivity changes.

© 2021 The Authors. Electronics Letters published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Received: 1 November 2020  Accepted: 7 January 2021
doi: 10.1049/ell2.12090
References

1 Wang, C.X., et al.: Radar stealth and mechanical properties of a broad-band radar absorbing structure. Composites Part B 123, 19–27 (2017)
2 Nam, Y.W., et al.: Radar-absorbing structure with nickel-coated glass fabric and its application to a wing airfoil model. Compos. Struct. 180, 507–512 (2017)
3 Oh, J.H., et al.: Design of radar absorbing structures using glass/epoxy composite containing carbon black in X-band frequency ranges. Composites Part B 35, 49–56 (2004)
4 Choi, I.B., et al.: Radar absorbing sandwich construction composed of CNT, PMI foam and carbon/epoxy composite. Compos. Struct. 94, 3002–3008 (2012)
5 Choi, W.H., et al.: Wideband radar absorbing structure with low density material and load-bearing MWCNT added composite material. Electron. Lett. 49(9), 620–622 (2013)
6 Ding, D.H., et al.: Electromagnetic interference shielding and dielectric properties of SiC/SiC composites containing pyrolytic carbon interphase. Carbon 60, 558–561