Effect of Temperature on the Microwave-Absorbing Properties of an \( \text{Al}_2\text{O}_3-\text{MoSi}_2 \) Coating Mixed with Copper

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Abstract: To obtain a high temperature-resistant microwave absorbing coating, an \( \text{Al}_2\text{O}_3-\text{MoSi}_2/\text{Cu} \) composite coating was prepared by atmospheric plasma spraying. Compared with a normal temperature environment, there are a few reports on Cu as an absorbent for high temperature microwave absorbing coatings. Therefore, in this regard, wave absorbing property can be improved by using a Cu absorbent. The microstructure of a \( \text{Al}_2\text{O}_3-\text{MoSi}_2/\text{Cu} \) coating was observed, and the dielectric properties of the composite coating in the high-temperature environment of the X-band were tested. The experimental results show that with the increase in temperature, Cu transforms \( \text{Cu} \) into \( \text{Cu}_2\text{O} \) in the high-temperature environment and improves the coating’s wave absorption performance with \( \text{MoSi}_2 \). In addition, a 1.4 mm-thick coating showed best microwave absorbing performance at 700 °C. The reflection loss was −19.09 dB, and the effective microwave absorbing bandwidth was 2.83 GHz (Reflection Loss < −10 dB). It was found that the \( \text{Al}_2\text{O}_3-\text{MoSi}_2/\text{Cu} \) composite coating has good wave-absorbing performance in a 700 °C high-temperature environment.

Keywords: atmospheric plasma spraying; microwave absorption coating; high-temperature; Cu

1. Introduction

Recent studies have shown that due to radar detection technology’s rapid development, an increasing amount of attention has been paid to radar stealth technology research. Meanwhile, an increasing number of researchers have investigated high-temperature microwave absorbing materials [1–9]. The high-temperature absorbing coating prepared by the plasma spraying method has good absorbing performance [10–13]. \( \text{Al}_2\text{O}_3 \) and \( \text{MoSi}_2 \) are widely used in high-temperature resistant coatings due to their excellent high-temperature resistance [14–16]; Cu is rarely studied in a high-temperature environment as an absorbing material.

As an electromagnetic wave absorber, \( \text{MoSi}_2 \) powder has certain characteristics—high melting point, low relative density, and excellent high-temperature oxidation resistance—and is widely used in high temperature-resistant coating materials, composite materials, and high temperature-resistant structures [17]. Researchers have carried out in-depth studies on the wave absorption performance and high-temperature oxidation of \( \text{MoSi}_2 \). This research used \( \text{MoSi}_2-30\text{Al}_2\text{O}_3 \) as raw material, prepared a \( \text{MoSi}_2-\text{Al}_2\text{O}_3 \) electrothermal coating by atmospheric plasma spraying, and studied the electrothermal properties of the composite coating [18]. Shang et al. [19] prepared \( \text{MoSi}_2/\text{BC} \) porous composite microwave absorbing material by the solid-phase sintering method and found that it had good absorbing performance. When the \( \text{MoSi}_2/\text{BC} \) mass fraction was 50%, the reflection loss was the lowest; the effective absorption bandwidth of the microwave absorbing material was approximately 1.0 GHz, and the reflection loss was −13 dB. Jiao et al. [20] prepared a \( \text{MoSi}_2-\text{CoNiCrAlY} \) composite coating on the surface of a GH4169 alloy, and studied...
the cyclic oxidation behavior of the composite coating under a 900 °C static atmosphere environment; they found that the composite coating has good high-temperature oxidation resistance. Wu et al. [21] prepared MoSi$_2$/Al$_2$O$_3$ coatings with different MoSi$_2$ contents by atmospheric plasma spraying; it was found that with the increase in MoSi$_2$ content, the electrical conductivity and dielectric loss of the coatings also increased.

Cu is an electromagnetic shielding material. Its electromagnetic shielding performance has been widely studied; it has good conductivity and wear resistance, and can thus be used as an effective absorbent in coatings. However, for the preparation of mixed high temperature-resistant microwave absorbing coatings, research is rare. Moustafa et al. [22] prepared copper–graphite composite materials with different graphite contents by powder metallurgy metohes and copper coating on graphite powder by the electroless coating technique. The results show that the graphite powder made by the two metohes has a lower wear rate and friction coefficient. Sun et al. [23] used the micro-arc discharge method for the synthesis of a carbon-coated copper nanocapsule made with Cu nanocapsule as the core and carbon absorbing material as the shell of the core-shell structure; the study found that the thickness of 1.9 mm of the carbon-coated copper nanocapsule and a reflection loss of $-40$ dB was achieved at 10.52 GHz. The carbon-coated copper nanocapsule has excellent absorbing performance. Zhao et al. [24], through a simple solution reduction method, made a new leaf-like NiCu alloy composite. The experiment discovered that 40 wt.% of NiCu has good microwave absorbing performance, since reflection loss reached $-21.1$ dB, and the microwave absorption bandwidth was 3.4 GHz.

In this research, both Al$_2$O$_3$ and MoSi$_2$ have good high-temperature stability and can be used in temperature environments. Therefore, an Al$_2$O$_3$–MoSi$_2$ composite coating was used as the substrate, and Cu particles were sprayed onto the surface of the Al$_2$O$_3$–MoSi$_2$ composite coating by plasma spraying. Cu in high-temperature microwave absorbing coatings is rarely studied; however, it has a lot of research value. In high-temperature environments with sufficient O$_2$, Cu is transformed into CuO [25] and Cu$_2$O [26], and the copper oxide formed by Cu transformation will improve the wave absorbing performance of the Al$_2$O$_3$–MoSi$_2$/Cu composite coating. An Al$_2$O$_3$–MoSi$_2$/Cu composite high-temperature absorbing coating was successfully prepared by atmospheric plasma spraying. The microstructure, composition, and dielectric properties of the Al$_2$O$_3$–MoSi$_2$/Cu composite coatings at different temperatures were summarized, and the wave absorption properties of three thickness coatings were researched at different temperatures. Therefore, this research provides a new insight into the preparation of high-temperature absorbing coatings.

2. Materials and Methods

An Al$_2$O$_3$–MoSi$_2$/Cu coating was prepared by the atmospheric plasma spraying method, and its high temperature microwave absorbing performance tested in the X-band. After the coating was finished by plasma spraying, the coating sample was cut into the size required by the instrument test. It was analyzed by X-ray diffraction (XRD, D8-Advance, Bruker, Bremen, Germany, Cu–Kα radiation). The microstructure of the coating surface was observed by a scanning electron microscope (SEM, Quanta 450 FEG, FEI Company, Hillsboro, OR, USA), and the high-temperature electromagnetic and wave absorption properties of the coating were measured by a vector network analyzer (Agilent E8363B PNA, Santa Clara, CA, USA).

2.1. Preparation of Spraying Feedstock

MoSi$_2$ powder was produced by Shanghai Naiou Nanotechnology Co., Ltd. (Shanghai, China). The powder size was between 15 and 40 µm, and the shape of MoSi$_2$ was irregular. Cu particles were produced by Shanghai Naiou Nano Technology Co., Ltd. (Shanghai, China). The size of Cu powder particles was different, with the large particle size ranging from 20 to 35 µm and the small particle size ranging from 10 to 15 µm. Al$_2$O$_3$ powder was produced by Shanghai Xiangtian Nanomaterials Co., Ltd. (Shanghai, China). The particle size of the powder was 30–60 µm. MoSi$_2$ powder, Cu powder, and Al$_2$O$_3$ powder are
all micron powder, and micron-sized powder can be used to make the powder mixture uniform and powder feeding uniform in the spraying process. The raw powder content information is shown in Table 1.

Table 1. Al$_2$O$_3$–MoSi$_2$ mix particles and Cu particles of feedstock materials (wt. %).

| Powder                  | Purity | Mo | Cu | Si | Fe | Ni | Fe$_2$O$_3$ | SiO$_2$ | Others |
|-------------------------|--------|----|----|----|----|----|-------------|---------|--------|
| MoSi$_2$               | 99.9   | 64.5 | 0.01 | 35.3 | 0.001 | 0.002 | - | - | Bal. |
| Al$_2$O$_3$            | 99.9   | - | - | - | - | - | 0.05 | 0.05 | Bal. |
| Cu                     | 99.9   | - | 99.8 | - | 0.01 | 0.05 | - | - | Bal. |

To mix Al$_2$O$_3$ and MoSi$_2$, the ball mill method was used at a speed of 380 r/min for 3.5 h, and appropriate alcohol was added. After ball milling, the mixed powder solution was poured into the container, placed into a blower, and the drying temperature was set at 90 °C. The Al$_2$O$_3$–MoSi$_2$ (80 wt% Al$_2$O$_3$ + 20 wt% MoSi$_2$) mixed powder was dried via an air dryer and grinded into a uniform and delicate powder using a mortar. The preparation process of Cu powder is the same as that of the Al$_2$O$_3$–MoSi$_2$ mixed powder. The mix powder phase of the samples was determined by X-ray diffraction in the 2θ range from 20 to 80°.

2.2. Plasma Spraying Experiment

Before plasma spraying, the substrate had to be pretreated, which included two processes: oil removal and sandblasting. The plasma spraying equipment included the SX-80, produced by Guangdong Sanxin Company (Guangzhou, China). In the spraying process, Al$_2$O$_3$–MoSi$_2$ mixed particles are first sprayed on the substrate. After the preparation of the Al$_2$O$_3$–MoSi$_2$ composite coating, 0.05 mm-thick Cu particles were sprayed onto the surface of the Al$_2$O$_3$–MoSi$_2$ coating. Ar was used as the main gas in plasma spraying as Ar is an inert gas that has an excellent protective effect on spraying particles, and Ar has a lower enthalpy and a faster temperature rise. H$_2$ is mainly used as a secondary gas. H$_2$ has excellent heat transferability, which is conducive to the refractory powder’s melting and can prevent the spraying powder’s oxidation. An SEM micrograph of the Al$_2$O$_3$–MoSi$_2$/Cu composite coating is shown in Figure 1, and the plasma spraying parameter settings are shown in Table 2.

Table 2. Atmosphere plasma spraying parameters.

| Parameters                  | Value |
|-----------------------------|-------|
| Arc Current (A)             | 410   |
| Arc Voltage (V)             | 30    |
| Primary gas (Ar) flow rate (L/h) | 2100  |
| Secondary gas (H$_2$) rate (L/h) | 10    |
| Spray distance (mm)         | 80    |
| Powder carrier gas (Ar) flow rate (L/h) | 200   |
| Powder feed rate (g/min)    | 20    |

2.3. Dielectric Properties of the Coating

The Agilent E8363B PNA series vector network analyzer was used for the high-temperature wave absorption test. The electromagnetic parameters of the samples were tested by the wave-guide method [27] in the frequency range of 8.2 GHz–12.4 GHz (X-band). Before the test, the coating was cut into the sample holder with dimensions of 22.86 mm × 10.16 mm × 2 mm (X-band sample size); if the coating sample needed to be heated to more than 100 °C, heat preservation was done at 100 °C for 2 h, and then the dielectric constant of the coating was tested by E8363B from 25 °C to 700 °C in the X-band. The temperature of the waveguide increased at a rate of 10 °C per minute, monitored by a thermostat and software. The high temperature electromagnetic parameter test system is show in Figure 2.
Figure 1. Three-elements distribution on the upper surface of the Al2O3–MoSi2/Cu coating and feedstock: (a) Cu; (b) MoSi2; (c) Al2O3; (d) the corresponding particle size distribution histograms of the Cu, MoSi2, and Al2O3 particles.

Figure 2. High-temperature electromagnetic parameter test system: (a) Vector network analyzer; (b) Cooling system; (c) thermostat; (d) Coaxial line; (e) Rectangular waveguide; (f) Sample; (h) Thermocouple.
The Al₂O₃–MoSi₂/Cu coating is a dielectric microwave absorbing material, and its complex dielectric constant can be calculated by Equation (1) [28]:

$$\varepsilon_r = \varepsilon' - j\varepsilon''$$  \hspace{1cm} (1)

The reflection loss dB of the coating can be calculated by transmission line theory Equation (2) [29] and Equation (3) [30]:

$$R = 20\log\left|\frac{Z_{in} - Z_0}{Z_{in} + Z_0}\right|$$  \hspace{1cm} (2)

$$Z_{in} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left[j\frac{2\pi fd}{c}\sqrt{\mu_r\varepsilon_r}\right]$$  \hspace{1cm} (3)

where $\varepsilon_r$ of Equation (1) represents the complex dielectric constant of the material. $Z_0$ represents the air impedance of the microwave absorbing material, and $Z_{in}$ represents the material’s input impedance. In the formula, $f$ represents the frequency of the electromagnetic wave, $d$ represents the thickness of the material, $c$ represents the speed of the electromagnetic wave up propagation under vacuum, and $j$ is an imaginary unit. Al₂O₃–MoSi₂/Cu is a pure dielectric material, so $\mu_r$ in the formula is 1.

3. Results and Discussion

3.1. Microstructure of the Coating

The XRD analysis of the Al₂O₃–MoSi₂ powder is shown in Figure 3. It can be seen from the figure that the XRD of the particles is composed of MoSi₂ and α-Al₂O₃, with many peaks of different degrees; the strongest peak is MoSi₂. A new α-Al₂O₃ phase was produced in the process of preparing Al₂O₃–MoSi₂ powder by ball milling. In addition, there were no new compounds. The XRD analysis of the Cu powder is shown in Figure 4. It can be seen from the figure that the peak of Cu is very sharp, and there is no peak of other elements, so the purity of the Cu powder is very high.
The XRD analysis of the Al2O3–MoSi2/Cu composite coating is shown in Figure 5a. The coating is mainly composed of Al, O, Si, Mo, and Cu. By comparing the XRD of the powder and the coating, it can be seen that new phases of MoSi2 and Cu are formed. The coating surface comprises of seven phases: MoSi2, Hex–MoSi2, Mo5Si3, α-Al2O3, γ-Al2O3, Cu, and Cu2O. The sharpest peaks are Cu and α-Al2O3, with different strength peaks caused by the powder’s high temperature and oxidation during the plasma spraying. A small amount of new Cu2O phase appeared in the coating as a small amount of oxygen entered the plasma flame during the spraying process, and part of the Cu powder was oxidized during the accelerated melting process, generating a Cu2O new phase [31]. A small amount of Mo5Si3 and Hep–MoSi2 appeared in the coating as MoSi2 was mixed with a small amount of oxygen in the plasma spraying process [32]. The experiments show that the addition of Al2O3 to MoSi2 could change the resistivity and low-temperature oxidation resistance of MoSi2 [33]. This “pesteing” is a coating defect as MoSi2 at 400–600 °C causes a phenomenon that transforms the material into powder; the addition of Al2O3 can prevent the rapid oxidation of the MoSi2 phenomenon [34]. In the XRD analysis, the Al2O3–MoSi2/Cu composite coating was heated at 700 °C and heat preservation for 0.5 h is shown in Figure 5b. CuO and SiO2 appeared on the composite coating surface at 700 °C. CuO was produced as in the full reaction of Cu2O with O2: Cu2O (inner layer) slowly converted to CuO (coating surface) [35]. SiO2 generation is the full reaction of MoSi2 with O2.

![X-ray diffraction of the Al2O3–MoSi2/Cu composite coating surface](image)

**Figure 5.** X-ray diffraction of the Al2O3–MoSi2/Cu composite coating surface: (a) T = 25 °C (b) T = 700 °C.

Figure 6 shows the SEM micrograph of the Al2O3–MoSi2/Cu composite coating. It can be clearly seen that Cu, Al2O3, and MoSi2 particles are irregularly distributed on the coating surface, while there are a few pores on the coating surface.

![SEM micrographs of the Al2O3–MoSi2/Cu coating upper surface](image)

**Figure 6.** SEM micrographs of the Al2O3–MoSi2/Cu coating upper surface: (a) some pores exist in the coating surface (b) MoSi2, Al2O3, and Cu particles.
3.2. Dielectric Properties of the Coating

As shown in Figure 7, the $\varepsilon'$ and $\varepsilon''$ of the coating increased with the increase in temperature. The $\varepsilon'$ and $\varepsilon''$ of the coating are 10.23 and 2.11 at 25 °C, 13.1 and 3.55 at 200 °C, and 22.4 and 5.09 at 500 °C, respectively. The dielectric constant of the Al$_2$O$_3$–MoSi$_2$/Cu coating changed with the increase in temperature. It can be seen from Figure 7a that the $\varepsilon'$ increased with the increase in temperature. At two different temperature ranges in 200 °C and 600 °C, we can find that the $\varepsilon'$ gradually moved to the high-frequency range. $\varepsilon'$ at a high temperature can be expressed by Debye’s theory in Equation (4) [36]:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + [\omega \tau(T)]^2}$$  \hspace{1cm} (4)

where $\varepsilon_\infty$ is the limit value of the permittivity changing with the increase in $\omega$, $\varepsilon_S$ is the static permittivity, and $\tau(T)$ is the relaxation period. The relationship between relaxation time and temperature can be expressed by the Arrhenius formula in Equation (5) [37]:

$$\tau(T) = \tau_0 \exp\left(\frac{E_a}{RT} \right)$$  \hspace{1cm} (5)

where $E_a$ is the activation energy, $\tau_0$ is the pre-factor, and $T_0$ is the temperature. $R$ is Avogadro’s constant.

![Figure 7](image.png)

**Figure 7.** Dielectric properties of the Al$_2$O$_3$–MoSi$_2$/Cu composite coating: (a) $\varepsilon'$ of the Al$_2$O$_3$–MoSi$_2$/Cu composite coating; (b) $\varepsilon''$ of the Al$_2$O$_3$–MoSi$_2$/Cu composite coating.

As shown in Figure 7b, $\varepsilon''$ also increases with the material temperature. The material was tested at two different temperatures of 200 and 600 °C, showing that the higher the temperature, the lower the relaxation time. At a high temperature, $\varepsilon''$ can be expressed in Equation (6) [36]:

$$\varepsilon'' = \varepsilon_\infty + \frac{(\varepsilon_S - \varepsilon_\infty)\omega \tau(T)}{1 + \omega^2 \tau(T)^2} + \frac{\sigma(T)}{\omega \varepsilon_0}$$  \hspace{1cm} (6)

where $\sigma(T)$ is the conductivity of the medium, and the $\varepsilon'$ and $\varepsilon''$ of the Al$_2$O$_3$–MoSi$_2$/Cu increased gradually with the increase in temperature. $\varepsilon'$ moved from the low-frequency region to the high-frequency region with increased temperature, and $\varepsilon'$ decreased with the frequency increase. This phenomenon is called the dispersion effect [38]. This may be due to the formation of a conductive network between MoSi$_2$ and Al$_2$O$_3$ [39], and the increase in temperature led to an increase in the conductivity of Al$_2$O$_3$–MoSi$_2$/Cu and the enhancement of conduction loss. $\varepsilon''$ moved from the low-frequency region to the high-
frequency region with the increase in temperature. The main effect is that the increase in temperature led to the coating’s improved electrical conductivity [40]. Additionally, it can be seen from Figure 6 that the relaxation time became shorter as the temperature increased and that the real and imaginary parts of the complex dielectric constant of the Al₂O₃–MoSi₂/Cu coating were lower at 25 °C. The Al₂O₃–MoSi₂/Cu coating has remarkable dielectric properties at high temperatures.

3.3. Absorbing Performance of the Coating

The wave absorption performances of the coatings are shown in Figure 8. According to transmission line theory Equations (2) and (3), the absorption peak frequency of the 1.0 mm-thick coating was 11 GHz, and the reflection loss was −11.69 dB. When the coating reached 700 °C, the wave absorption performance was the best. The lowest of the 1.2 mm coating frequency was 10.8 GHz, and the reflection loss was −14.87 dB. When the coating’s temperature reached 700 °C, the wave absorption performance was the best. The thickness of the coating was 1.4 mm, the frequency of the best absorption performance was in 10.51 GHz, the reflection loss was −19.09 dB, and the absorption performance was the best when the temperature reached 700 °C. It can be seen that the Al₂O₃–MoSi₂/Cu coating has good high-temperature wave absorbing performance.

![Figure 8](image_url)

**Figure 8.** Reflection loss of the Al₂O₃–MoSi₂/Cu composite coatings: (a) d = 1 mm, (b) d = 1.2 mm, (c) d = 1.4 mm.

With the increase in coating thickness, the wave absorption performance of the Al₂O₃–MoSi₂/Cu coating gradually increased. The coating’s thickness was 1.0 mm, reflection loss
was −3.99 dB, absorbing performance was weak at room temperature (25 ◦C), absorption frequency was at 11 GHz, the coating’s reflection loss was −11.69 dB, and the temperature was 700 ◦C. When the thickness of the Al2O3–MoSi2/Cu coating was 1.4 mm, the coating’s minimum reflection loss was −6.66 dB at 25 ◦C, and the reflection loss of the coating was −19.09 dB at 700 ◦C. As can be seen from Figure 8c, the coating thickness is 1.4 mm, the reflection absorption frequency gradually moved to the left as the coating temperature increased, which can be explained by Equation (7) [41]. When the coating thickness was the same, the value of $\varepsilon'$ increased with the increase in temperature, which moved the frequency band of the interference from high frequency to low frequency so that the coating reached the role of broadband absorption. Parts of the wave-absorbing performance of the coatings are shown in Table 3.

\[ f_m = \frac{c}{4d\sqrt{\varepsilon_r}} \]  

(7)

where $f_m$ is the matching frequency, $c$ is the speed of light in vacuum, and $d$ is the thickness of the coating.

| Thickness (mm) | Temperature (◦C) | Minimum RL Values (dB) | Effective Bandwidth (GHz) |
|---------------|------------------|------------------------|---------------------------|
|               |                  |                        |                           |
| 1.0           | 25               | −3.9                   |                           |
|               | 400              | −8.4                   | -                         |
|               | 700              | −11.69                 | 1.78                      |
| 1.2           | 25               | −6.2                   | -                         |
|               | 400              | −12.48                 | 2.19                      |
|               | 700              | −14.87                 | 2.42                      |
| 1.4           | 25               | −6.66                  | -                         |
|               | 400              | −13.89                 | 1.68                      |
|               | 700              | −19.09                 | 2.83                      |

Cu is often used in electromagnetic shielding material and has good conductivity. The Al2O3–MoSi2/Cu composite coating does not have good wave absorption performance at room temperature (25 ◦C) due to the addition of Cu, the coating thickness is 1 mm with a minimum reflection loss of −3.9 dB, as shown in Table 3. According to the XRD pattern in Figure 5, with the increase in temperature, Cu was gradually transformed into Cu2O, and in a sufficient O2 environment, Cu2O was transformed into CuO in the process of heating up in the 700 ◦C heat preservation test. It can be seen from report [26] that Cu2O plays a role in improving the absorbing performance of the coating, which is mainly attributed to the conductive network formed by Cu2O with the increase in temperature. Cu2O exists on the inner layer of the coating together with Al2O3–MoSi2 to increase the electrical conductivity of the coating, which enhances the wave-absorption performance of the coating. In Figure 8c, the coating thickness is 1.4 mm, the minimum reflection loss at 25 ◦C is only −6.66 dB, but min RL at 700 ◦C is 19.09 dB. It can be seen from Figure 8 that with the increase in temperature, the coating gradually has good absorbing performance. Specifically, the Cu is transformed into CuO and Cu2O improves the electrical conductivity of the coating, and improves the wave-absorbing performance of the coating.

The experimental results show that the Al2O3–MoSi2/Cu absorbing coating by plasma spraying in this work is a new type of absorbing coating used at high temperature, and copper oxide has an influence on the absorbing performance of the coating. Therefore, compared to other wave absorbing coatings, the Al2O3–MoSi2/Cu coating’s wave absorption performance is not obvious at room temperature of 25 ◦C, but it has good wave absorption performance at high temperatures of 700 ◦C. The characteristics of wave-absorbing performance with temperature variation deserve attention in future.
4. Conclusions

The results show that the wave absorption performance of the Al$_2$O$_3$–MoSi$_2$/Cu composite high temperature-resistant coating is gradually enhanced with the increase in temperature. This study conducted the XRD analysis of mixed powder elements and composite coating compounds, and SEM to observe the structure of the composite coating. The SEM micrograph showed that copper oxide exists on the coating surface. The vector network analyzer measured the dielectric properties and calculated Reflection Loss under different temperatures. It was found that Cu$_2$O formed by Cu at high temperatures can enhance the coating’s absorbing properties. Coating thickness was 1.4 mm with the best reflection loss. The coating’s reflection loss was $-19.09$ dB at a temperature of 700 °C and frequency of 10.5 GHz. The results show that the coating has a good high-temperature microwave absorbing performance in the X-band.

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