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PREPARATION AND PROPERTIES OF NICKEL-PLATED ALUMINUM POWDER

PRIPRAVA IN LASTNOSTI Z NIKLJEM PLATIRANIH PRAŠNIH DELCEV ALUMINIJA

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Nickel-plated aluminum powder was prepared by a double reduction system of sodium hypophosphite and hydrazine. The effects of different amounts of nickel coating on the morphology, phase, compaction resistivity and electromagnetic parameters of nickel-plated aluminum powder coating were studied. The results of XRD and SEM clearly show that the nickel-plated aluminum powder was prepared successfully in a dual reduction system. In addition, the nickel-plated aluminum powder also has good absorbing properties in the X-band. The results show that when the nickel coating amount is 50 *w*/ % and the impedance matching thickness is 2.6 mm, the reflection loss value is less than –10 dB in the range 8.49–12.40 GHz. At the same time, when the impedance-matching thickness is 2.4 mm and the frequency is 10.45 GHz, the reflection-loss value reaches its best value of –25.88 dB. The composite material presents excellent corrosion resistance and electromagnetic shielding properties, which provides a new strategy for the development of electroless plating composite materials.

Keywords: nickel-plated aluminum powder, absorbing materials, double reduction system

Avtorji v članku opisujejo pripravo in lastnosti z nikljem (Ni) platiranih prašnih delcev aluminija (Al). Izdelavo oplaščenih delcev so izvedli z sistemom dvojne redukcije natrijevega hipofosfita in hidrazina. Nato so študirali vpliv različne debeline plasti Ni, na morfologijo, faze, kompaktne upornosti in elektromagnetnih parametrov prašnih z Ni platiranih Al delcev. Rezultati rentgenske difrakcije (XRD) in vrstične elektronske mikroskopije (SEM) so pokazali, da so avtorji tega članka uspešno pripravili z Ni platirane prašne delce Al z metodo dvojne redukcije, ki ima tudi dobre absorbcijske lastnosti v X-pasu. Rezultati raziskave so pokazali, da so pri 50 % vsebnosti Ni prevleke in impedančno ciljani debelini prevleke 2,6 mm vrednosti izgub refleksije manjše od –10 dB v območju med 8,49 GHz in 12,40 GHz. Pri enakem času, ko je bila impedančno ciljana debelina 2,4 mm in frekvenca 10,45 GHz so imele izgube odboja najnižjo vrednost –25,88 dB. Kompozitni material ima tudi odlično odpornost proti koroziji in je tudi odličen material za elektromagnetno zaščito. Ta material po mnenju avtorjev predstavlja novo strategijo razvoja postopkov za izdelavo kompozitnih materialov z ne-električnim platiranjem.

Ključne besede: z nikljem oplaščen aluminijev prah, absorbcijski materiali, sistem dvojne redukcije

1 INTRODUCTION

The research and development of absorbing materials is one of the important technologies to solve electromagnetic pollution and radar stealth. It permeates every facet of daily life and production, tightly intertwined with homeland security. According to the absorbing mechanism, absorbing materials should meet the conditions of "thin, light, wide and strong". In recent years, anti-electromagnetic pollution and radar stealth technology are also constantly improving, and traditional types of absorbing materials can no longer meet the requirements. Therefore, the research of absorbing materials in the future will develop towards composite, multi-frequency, lightweight and integration.

Nickel has good magnetic properties, while aluminum has good electrical conductivity. The nickel-plated aluminum powder prepared by coating nickel on aluminum powder can produce a damping effect under the action of electromagnetic wave, so as to absorb and dissipate electromagnetic wave energy. He Zhenhua et al.[1] used hydrazine as a reducing agent to prepare nickel-plated aluminum powder by electroless plating, and proposed the unsteady plating mechanism of the new process of hydrazine electroless nickel plating. The sodium hypophosphite system and hydrazine hydrate system are two common nickel-plating process systems. They have advantages and disadvantages in the nickel-plating process. Nickel plating in sodium hypophosphite is low cost, has a fast electrodeposition speed and good stability, but a large amount of phosphorus is introduced into the coating. Nickel plating in hydrazine hydrate can eliminate phosphorus in the coating, but the reducibility is too strong.

In this study, nickel-coated aluminum powder with a dense and uniform nickel film was prepared by a double reduction system of sodium hypophosphite and hydrazine hydrate. The effects of different amounts of nickel

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plating on the electrical and electromagnetic properties of nickel-plated aluminum powder were studied. The relationship between the amount of nickel plating and the electromagnetic shielding performance of nickel-plated aluminum powder was analyzed.

2 EXPERIMENTAL PART

In this study, nickel plating was carried out in a double reduction system, and the particle size of the aluminum powder used was 40.84 μm.

2.1 Preparation process

The spherical aluminum powder was added to 1 g/L sodium hydroxide solution for alkali washing. The aluminum powder after alkali washing was added to the displacement nickel-plating solution (33 g/L nickel sulfate hexahydrate solution, 8 g/L ammonium fluoride, 2 g/L citric acid and 0.6 g/L sodium dodecyl sulfonate), reacted at 70 °C for 20 min, and then washed and dried. The dried aluminum powder was added to a mixed solution of sodium citrate, sodium dodecyl sulfonate, ammonium sulfate, and nickel sulfate hexahydrate, and then sodium hypophosphite solution was added and stirred for 2 h to fully react. Add 2.5 ml/L hydrazine hydrate, and then dropwise add sodium hydroxide solution to maintain the pH value at 9. Wash and dry when the nickel-plated mixture does not form bubbles to obtain nickel-plated aluminum powder. **Figure 1** is a schematic diagram of the preparation.

2.2 Characterization

The phase composition of nickel-coated aluminum powders with different amounts of nickel coating was analyzed by X-ray diffraction (XRD). The morphology was observed by cold field-emission scanning electron microscope (SEM, Quanta-450-FEG), and the composition elements of nickel-plated aluminum powder and the content of each element were analyzed with an energy-dispersive spectrometer (EDS, X-MAX50). The nickel-plated aluminum powder was pressed into a circular sheet by a tablet press (FW-4A) with JB / T13537-2018 as the standard at a pressure of 8 MPa. The thickness and diameter of the sheet were measured. The resistance of the sheet was tested by a DC resistance tester, and the compaction resistivity formula was used to calculate the compaction resistivity of the nickel-plated aluminum powder. The electromagnetic parameters of nickel-plated aluminum powder in the frequency range 8.2–12.4 GHz were tested with a vector network analyzer (E8362B).

3 RESULTS

Figure 2 is the XRD diffraction pattern of nickel-plated aluminum powder prepared under different nickel-coating conditions. It can be seen from **Figure 2** that there are eight diffraction peaks corresponding to Al (111), (200), (220), (311) and (222) crystal planes and Ni (111), (200) and (220) crystal planes. The diffraction peaks under different nickel coating conditions are basically the same, and no diffraction peaks of other substances appear, indicating that the prepared nickel-plated aluminum powder is composed of Al and Ni, i.e., the surface of spherical aluminum powder is coated with a layer of nickel. At the same time, a diffuse scattering diffraction peak appears near $2\theta = 45°$, because the nickel-phosphorus in the coating forms a solid solution, resulting in an amorphous structure of the nickel-plated

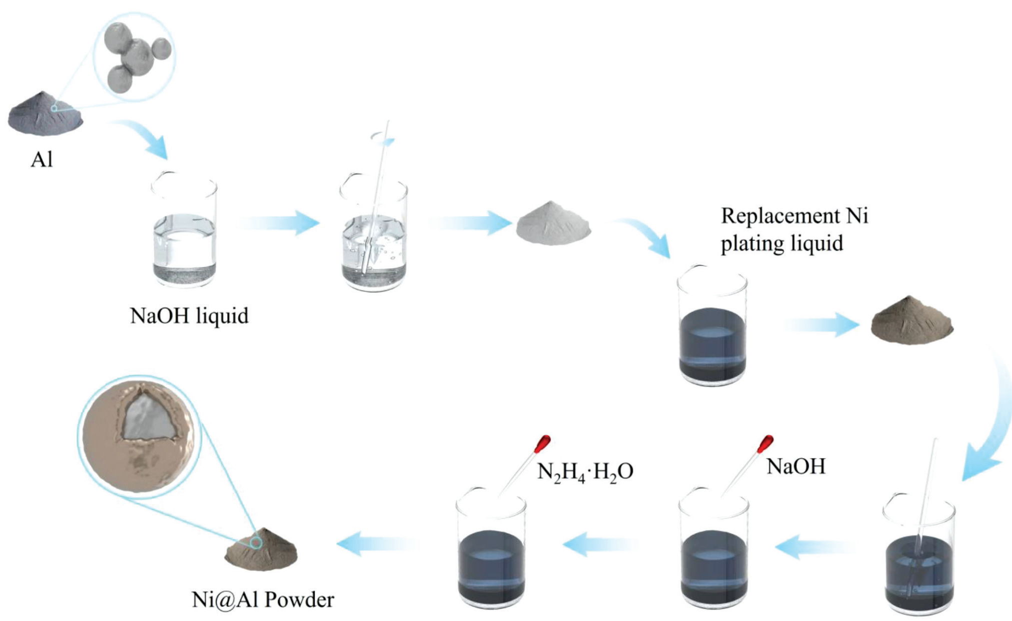

Figure 1: Schematic diagram of the preparation process for Ni@Al powder

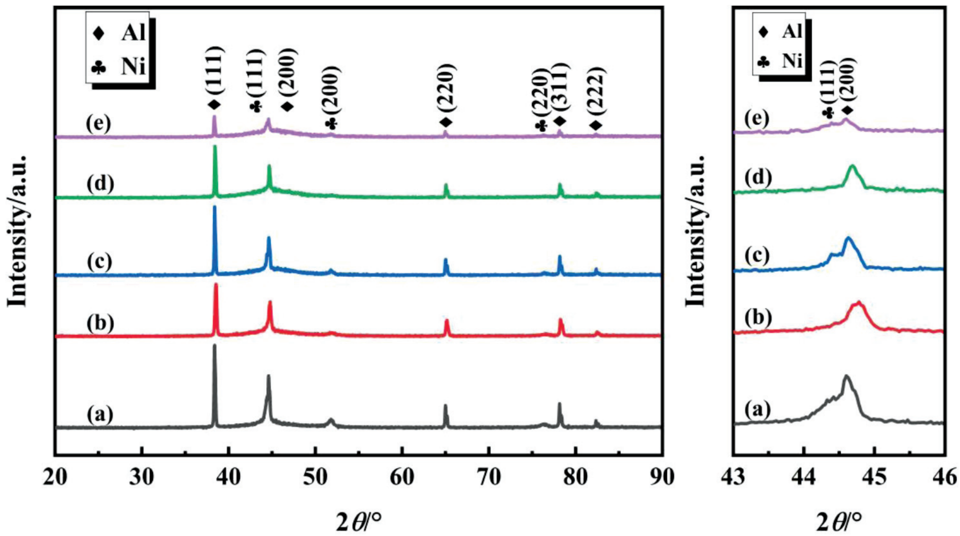

Figure 2: XRD patterns and enlarged part of XRD patterns of nickel-plated aluminum powder prepared under different nickel-coating conditions: a) 40 %, b) 50 %, c) 60 %, d) 70 %, e) 80 %

layer.[2–4] With the increase in the amount of nickel coating, the intensity of the diffraction peaks of Al (111), (200), (311) and (222) crystal planes decrease continuously. When the amount of nickel coating is 80 %, the Al (222) crystal plane basically disappears, and the X-ray penetrates the nickel coating to reach the aluminum core and the diffraction weakening is obvious. Therefore, the characteristic peak intensity of aluminum decreases gradually, and the intensity of the Ni (200) crystal plane generated by pretreatment also decreases continuously. When the nickel coating amount is 80 %, it basically disappears, indicating that the effect of nickel coating on the surface of aluminum powder is improving steadily. Therefore, when the amount of nickel coating is 80 %, the effect of the nickel coating on the surface of aluminum powder is the best.

Nickel sulfate was used as the nickel source to provide nickel ions, and the coating effect was controlled by adjusting the amount of nickel coating. **Figure 3** is the SEM and EDS spectra of nickel-plated aluminum powder prepared with nickel coating amounts of 40 %, 50 %, 60 %, 70 % and 80 %. **Figure 4** is the surface-analysis element-distribution map of nickel-plated aluminum powder prepared with a nickel coating amount of 80 %.

As shown in **Figure 3**, with the continuous increase in the amount of nickel coating, the nickel-plating layer on the surface of aluminum powder gradually coated completely, and the granular nickel-plating layer gradually became smooth. When the nickel coating amount is 80 %, the nickel coating is complete, dense and uniform. When the nickel coating amount is 40 %, the nickel-plating layer falls off, and the aluminum powder is not completely coated. The surface of the nickel-coated aluminum powder contains three elements: nickel, phosphorus and aluminum. When the nickel coating amount is 40 %, the aluminum element can be detected on the surface of

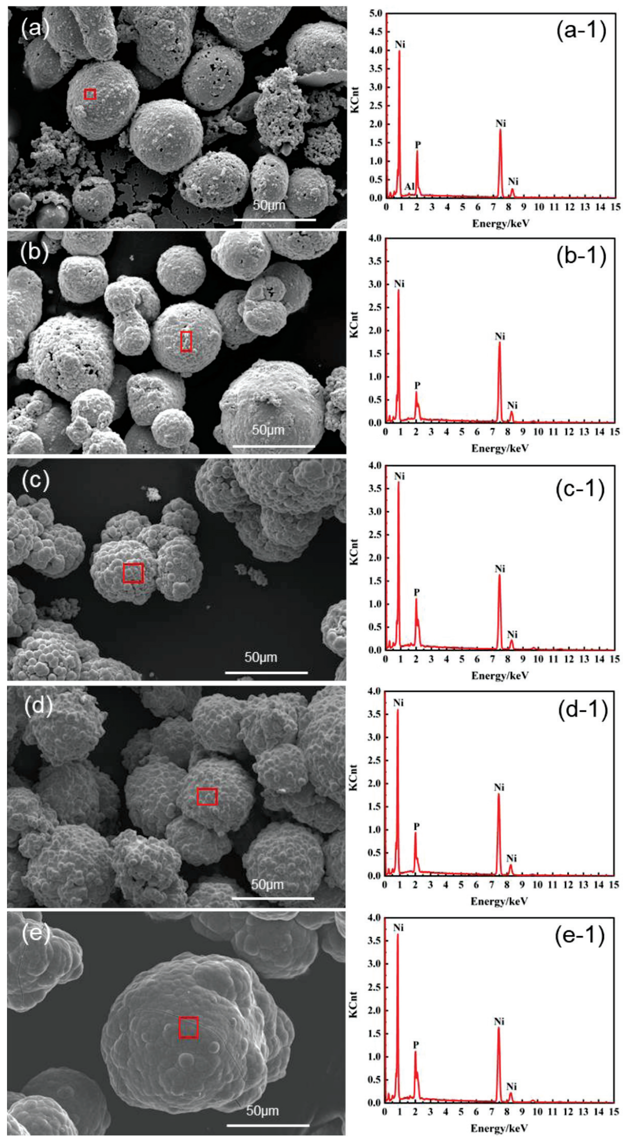

Figure 3: SEM profile of nickel-plated aluminum powders prepared under different nickel-coating conditions: a) 40 %, b) 50 %, c) 60 %, d) 70 %, e) 80 %

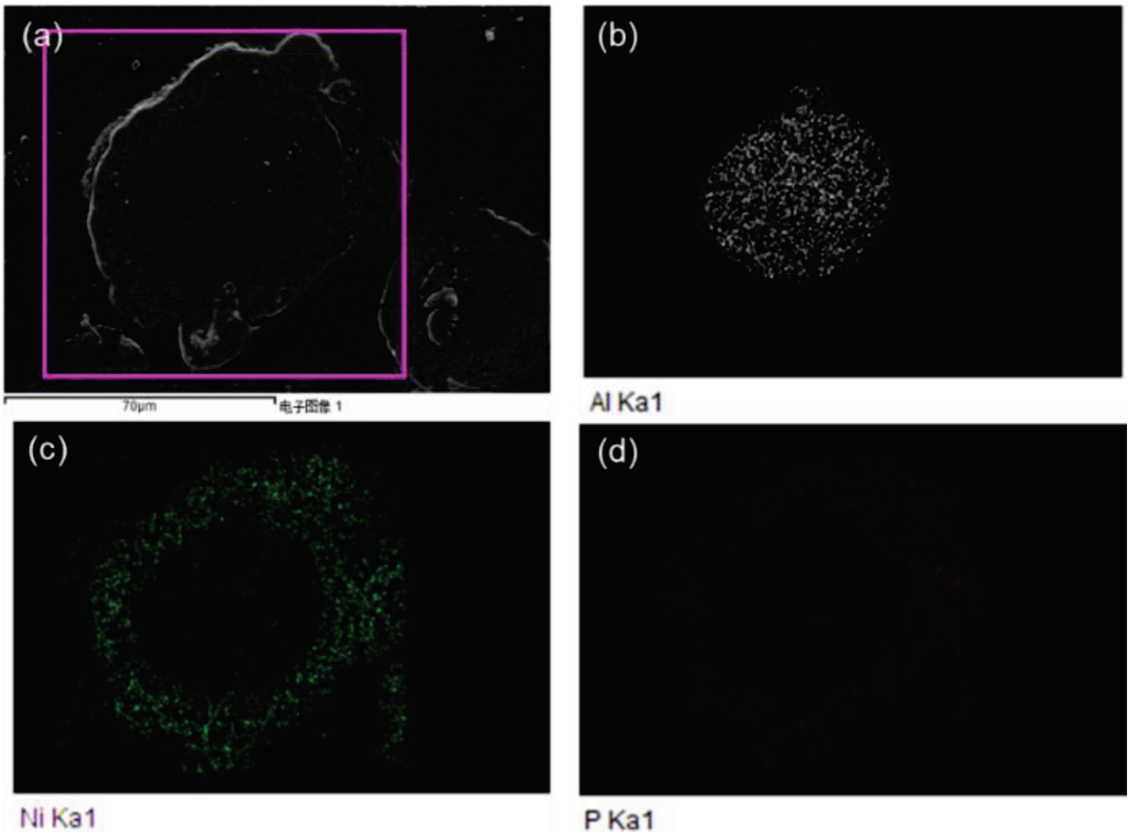

Figure 4: Surface analysis elemental distribution of nickel-plated aluminum powder prepared with a nickel coating capacity of 80 %

the nickel-coated aluminum powder, which is due to the incomplete coating of nickel on the aluminum powder. The phosphorus element is caused by the introduction of sodium hypophosphite during the reduction nickel-plating process. Some phosphorus ions in the reduced nickel-plating are reduced to phosphorus and deposited on the coating, so that the nickel-plating layer contains phosphorus. To further explain the coating effect, the powder was embedded in the resin, and the microstructure observation and element analysis were carried out after grinding and polishing. As shown in **Figure 4**, the surface of aluminum powder is completely coated by a nickel-plating layer, and the interface between the aluminum and nickel is closely combined without falling off. However, there is a clear boundary between the aluminum matrix and the nickel-plating layer, which may

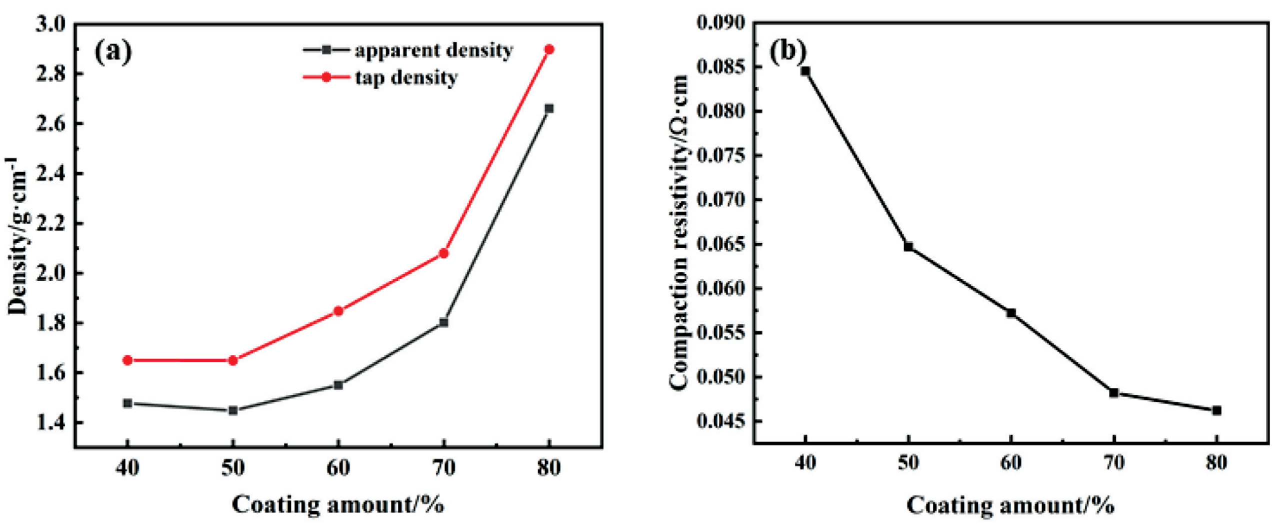

Figure 5: Density and compaction resistivity diagram of nickel-plated aluminum powder prepared under different nickel-coating conditions: a) apparent density and tap density, b) compaction resistivity

be due to the different growth modes of the nickel-plating layer in the process of pretreatment replacement nickel-plating and reduction nickel-plating, and the nickel-plating layer is broken, indicating that the internal stress of the nickel-plating layer is large. At the same time, according to the element distribution map, it can be intuitively observed that the surface of aluminum particles is coated with a nickel-plating layer. The nickel-plating layer mainly contains nickel and phosphorus, and the content of nickel is high.

Figure 5 is the density and compaction resistivity diagram of nickel-plated aluminum powder prepared under different nickel-coating conditions. As shown in Figure 5, with the increase in the amount of nickel coating, the apparent density and tap density show an increasing trend. This is because with the increase in the amount of nickel coating, the nickel-plating layer is gradually coated completely and thickened, and the relative atomic mass of nickel is much larger than that of aluminum, so the apparent density and tap density increase. When the

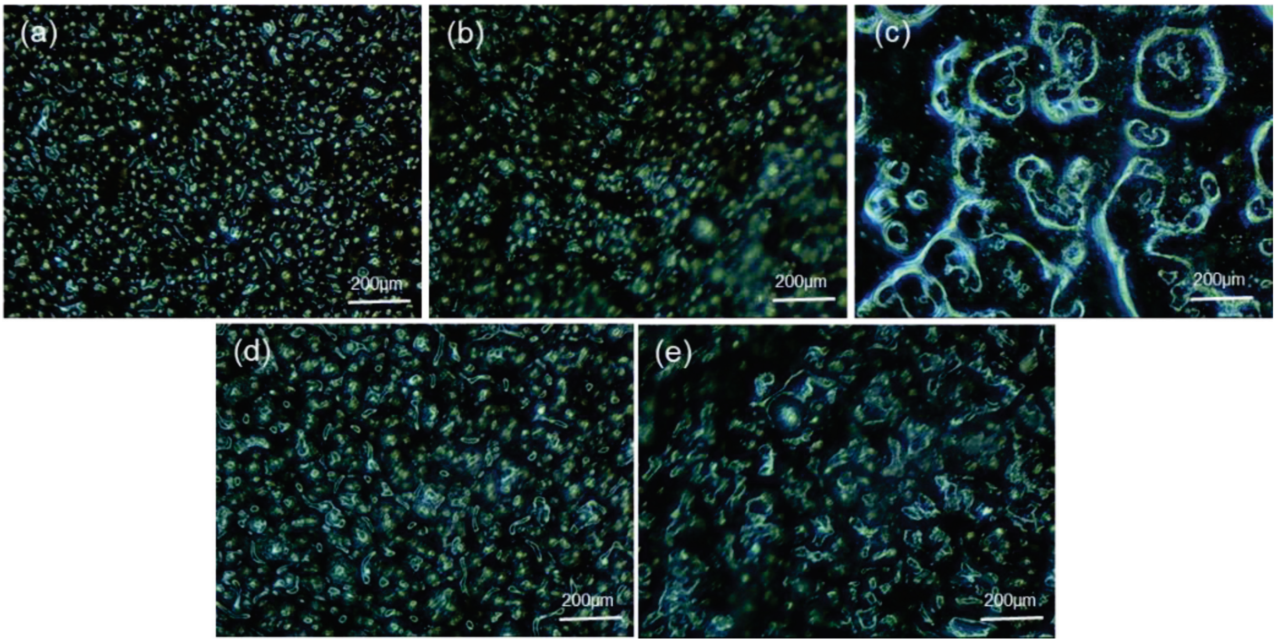

Figure 6: Metallographic micrographs of different amounts of nickel coating before the corrosion of nickel-plated aluminum powder (500×): a) 40 %, b) 50 %, c) 60 %, d) 70 %, e) 80 %

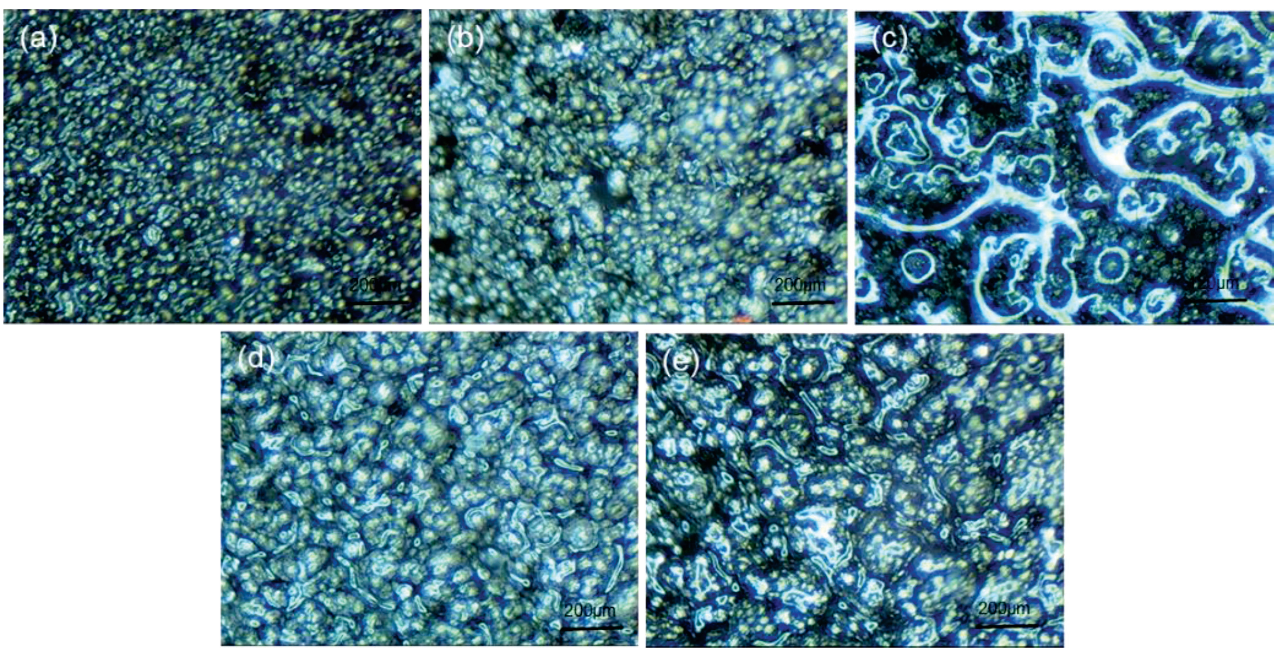

Figure 7: Metallographic micrographs of different amounts of nickel coating after corrosion of the nickel-plated aluminum powders (500×): a) 40 %, b) 50 %, c) 60 %, d) 70 %, e) 80 %

nickel coating amount is 80 %, the apparent density and tap density are the largest. In contrast, the compaction resistivity decreases with the increase of nickel. When the nickel coating is 80 %, the compaction resistivity is the smallest. This is because the nickel coating is complete, dense, uniform and the coating thickness is the best. The conductivity of nickel-plated aluminum powder mainly depends on the nickel coating on the surface of the aluminum powder. The thicker the nickel coating is, the better the conductivity, so the compaction resistivity is smaller. In summary, the best nickel coating amount is 80 %.

Figure 6 and **7** are the metallographic micrographs before and after corrosion of the nickel-plated aluminum powder with different amounts of nickel coating. The nickel-plated aluminum powder and the self-made resin were mixed in a ratio of 4:1 to prepare a slurry, which was coated on the PET film, and then cured at 100 °C for 30 min. Figure 6 is the metallographic micrograph of nickel-plated aluminum powder with different amounts of nickel coating before corrosion. The PET film was placed in a 5 *w*/ % NaCl solution at room temperature to accelerate the test of saltwater corrosion resistance. The corrosion results are shown in **Figure 7**. After soaking nickel-plated aluminum powder with different nickel amounts in a 5 *w*/ % NaCl solution at room temperature for 168 h, there were no rust spots and nickel-plated aluminum powder particles on the nickel-plated aluminum powder coating. After corrosion, the NaCl solution was still colorless and transparent. Therefore, nickel-plated aluminum powder has good corrosion resistance.

The nickel-coated aluminum powder and paraffin were mixed in a mass ratio of 3:7 with aluminum powder and nickel coatings of 40 %, 50 %, 60 %, 70 % and 80 % to prepare a nickel-coated aluminum powder/paraffin sample. Paraffin has extremely low complex permittivity and complex permeability, so it has no effect on the dielectric and magnetic properties of nickel-coated aluminum powder. **Figure 8** is the relationship between the dielectric properties of nickel-coated aluminum powder/ paraffin samples with different amounts of nickel coating and frequency.

As shown in **Figure 8**, the real and imaginary parts of the complex dielectric constant of the aluminum powder after nickel-plating are improved. The real part of the dielectric constant of the aluminum powder fluctuates around 4.46, and the imaginary part fluctuates around 0.20. At the same time, there is a peak between 11.68 GHz and 11.87 GHz, and the highest value is 2.03, indicating that the aluminum powder is a low-dielectric-loss material. Only when the amount of nickel coating is 50 %, the real and imaginary parts of the dielectric constant of the nickel-plated aluminum powder are the largest, and when the nickel coating amount further increases, the real and imaginary parts of the dielectric constant of the nickel-plated aluminum powder decrease to the dielectric constant value of the aluminum powder. The real part of the complex permittivity is mainly caused by the polarization effect inside the material, while the imaginary part of the complex permittivity is caused by the combined effect of polarization and conductivity. When the amount of nickel coating is 50 %, the nickel coating is incomplete. Compared with the nickel-coated aluminum powder with a nickel coating of 40 %, there is no coating shedding and free nickel particles, and more interfaces are formed between the aluminum powder and the nickel coating. The increased number of interfaces enhances the interfacial polarization effect of the powder, so the ε' is higher when the nickel coating is 50 %. At the same time, when the coating of aluminum powder and nickel is 40 %, 60 %, 70 % and 80 %, the real part of the complex dielectric constant resonates in the range 10.00–12.00 GHz. The reason may be that under the action of electromagnetic wave, the eddy current generated

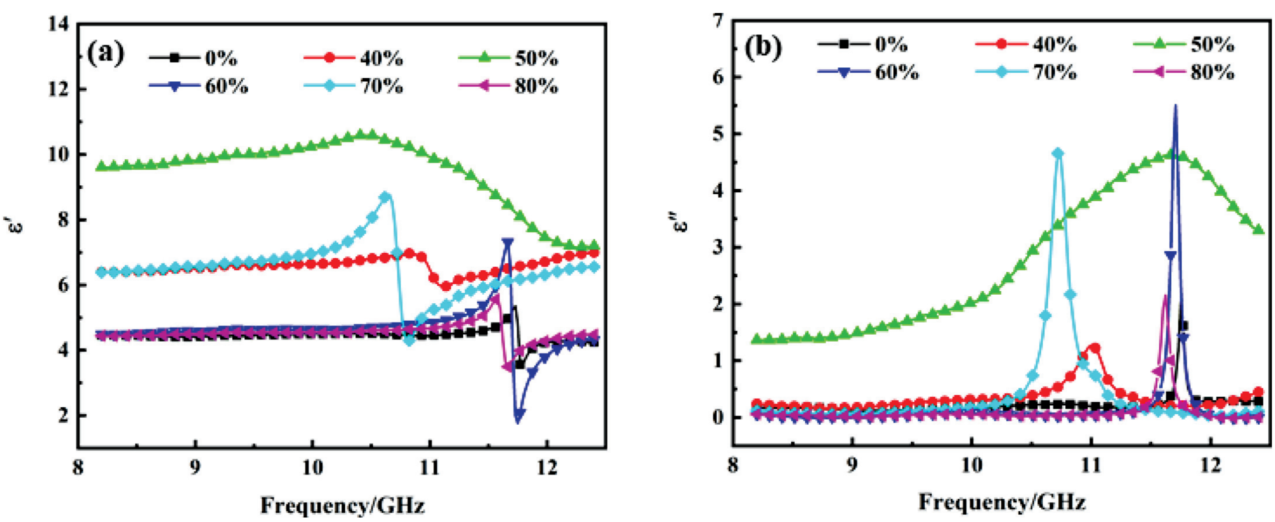

Figure 8: Graph of dielectric properties of nickel-plated aluminum powder/paraffin samples with different amounts of nickel coating as a function of frequency: a) the real part of the complex permittivity (ε'), b) the imaginary part of the complex permittivity (ε'')

by the conductive network in the nickel-plated aluminum powder/paraffin sample reacts to the electromagnetic wave and the uneven distribution of the powder in paraffin during sample preparation leads to this. With the increase of nickel coating, the interface between aluminum powder and nickel coating is reduced, and the ε' value is reduced. When the coating of the aluminum powder and nickel is 40 %, 60 %, 70 % and 80 %, the imaginary part of the complex permittivity peaks between 10.00 GHz and 12.00 GHz. The reason is the different thicknesses of the coating, which are integer multiples of the quarter wavelength of electromagnetic waves, causing resonance phenomena to occur.[5] The nickel-coated aluminum powder with nickel coatings of 60 % and 70 % even exceeds the ε" of the nickel-coated aluminum powder with nickel coating of 40 %. The peak value may be related to the large number of relaxation processes and different relaxation time of the sample. The imaginary part of the complex permittivity is also affected by the conductivity of the material. The larger the nickel coating amount, the smaller the resistance, but the density and particle size of the nickel-plated aluminum powder increase, resulting in the uneven distribution of the nickel-plated aluminum powder in paraffin wax, failing to form a large number of conductive networks, and the conductivity decreases instead. Therefore, the combined effect of polarization loss and leakage loss fails to make the imaginary part of the complex permittivity change significantly.

Figure 9 is the relationship between the complex permeability of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating and frequency. As shown in the figure, the lowest μ' value of 50 % nickel coating is 1.06≈0.87, with an average value of 0.95, while the highest μ' value of 60 % nickel coating

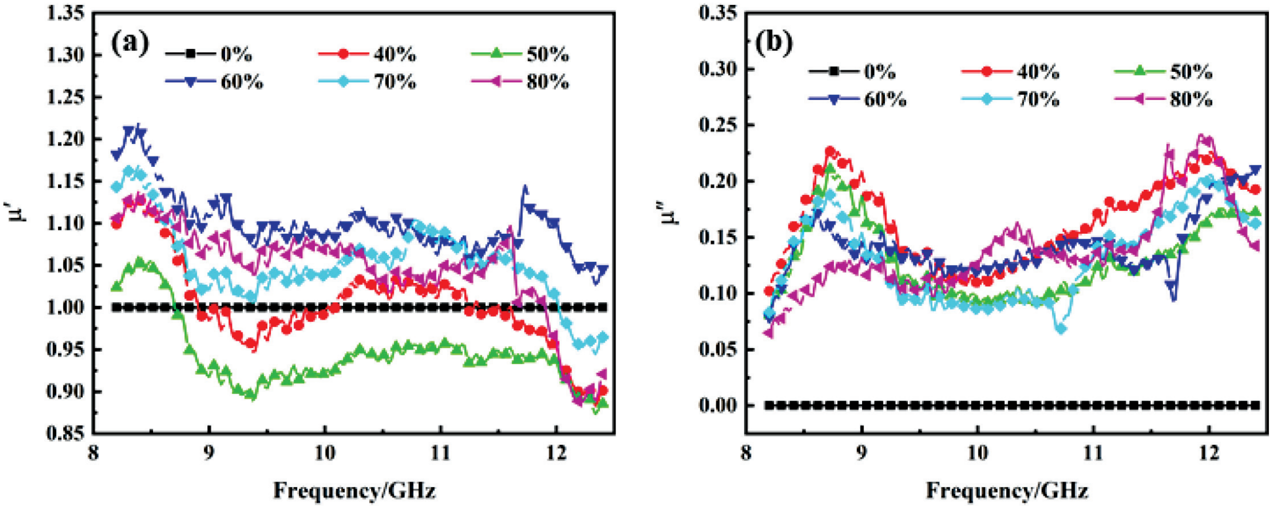

Figure 9: Graph of the change of complex permeability with frequency of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating: a) the real part of the complex permeability (μ'), b) the imaginary part of the complex permeability (μ")

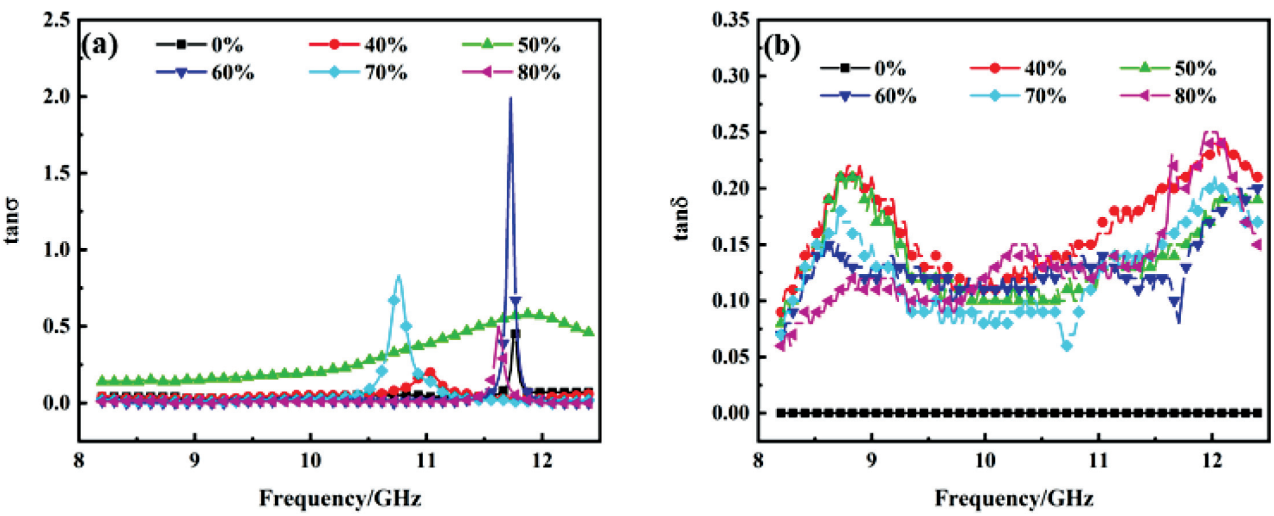

Figure 10: Graph of loss factors with frequency of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating: a) dielectric loss factor, b) magnetic loss factor

is 1.21–1.02, with an average value of 1.10. The μ' values from large to small are 60 %, 70 %, 80 %, 40 % and 50 %, but the mean values fluctuate around 1, and the change rules are basically the same, and the maximum values appear in the range 8.20–9.33 GHz. The μ" values of the nickel-plated aluminum powder with different amounts of nickel coating are basically the same, showing a trend of increasing first and then decreasing, fluctuating between 0.06 and 0.24. At the same time, when the nickel coating amount is 40 %, the average value of μ" is up to 0.17. This shows that increasing the amount of nickel coating can effectively improve the μ' value, but the μ" value is not obvious.

To further study the loss mechanism of nickel-coated aluminum powder/paraffin samples, the dielectric loss tangent (tan σ) and magnetic loss tangent (tan δ) of the samples were analyzed. **Figure 10** is the relationship between the loss factor of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating and frequency. The tan σ of aluminum powder is close to 0, and the peak appears in the range 11.60–11.87 GHz, and the highest value is only 0.45. The amount of nickel coating of 40 %, 60 %, 70 % and 80 % also shows similar changes, but the frequency range of the peak is different. When the nickel coating amount is 60 % and 70 %, the maximum tan σ is higher than that of the nickel-coated aluminum powder with nickel coating amount of 50 %, which is 1.99 and 0.83, respectively. When the nickel coating amount is 50 %, the tan value fluctuates in the range 0.14–0.58, and the higher the frequency, the greater the tan σ. The tan δ of aluminum powder is 0, and the tan δ value of aluminum powder increases obviously after nickel plating. The change trend of nickel-coated aluminum powder with different nickel coating amounts with frequency is basically the same, showing a trend of increasing first, then decreasing and then increasing. At the same time, the average tan δ values of nickel-coated aluminum powder with nickel coating amounts of 40 %, 50 %, 60 %, 70 % and 80 % are 0.17, 0.14, 0.13, and 0.13, respectively. At the same time, the tan σ value of nickel-plated aluminum powder with nickel coating amounts of 40 %, 60 %, 70 % and 80 % is smaller than the tan δ value, which indicates that the magnetic loss is the main loss mechanism after nickel-plating of aluminum powder.

To further explain the dielectric loss process of nickel-plated aluminum powder, the real part of the complex dielectric constant (ε') is used as the abscissa, and the imaginary part of the complex dielectric constant (ε") is used as the ordinate as the Cole-Cole semicircle. The semicircle represents the polarization loss, and the long straight line represents the conduction loss.

Figure 11 is the Cole-Cole curve of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating. From Figure 11, the number of semicircles corresponding to aluminum powder and nickel-coated aluminum powder with 40 %, 50 %, 60 %, 70 % and 80 % nickel coating is 2, 2, 3, 2, 2 and 2, respectively. At the same time, when the nickel coating amount is 40 % and 50 %, the Cole-Cole curve begins to appear as a long straight line, indicating that the nickel-plated aluminum powder/paraffin sample has a conductive loss. Among them, the nickel-coated aluminum powder with a nickel coating amount of 50 % has

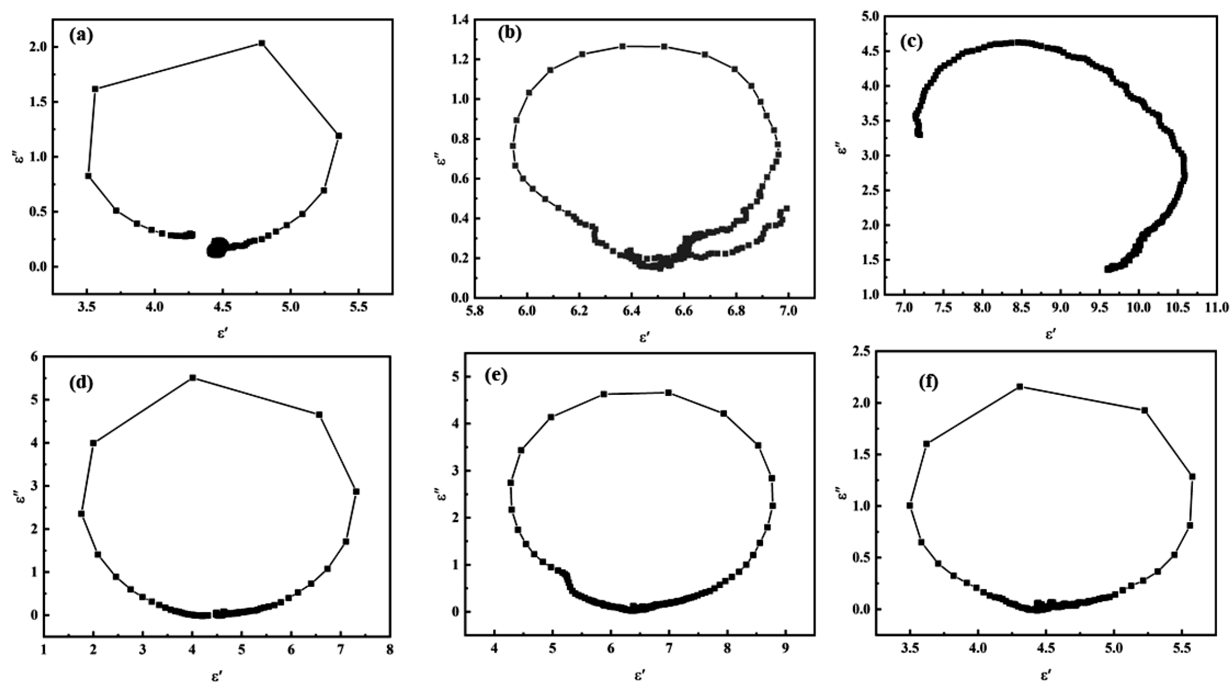

Figure 11: Cole-Cole curves of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating: a) 0, b) 40 %, c) 50 %, d) 60 %, e) 70 %, f) 80 %

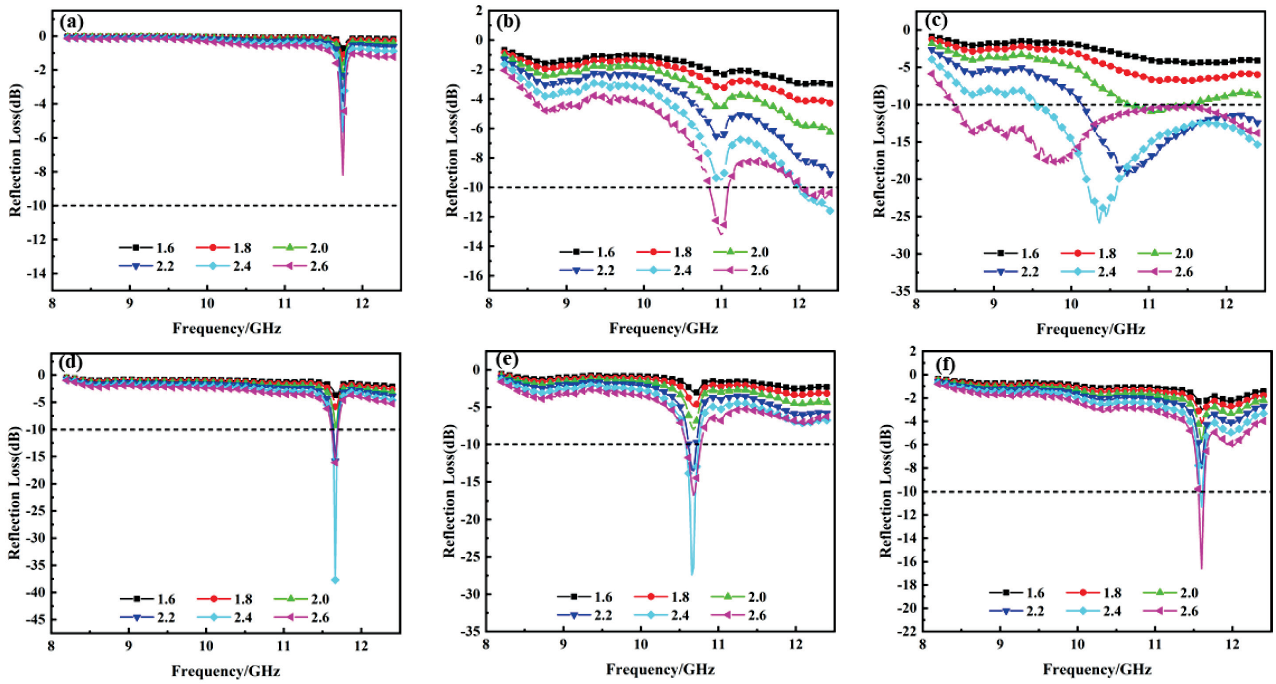

Figure 12: Reflectance curves of nickel-plated aluminum powder/paraffin samples with different amounts of nickel coating: a) 0, b) 40 %, c) 50 %, d) 60 %, e) 70 %, f) 80 %

the largest number of semicircles. Therefore, it has more heterogeneous interfaces and defects (such as Al-Ni, Ni-P, Ni-paraffin, Ni-air, etc.), thus exhibiting more polarization relaxation processes. In addition, the Cole-Cole semicircle of 50 % nickel-coated aluminum powder is not a regular semicircle, indicating that in addition to the Debye relaxation process, there are other dielectric losses, such as electron polarization, dipole polarization and other polarization processes.[6]

Figure 12 shows the reflectivity curves of the nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating. The thickness of the samples is 1.6 mm, 1.8 mm, 2.0 mm, 2.2 mm, 2.4 mm and 2.6 mm, respectively. **Figure 12a** shows that the reflectivity of aluminum powder/paraffin samples fluctuates between 0 and –8.19 dB at different thicknesses. **Figure 12b** to **12f** is the reflectivity of the nickel-plated aluminum powder/paraffin samples with different amounts of nickel coating at different thicknesses. It can be seen from **Figure 12c** that the absorption peak of the nickel-coated aluminum powder/paraffin sample with a nickel coating amount of 50 % gradually moves to the low-frequency direction as the sample thickness increases.

As shown in **Figure 12c**, when the nickel coating amount is 50 %, the reflectivity of the nickel-coated aluminum powder/paraffin sample is less than –10 dB in some frequency ranges when the thickness of the nickel-coated aluminum powder/paraffin sample is greater than or equal to 2.0 mm. At the same time, when the frequency is 10.45 GHz and the thickness is 2.4 mm, the reflectivity of the nickel-coated aluminum powder/paraffin sample is –25.88 dB. At the same time, when the sample thickness is 2.6 mm and the frequency is 8.49–12.40 GHz, the reflectivity is less than –10 dB. As shown in **Figure 12b**, when the nickel coating amount is 40 %, the minimum reflectivity of the nickel-coated aluminum powder/paraffin sample is less than -10 dB when the thickness is 2.4 mm and 2.6 mm. When the thickness of the nickel-coated aluminum powder/paraffin sample is 2.6 mm and the frequency is 10.99 GHz, the minimum reflectivity is -13.20 dB. As shown in **Figure 12d**, when the nickel coating amount is 60 %, the lowest reflectivity of the nickel-plated aluminum powder/paraffin sample between 2.2 mm and 2.6 mm is less than –10 dB. When the sample thickness is 2.4 mm and the frequency is 11.66 GHz, the lowest reflectivity is –37.69 dB. As shown in **Figure 12e**, when the nickel coating amount is 70 %, the minimum reflectivity of the nickel-plated aluminum powder/paraffin sample between 2.2 mm and 2.6 mm is less than –10 dB. When the sample thickness is 2.4 mm and the frequency is 10.66 GHz, the minimum reflectivity is -27.42 dB. As shown in **Figure 12f**, when the nickel coating amount is 80 %, the minimum reflectivity of the nickel-plated aluminum powder/paraffin sample is less than –10 dB when the thickness is 2.4 mm and 2.6 mm. When the sample thickness is 2.6 mm and the frequency is 11.60 GHz, the minimum reflectivity is –16.61 dB. The overall analysis shows that the lowest reflectivity of nickel-plated aluminum powder increases after nickel-plating, and the nickel-plated aluminum powder with a nickel coating amount of 50 % has a wide absorption frequency and low reflectivity.

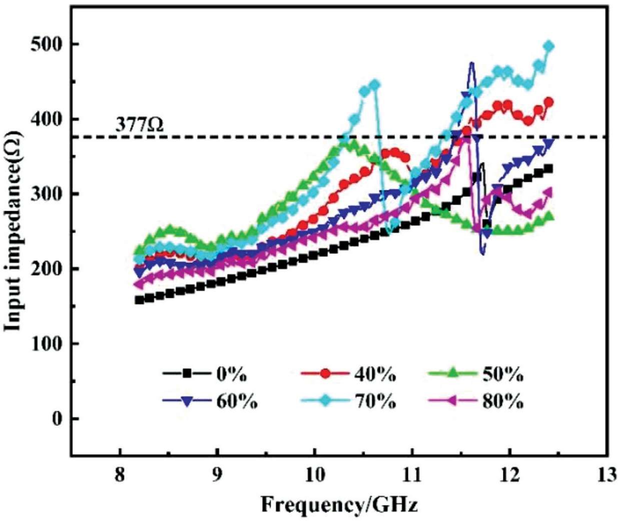

Figure 13: Input impedance values for nickel-plated aluminum powder/paraffin samples with different amounts of nickel coating

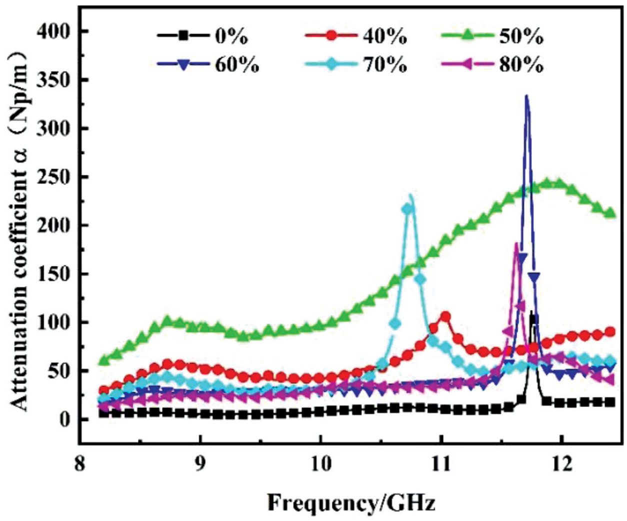

Figure 14: Attenuation coefficients of nickel-plated aluminum powder/paraffin samples with different amounts of nickel coating

In this paper, nickel-plated aluminum powder prepared by the double reducing agent system is used. When the nickel coating amount is 50 % and the thickness of the nickel-plated aluminum powder/paraffin sample is 2.4 mm, the microwave absorption performance is the best. The lowest reflectivity is –25.88 dB at 10.45 GHz. At the same time, the reflectivity of 40 % nickel-plated aluminum powder prepared by sodium hypophosphite system is lower than that of 50 % nickel-plated aluminum powder prepared by a double reducing agent system. The analysis shows that the absorbing properties of nickel-plated aluminum powder may be related to the distribution of nickel particles on the surface of the aluminum powder. The average particle size, density and compaction resistivity of 40 % nickel-plated aluminum powder prepared by sodium hypophosphite system are close to those of 50 % nickel-plated aluminum powder prepared by double reducing agent system, but the morphology of the coating is different. The nickel particles on the surface of nickel-plated aluminum powder prepared by sodium hypophosphite system are obvious and uniform, and the connection has not yet become dense. The nickel coating of nickel-plated aluminum powder prepared by double reducing agent system is relatively flat, the nickel particles are small and there are holes. Therefore, the nickel coating morphology of nickel-plated aluminum powder prepared by sodium hypophosphite system increases the interface between the aluminum powder and the nickel coating and the interface between adjacent nickel particles, which deepens the interfacial polarization degree and reduces the reflection of electromagnetic waves at the interface of the nickel-plated aluminum powder, thus improving the microwave absorption performance of the nickel-plated aluminum powder.

Figure 13 is the input impedance value of nickel-coated aluminum powder/paraffin samples with different nickel coating amounts with a thickness of 2 mm. From **Figure 13**, as the frequency increases, the input impedance values of aluminum powder and nickel-coated aluminum powder with a nickel coating amount of 40–80 % also increase. The average input impedance values are 236 Ω, 301 Ω, 279 Ω, 275 Ω, 326 Ω, and 251 Ω, respectively. The input impedance value of the nickel-coated aluminum powder/paraffin sample with a nickel coating amount of 70 % is closer to the free space impedance value (377 Ω), while the input impedance value of the aluminum powder/paraffin sample is the smallest. This shows that the interface of nickel-plated aluminum powder/paraffin sample has less reflection of electromagnetic wave, which can make more electromagnetic wave enter the material, so that the nickel-plated aluminum powder/paraffin sample has better absorbing performance.

Figure 14 shows the attenuation coefficient of nickel-coated aluminum powder/paraffin samples with different amounts of nickel coating. From the figure, the attenuation coefficient of nickel-coated aluminum powder/paraffin samples with 50 % nickel coating is the largest, fluctuating in the range 59.43–244.19Np / m; the attenuation coefficient of the aluminum powder/paraffin sample is the smallest, fluctuating in the range 6.76–111.93Np/m. When the nickel coating amount is 50 %, 60 %, 70 % and 80 %, the attenuation coefficient is slightly higher than that of aluminum powder, and there is a peak in some frequency ranges. When the nickel coating amount is 60 % and 70 %, the peak is higher than the attenuation coefficient of nickel coating amount of 50 %. However, the attenuation coefficient of the nickel-coated aluminum powder/paraffin sample with an overall coating amount of 50 % is higher than that of other samples, and has good attenuation characteristics. The surface coating of nickel-plated aluminum powder improves the electromagnetic loss efficiency, which in turn affects the microwave absorption performance of nickel-plated aluminum powder. However, it is not true that the higher the nickel coating amount, the higher the attenuation coefficient. Many factors such as the particle size, density, conductivity and sample thickness of the absorbent should also be considered.

5 CONCLUSIONS

In this study, nickel-plated aluminum powder was prepared by double reducing agent system. Nickel sulfate hexahydrate was used as the nickel source, sodium hypophosphite and hydrazine hydrate were used as reducing agents to reduce the nickel on the aluminum powder after the nickel plating. The experimental results show that the optimal absorbing performance can be obtained by adjusting the amount of nickel coating of nickel-coated aluminum powder. When the nickel coating amount is 50 %, the sample can achieve relatively excellent absorbing performance over a wide frequency range. When the impedance matching thickness is 2.4 mm and the frequency is 10.45 GHz, the lowest reflectivity is –25.88 dB. At the same time, when the impedance matching thickness is 2.6 mm and the frequency is in the range of 8.49–12.40 GHz, the reflectivity is lower than–10 dB, which has the largest loss frequency range.

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