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Study on the Electromagnetic and Mechanical Properties of Coated Composites

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Abstract

In this paper, a single-layer coated composite was prepared using PU2540 polyurethane as the matrix, nickel powder as the wave-absorbing functional particle, and coating technology on plain cotton fabric. The influence of the content of nickel powder on the dielectric properties (the real and imaginary parts and the loss tangent value), the shielding effectiveness and the mechanical properties was studied adopting the method of controlling variables. The result showed that when the content of nickel powder was 0~20% and that of nickel powder relative to that of polyurethane was 20%, the real and imaginary parts of the dielectric constant of the coating were the largest, and its polarising and loss ability with respect to electromagnetic waves were the strongest; when the content of nickel powder relative to that of polyurethane was 15%, the loss tangent value of the coating was the largest, and its absorption and attenuation ability with respect to electromagnetic waves was the strongest. When the values of the coating thickness were at 0.5~2 mm, the real and imaginary parts of the dielectric constant of the coating with a thickness of 1 mm were the largest, and the polarising and loss ability with respect to electromagnetic waves were the strongest. When the loss tangent value and the shielding-attenuation value of the coating with a thickness of 2 mm were the largest, the absorbing-attenuation and shielding-attenuation ability with respect to electromagnetic waves were the strongest.

Key words: *nickel powder, single-layer coating, electromagnetic shielding, dielectric properties.*

Introduction

Electromagnetic radiation acts on the human body through the thermal effect, non-thermal effect and cumulative effect, three ways which affect the human body's circulation, immunity, reproductive metabolism and other functions [1-3]. At the same time, the transient overvoltage caused by electromagnetic radiation will also affect the stable operation of specific instruments and airborne systems. It can be applied to large-scale integrated circuits and produce tiny induction electric potentials to interfere with normal work signals, causing sensitive components to work in disorder, causing property damage in light cases, or endangering public safety in the worst [4-7]. Electromagnetic shielding textiles with characteristics of reflecting or absorbing electromagnetic waves can be obtained by compounding electromagnetic protection materials and textiles with high and new technologies [8-12].

Nickel powder is a magnetic material with good ferromagnetism [13]. Nickel has a larger specific surface area, small density, good surface activity as well as other physical properties and structures. The crystal of nickel is of a face-centered cubic structure at a low temperature, and at a higher temperature it is of a hexagonal structure, with a density of 8.902 g/cm³ and electrical resistivity of 6.9×10^{-6} W·m

[14]. And it has good electric conductivity; the electrical resistivity of nickel powder is superior to that of graphite but worse than that of graphene, being average among the metal conductors. Nickel powder has characteristics such as a moderate price, strong antioxidant capacity, strong absorption and scattering capability, stable chemical performance, strong corrosion resistance, good properties of magnetic permeance, resistance to humidity, and it can effectively prevent electromagnetic interference. Ultrafine nickel powder is one type of metal powder with high permeability, and it has the ability of absorption and loss [15-16]. Nickel is a type of absorbing material of the magnetic medium kind, and it has great complex permeability, a great complex dielectric constant, and higher microwave permeability. It relies on the magnetisation mechanism of the magnetic hysteresis loss, the domain wall resonance the natural resonance, and retarded resonance to carry out attenuation and absorption of electromagnetic waves [17-18]. The electronic vector capability of the coating of nickel powder to absorb and scatter rays is strong. The attenuation rate of the magnetic vector is larger when using an EM source, and the coating can effectively shield the radiation.

In this paper, using PU2540 polyurethane as the matrix on plain cotton fabric,

the influence of the content and coating thickness of nickel powder on the dielectric properties (the real and imaginary parts and the loss tangent value), shielding effectiveness and mechanical properties of single-layer coated composites was studied.

Experiment

Main experimental materials

The major experimental materials: cotton (plain woven), were provided by Nantong Linya Textile Co., LTD.

The main experimental drugs used are shown in *Table 1*.

Note: The PU2540 polyurethane resin was a 40% waterborne polyurethane dispersion with excellent performance, which has the advantages of good toughness and bending resistance. The density of the PU2540 polyurethane resin was 1.04 g/cm³. At 25 °C, the viscosity of the PU2540 polyurethane resin was less than 300 mPa·s. The role of thickener is to regulate the viscosity of polyurethane; the more the thickener, the greater the viscosity of polyurethane.

Main experimental instruments

The main experimental instruments are shown in *Table 2*.

Table 1. *Main experimental drugs.* **Note:** *Chemical composition of carbonyl nickel powder: nickel: 99.79%, carbon: 0.090%, oxygen: 0.11%, sulfur: 0.0010%, carbon monoxide: 0.001%, iron: 0.001%; Physical properties: the apparent density – 0.58 g/cm³, average particle size – 2.37 μm; appearance – group powder.*

Drug/reagent name	Specification	Manufacturer
Carbonyl nickel powder	W-5	Shenzhen Changxinda Shielding Materials Co., LTD
Polyurethane	PU2540	Guangzhou Yuheng Environmental Protection Material Co., LTD
Thickener	7011	Guangzhou Dianmu Composite Business Department

Table 2. *Main experimental instruments.*

Name of instruments	Type	Manufacturer
Single-phase series motor	U400/80-30	Shanghai Micro &Special Motor Co., LTD
Electric coating machine	XWR-150	Suzhou Xuanworui Functional Science and Technology Co., LTD
High-temperature blast drying oven	DGG-9148A	Shanghai Aozhen Instrument Manufacturing Co., LTD
Digital viscosimeter	SNB-2	Shanghai Hengping Instrument and Meter Plant
Dielectric spectrometer	E4991B	Shide Science And Technology (China) Co., LTD.,
Thickness gauge of fabric	YG141	Nantong Sansi Electromechanical Science and Technology Co., LTD
Vector network analyser	ZNB40	German Rohde & Schwarz Company
INSTRON universal machine	5969	American INSTRON company

Preparation of materials

Coating preparation

(1) Wave-absorbing functional particles were stirred evenly with the polyurethane and coating with good surface quality could be daubed.

(2) After the whole absorbing agent was added into the polyurethane, the thickener was added to increase the consistence of the coating, so as to achieve the required viscosity. The stirred coating was poured into a beaker of suitable size, and the viscosity was measured by a viscosity tester. The coating preparation was finished and waited to be used. The applicable range of the coating being applied is very wide: 20000~40000 mPa·s.

Preparation of the coating

In this experiment, the method of blading was adopted. A needle plate with base cloth was fixed on a coating machine for small samples, and parameters such as the coating thickness and stroke were adjusted, leading to a coating with a certain thickness and length of 30 cm being prepared by the coating machine. An appropriate amount of the coating was daubed on the fabric surface, and the coating was finished in the shape of an inverted triangle, where the scraper was set at a speed of 60 cm/min, and while it went forward, the coating on the edge was finished, with the width of the coating maintained at 15 cm. Finally, it was coated beautifully. After the comple-

tion of the coating, the coated fabric was immediately placed into a drying oven, the temperature of which was 80 °C, and then it was dried for a certain time. At this point, the preparation of the single-layer coating of the coated fabric was completed. After drying, the coating was removed and kept at room temperature until it was aired naturally.

Requirements of specific parameters of the coating

(1) The influence of the content of nickel powder on the electromagnetic properties and mechanical properties of the single-layer coated composite was investigated.

When coatings 1 #, 2 #, 3 #, 4 #, and 5 # were prepared, the content of nickel powder was varied, the viscosity fixed at 20000 mPa·s, and the coating thickness was 0.5 mm. The content of nickel powder (relative to the polyurethane: 0%, 5%, 10%, 15%, 20%) was changed to create a single-layer coated composite with five different types of contents of nickel powder.

The influence of the coating thickness on the electromagnetic properties and mechanical properties of the single-layer coated composite was investigated.

When coatings 1 #, 2 #, 3 #, and 4 # were prepared, the coating thickness was the variable, where the mass of nickel powder relative to the polyurethane was se-

lected at 20%, maintaining the viscosity at 30000 mPa·s while changing the coating thickness of the nickel powder (0.5 mm, 1 mm, 1.5 mm and 2 mm) to create a single-layer coated composite with four different types of thicknesses of the coating.

Test indexes

Test of the dielectric constant

In accordance with the SJ20512-1995 standard: "The Test Method of the Complex Dielectric Constant and Complex Magnetic Permeability of Microwave Solid Materials with Large Loss", the dielectric constant of the coated fabric was measured using a Keysight E4990A. The test frequency was 1 MHz~1.5 GHz, and a circular plate electrode of a diameter of 2.5 cm and a clip distance of 16453A was selected [19-23].

Test of the shielding effectiveness

The test method of the shielding effectiveness of electromagnetic shielding materials is given in the GB/T 12190 Standard. The shielding effectiveness of the coating was measured using a vector network analyser, at a test frequency range of 100 kHz~1.5 GHz. The size of circular samples required were of a diameter of 13 cm. The environmental requirements of the laboratory were as follows: (1) temperature – 15~30 °C, (2) environmental relative humidity – less than 80%.

Test of tensile properties

Testing of the tensile properties was conducted using an Instron universal material testing machine, following the test methods for GB1447-2005 fibre reinforced plastic tensile properties. The specifications of the samples were as follows: 200 x 25 mm, clamping distance 100 mm, and the speed of loading 2 mm/min. For each group 10 samples were tested, with the average taken.

■ Results and discussion

Influence of the content of nickel powder on the electromagnetic properties and mechanical properties of single-layer coated composites

Influence of the content of nickel powder on the dielectric properties of single-layer coated composites

In order to study the influence of the content of nickel powder on the dielectric properties (the real and imaginary parts and the loss tangent value) of single-lay-
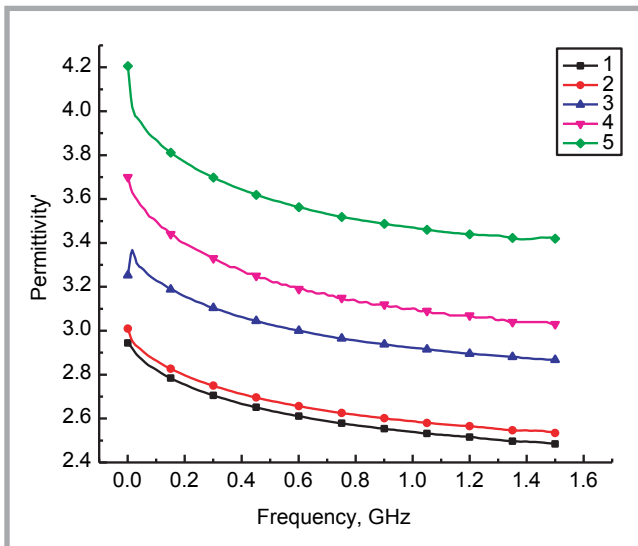
Figure 1. *Influence of the content of nickel powders on the real part of the dielectric constant of single-layer coated composites.*
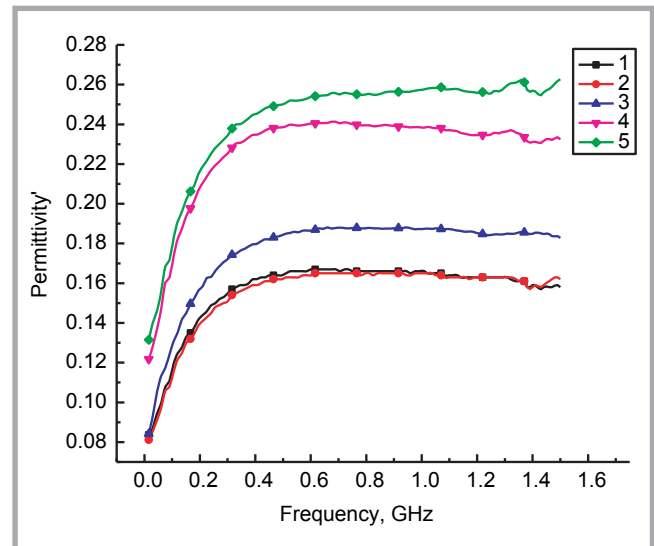

Figure 2. *Influence of the content of nickel powder on the imaginary part of the dielectric constant of single-layer coated composites.*

er coated composites, single-layer coated composites of five different types of contents of nickel powder were prepared (the mass percentages relative to the polyurethane were 0%, 5%, 10%, 15% and 20%, respectively on the plain cotton fabric, the specific process parameters of which are shown in *Table 3*.

Samples of the coated fabric were prepared, and the dielectric properties of the fabrics were tested within the range of 10 MHz to 1.5 GHz. Curves of the real and imaginary parts of the dielectric constant and the loss tangent value were drawn using Origin Pro, shown in *Figures 1, 2* and *3*.

As can be seen from *Figure 1*, when the frequency was 0.6~1.5 GHz, values of the real part of the dielectric constant of the five samples went on decreasing; however, the decreasing speed was smaller than before and even tended to zero. But the decreasing speed of the five samples was roughly the same. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the electric field, values of the real part of the dielectric constant of the five samples 1 #, 2 #, 3 #, 4 # and 5 # gradually decreased, and the

polarising ability with respect to electromagnetic waves was gradually reduced. When the frequency was 0.01~0.5 GHz, with increasing frequencies of the electric field, the decreasing speed of the value of the real part of the dielectric constant of 5 # sample was the fastest, and its real part was the largest within the spectrum. When the frequency of the applied electric field was 0.01 GHz, values of the real part of the dielectric constant of each sample were all the largest, as well as the polarising ability of the magnetic field produced in the single-layer coated composite with respect to the applied magnetic field. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the electromagnetic field, the real part of the dielectric constant of 5# was the largest, and the polarising ability with respct to electromagnetic waves was the strongest, followed by 4 #, 3 #, 2 # and 1 #, respectively. Namely, when the frequency was 0.01~1.5 GHz, the real part of the dielectric constant of the coating was the largest, and when the mass percentage of nickel powder relative to polyurethane was 20%, its polarising ability with respect to electromagnetic waves was the strongest, followed by mass percentage of nickel powder relative to polyurethane of 15%, 10%,

5% and 0%. respectively, When the content of nickel powder was 0~20%, with the increasing content of nickel powder, particles of nickel powder in the coating increased; the real part of the dielectric constant of the samples increased gradually, and its polarising ability with respect to electromagnetic waves was gradually enhanced. Along with the increasing contents of particles of the nickel powder, electrons, ions and natural dipoles were also on the rise, and the ability of storing charges of single-layer coated composite materials was enhanced; namely its polarising ability gradually increased. Because the contact state of particles of nickel powder was the basis of channel conduction, the more particles of nickel powder there are in the contact state, the smaller the gap between particles, thus the conductive network was more intensive, the contact resistance smaller, the electrical conductivity of the composite higher, and the ability of real part storing charges was also strengthened.

As can be seen from *Figure 2*, when the frequency was 0.3~0.7 GHz, values of the imaginary part of the dielectric constant of the five samples increased slowly, and then their respective maxi-

Table 3. *Process parameters of different contents of nickel powder.*

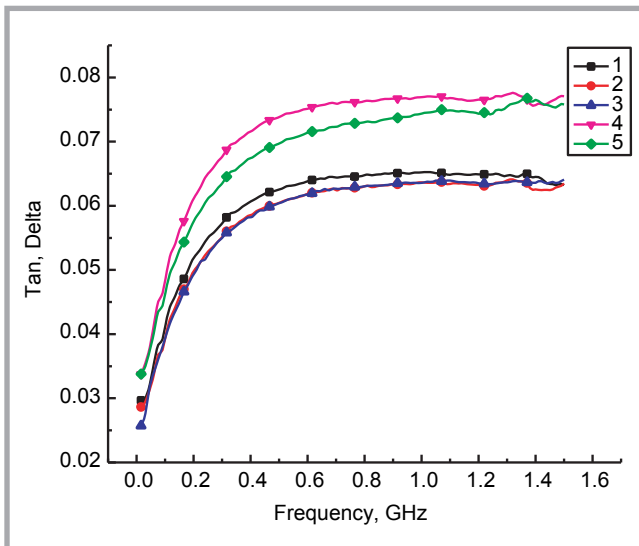| Number	Content of nickel powders, %	Stirring time, min	Viscosity, mPa·s	Coating thickness, mm	Velocity of coating machine, cm/min	Temperature of drying oven, °C	Drying time, min
1	0	40	20000	0.5	60	80	10
2	5	40	20000	0.5	60	80	10
3	10	40	20000	0.5	60	80	10
4	15	40	20000	0.5	60	80	10
5	20	40	20000	0.5	60	80	10

Figure 3. Influence of the content of nickel powder on the loss tangent value of single-layer coated composites.
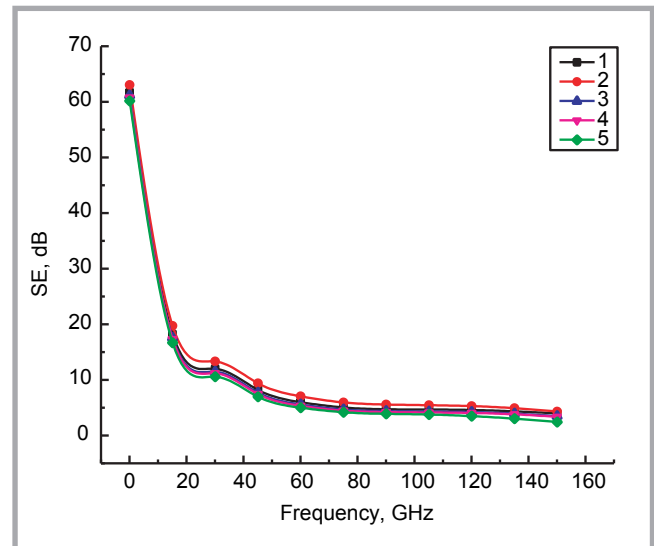

Figure 4. Influence of the content of nickel powder on the shielding effectiveness of single-layer coated composites.

mum was achieved. When the frequency was 0.7~1.5 GHz, the value for 3 # and 5 # fluctuated around the maximum, and there was a modest decline in the value for 1 #, 2 # and 4 #. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, values of the imaginary part of the dielectric constant of the five samples 1 #, 2 #, 3 #, 4 # and 5 # showed a trend of first increasing and then decreasing; namely, the same trend in the loss ability with respect to electromagnetic waves was shown. When the frequency was 0.01~0.3 GHz, the increased speed of the value of the imaginary part of the dielectric constant of 4 # sample was the fastest, followed by 5 #, 2 #, 3 # and 1 #. When the frequency was 0.01 GHz, the imaginary part of the dielectric constant of each sample was at the minimum and the loss ability with respect to electromagnetic waves was the weakest. When the frequency of the applied electric field was 0.7 GHz, the value of the imaginary part was the largest, as well as the loss ability of the magnetic field produced in the coating with respect to the applied magnetic field. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the electromagnetic field, the imaginary part of the dielectric constant of the coating was the largest when the mass percentage of nickel powder relative to the polyurethane was 20%, and its loss ability with respect to electromagnetic waves was the strongest, followed by mass percentages of nickel powder relative to polyurethane of 15%, 10%, 0% and 5%, respectively.

As can be seen from *Figure 3*, when the frequency was 0.01 GHz~0.3 GHz, the loss tangent value of sample 5 # increased the fastest, followed by that of 3 #, 4 #, 2 # and 1 # When the frequency was 0.3 GHz~1.5 GHz, the value for sample 5 # increased to a small extent, and those for samples 1 #, 2 #, 3 # and 4 # were almost constant. When the frequency was 0.01 GHz~1.5 GHz, with increasing frequencies of the applied electric field, loss tangent values of the five samples 1 #, 2 #, 3 #, 4 # and 5 # showed an increasing trend and then remaining constant, namely, the same trend in the attenuation ability of the magnetic field produced in the coating with respect to electromagnetic waves was shown. When the frequency was 0.01 GHz, the loss in the tangent value of each sample was at the minimum, and the attenuation ability of the magnetic field produced in the coating with respect to electromagnetic waves was the weakest. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, the loss in the tangent value within the spectrum of 4 # was the largest, and the attenuation ability of the magnetic field produced in the coating with respect to electromagnetic waves was the strongest, then, followed by that for 5 #, 1 #, 2 # and (3 #). When the frequency of the applied electric field was 0.6 GHz, the loss tangent value was the largest, and when the mass percentage of nickel powder relative to the polyurethane was 15%, its absorbing-attenuation ability with respect to electromagnetic waves was the strongest, folloed by mass percentage of

nickel powder relative to polyurethane of 20%, 0%, 10% & (5%), respectively. The loss tangent value of the coated fabric was closely related to the content of nickel powder. The only variable of samples 1 #, 2 #, 3 #, 4 # and 5 # was the content of nickel powder, when the coating thickness was a certain value, the content of nickel powder determined that of the absorbent, which affects the amount of electromagnetic waves absorbed into the coated fabric. Along with increasing contents of nickel powder, particles of which contained in the coating increased, and the attenuation ability with respect to electromagnetic waves was the strongest.

Influence of the content of nickel powder on the shielding properties of single-layer coated composites

In order to study the influence of the content of nickel powder on the shielding properties of single-layer coated composites, single-layer coated composites of five different types of content of nickel powder were prepared (the mass percentages relative to the polyurethane were 0%, 5%, 10%, 15% and 20% on the plain cotton fabric, respectively, the specific process parameters of which are shown in *Table 3*.

Samples of the coated fabric were prepared, and the shielding-attenuation value was tested. The testing scope was 100 kHz~150 MHz. Curves of the frequency-shielding attenuation value were drawn with Origin Pro, shown in *Figures 4 and 5* (the amplification for *Figure 4* was within the range of 30 to 60 MHz).
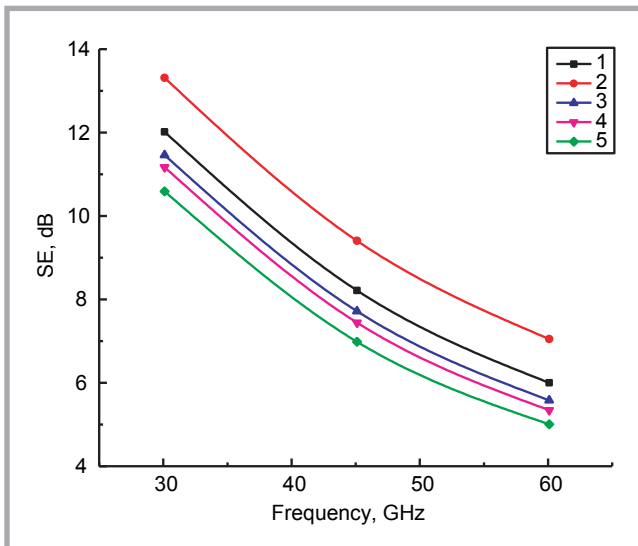
Figure 5. *Influence of the content of nickel powder on the shielding effectiveness of single-layer coated composites.*
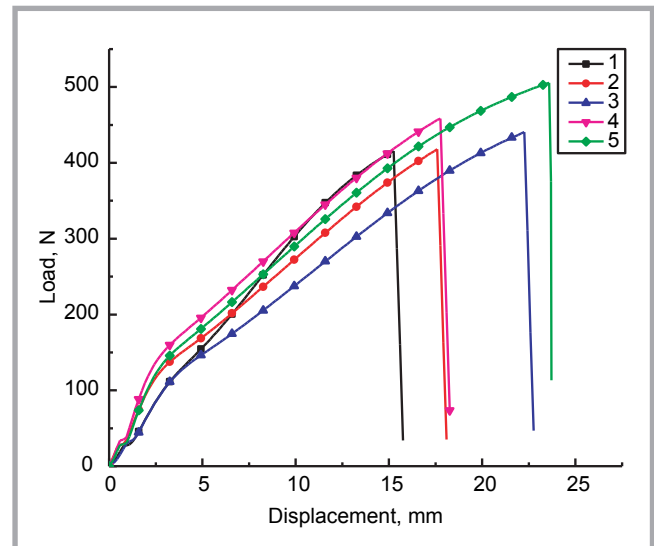

Figure 6. *Influence of the content of nickel powders on the tensile strength of single-layer coated composites.*

As can be seen from ***Figure 4***, when the frequency was 0.1~150 MHz, with increasing frequencies of the applied electric field, the shielding-attenuation value of the five samples decreased, with the size of the decrease speed being about the same. When the frequency was 0.1~20 MHz, the shielding-attenuation value of the five samples went on decreasing; however, the decease speed declined.

When the frequency was 0.1~150 MHz, with increasing frequencies of the applied electric field, the shielding-attenuation value of samples 1 #, 2 #, 3 #, 4 # and 5 # decreased gradually; in other words, when the frequency of the applied electric field was low, the coating had better shielding-attenuation ability with respect to electromagnetic waves. Thus, when the frequency was 0.1 MHz, the largest shielding-attenuation value was reached and the best shielding effect achieved.

As can be seen from ***Figure 5***, when the frequency was 30~60 MHz, with increasing frequencies of the applied electric field, the shielding-attenuation value of 2 # was the largest, followed by that of 1 #, 3 #, 4 # and 5 #. Namely, when the frequency was 30~60 MHz, the shielding-attenuation value was the largest, and the attenuation ability with respect to electromagnetic waves was the largest when the content of nickel powder was 5%, followed by mass percentages of nickel powder relative to polyurethane of 0%, 10%, 15% and 20%, respective-

ly. When the content of nickel powder was 0~20%, with an increasing content of which , the shielding-attenuation value presented a decreasing trend, and the attenuation ability with respect to electromagnetic waves decreased. The only variable for samples 1 #, 2 #, 3 #, 4 # and 5 # was the content of nickel powder in the coating. When the frequency was 30~60 MHz, the content of nickel powder was 5%, the coating had the largest shielding-attenuation value, and the shielding effect was the best.

Influence of the content of nickel powder on the mechanical properties of single-layer coated composites

In order to study the influence of the content of nickel powder on the mechanical properties of single-layer coated composites, single-layer coated composites of five different types of content of nickel powder were prepared (the mass percentages relative to the polyurethane were 0%, 5%, 10%, 15% and 20%, respectively, on the plain cotton fabric, the specific process parameters of which are shown in ***Table 3***.

A test of the tensile properties using an Instron universal material testing machine was carried out. The parameters of the mechanical properties are shown in ***Table 4***.

Samples of the coated fabric were prepared and the displacement-load curve drawn with Origin Pro, which is shown in ***Figure 6***.

Figure 6 shows that when the displacement was 0~5 mm (d was the displacement), the displacement-load curve of 1 #, 2 #, 3 #, 4 # and 5 # showed a nonlinear change, and when the displacement was 5~25 mm, with the increasing displacements, the load increased gradually, until the sample experienced fracture. When the load reached the maximum (also with the maximum load displacement), the coated fabric experienced fracture, while with increasing displacements, the load decreased. When the displacement was 0~25 mm, with increasing displacements, 2 # reached the maximum load first, followed by 4 #, 3 # and 1 # (5 #). When the content of nickel powder was 20%, the coating had the maximum
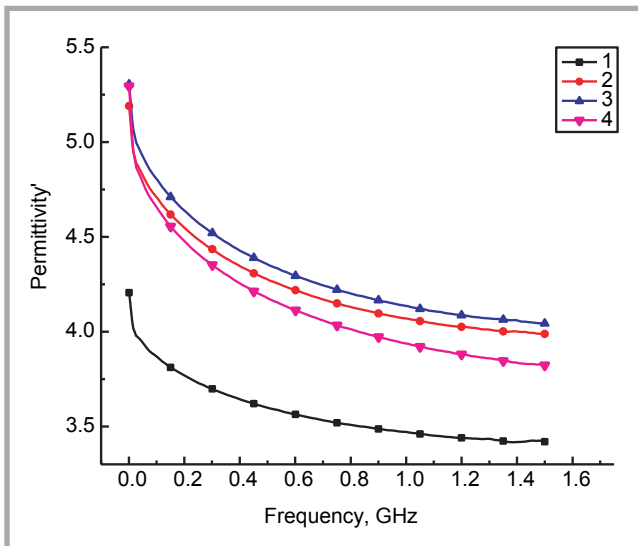
Table 4. *Related parameters of the mechanical properties of different contents of nickel powder.*

Number	Maximum load, N	Maximum load displacement, mm	Tensile stress value of maximum load, MPa	Elasticity modulus, MPa
1	454.03824	20.92332	9.08076	83.30554
2	392.99597	16.75684	7.85992	100.01 654
3	452.08942	16.09003	9.04179	95.05565
4	368.0874	15.75661	6.6836	80.3685
5	451.57877	20.92343	9.03158	74.05085

Figure 7. *Influence of the coating thickness on the real part of the dielectric constant of nickel powder of the coated composite with nickel powder.*
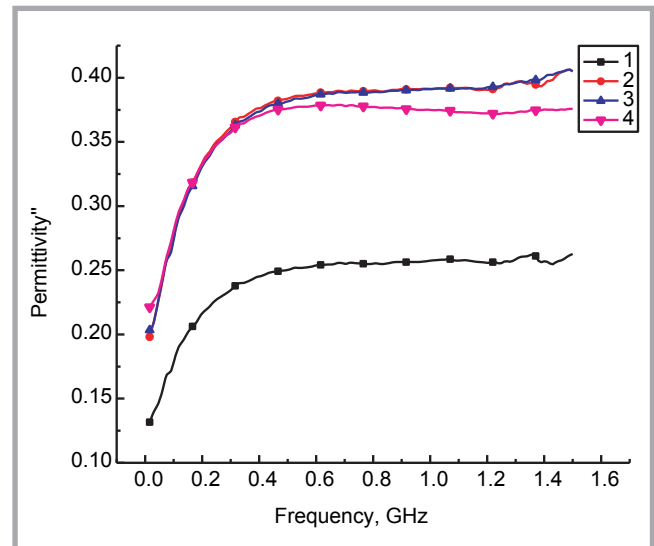

Figure 8. *Influence of the coating thickness on the imaginary part of the dielectric constant of nickel powder of the coated composite with nickel powder.*

load value, whereas when the content of nickel powder was 15%, the coating had the smallest load value.

Influence of the coating thickness on the electromagnetic properties and mechanical properties of coated composites

Influence of the coating thickness on the dielectric properties of coated composites of nickel powder

In order to study the influence of the coating thickness on the dielectric properties (the real and imaginary parts and the loss tangent value) of single-layer coated composites, single-layer coated composites of four different types of coating thickness were prepared (0.5 mm, 1 mm, 1.5 mm, 2 mm) on plain cotton fabric, the specific process parameters of which are shown in **Table 5**.

Samples of the coated fabric were prepared, and dielectric properties of the fabric were tested within a range of 10~1.5 GHz. Curves of the real and imaginary parts of the dielectric constant and the loss tangent value drawn with Origin Pro are shown in **Figures 7, 8** and **9**, respectively.

As can be seen from **Figure 7**, when the frequency was 0.01~1.5 GHz, with increasing frequencies of the electric field, values of the real part of the dielectric constant of the five samples 1 #, 2 #, 3 #, 4 # and 5 # gradually decreased, among which the decrease speed of the value of the real part of the dielectric constant of sample 3 # was the fastest, followed by samples 2 #, 1 # & 4 #; while when the frequency was 0.5~1.5 GHz, the real part of the dielectric constant of four samples continued to decrease, among which the decrease speed of the value of the real part of the dielectric constant of sample 3 # was the fastest, followed by samples 2 #, 1 # & 4 #. When the frequency was 0.01 GHz, the real part of the dielectric constant of samples 1 #, 2 #, 3 # and 4 # were all at its maximum value, which explained that when the frequency of the applied electric field was 0.01 GHz, the polarising ability of the magnetic field produced inside the wave-absorbing material with respect to the external magnetic field was the strongest.

When the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, the real part of the dielectric constant of samples 1 #, 2 #, 3 #

and 4 # decreased gradually, and the polarizsng ability of the magnetic field produced inside the wave-absorbing material with respect to the external magnetic field also decreased gradually, and when the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, the real part of the dielectric constant of 3 # was the largest, and the polarising ability with respect to electromagnetic waves was the strongest, followed by samples 2 #, 1 # & 4 #. When the frequency was 0.01~1.5 GHz, the real part of the dielectric constant of the coating with a thickness of 1.5 mm was the largest, and its polarising ability was the strongest, followed by coatings with thicknesses of 1 mm, 2 mm and 0.5 mm.

As can be seen from **Figure 8**, when the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, values of the imaginary part of the dielectric constant of four samples 1 #, 2 #, 3 # and 4 # showed an increasing trend and then a decreasing one, and the same trend in the loss ability of the magnetic field in the coating with respect to electromagnetic waves was shown. When the frequency was 0.01~0.3 GHz, the increase speed of the

Table 5. *Process parameters of different coating thicknesses.*

Number	Content of nickel powders, %	Stirring time, min	Viscosity, mPa·s	Coating thickness, mm	Speed of coating machine, cm/min	Drying oven temperature, °C	Drying time, min
1	20	40	30000	0.5	60	80	10
2	20	40	30000	1	60	80	10
3	20	40	30000	1.5	60	80	10
4	20	40	30000	2	60	80	10

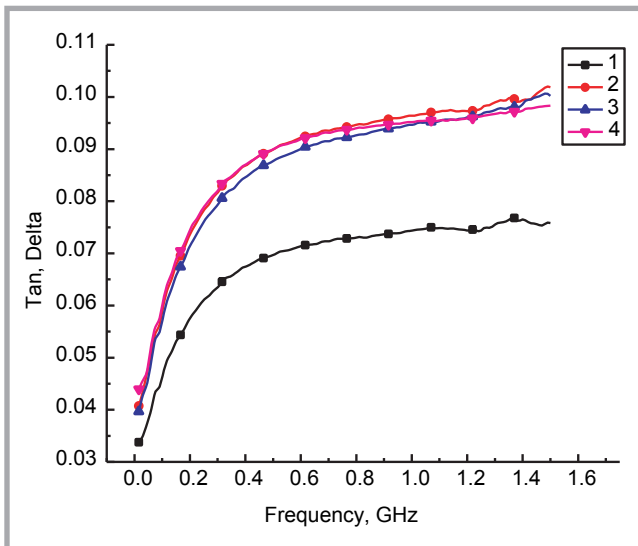**Figure 9.** *Influence of the coating thickness on the loss tangent value of nickel powder of the coated composite with nickel powder.*
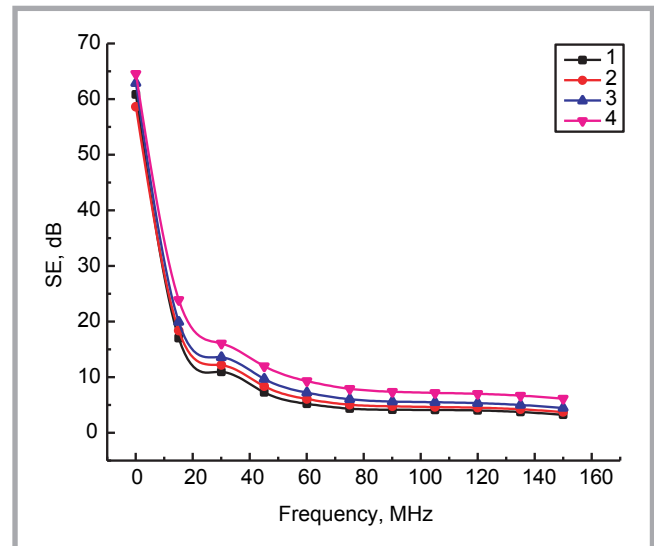

Figure 10. *Influence of the thickness of the coated fabric on shielding effectiveness.*

value of the imaginary part of the dielectric constant of sample 1 # was the fastest, followed by 4 #, 2 # and 3 #. When the frequency was 0.3~0.7 GHz, values of the imaginary part of the dielectric constant of the five samples increased slowly, and then their respective maximum was achieved. When the frequency was 0.7~1.5 GHz, there was a modest increase in the value for 1 #, 2 # and 3 #, and a modest decline for 4 #. When the frequency was 0.01 GHz, the imaginary part of the dielectric constant of each sample was at the minimum, and the loss ability with respect to electromagnetic waves was the weakest. When the frequency of the applied electric field was 0.5 GHz, the value of the imaginary part was the largest, as well as the loss ability of the magnetic field produced in the coating with respect to the applied magnetic field. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the electromagnetic field, the imaginary part of the dielectric constant of 2 # and 3 # was the largest, followed by 4 # and 1 #. Namely, when the frequency was 0.01~1.5 GHz, the imaginary part of the dielectric constant of the single-layer coated composite with a thickness of 1 mm (1.5 mm) was the largest, and the loss ability of the magnetic field produced in the coating with respect to the electromagnetic field was the strongest, followed by coating with a thickness of 2 mm and 0.5 mm. The only variable of samples 1 #, 2 #, 3 # and 4 # was the coating thickness, when the coating thickness was 0.5~2 mm, with increasing thicknesses of the coating, the im-

aginary part of the dielectric constant showed an increasing trend first and then remained constant, and the loss ability with respect to electromagnetic waves increased first and then decreased.

As can be seen from *Figure 9*, when the frequency was 0.01~0.3 GHz, the loss tangent value of sample 1 # increased the fastest, followed by 4 #, 2 # and 3 #. When the frequency was 0.3~0.7 GHz, the loss tangent value of samples 1 #, 2 #, 3 # and 4 # slowly increased. When the frequency was 0.7~1.5 GHz, with increasing frequencies of the applied electric field, the value of that of 1 #, 2 #, 3 # and 4 # all had a modest rise. When the frequency was 0.01 GHz, the loss tangent value of each sample was at the minimum, and the attenuation ability of the magnetic field produced in the coating with respect to electromagnetic waves was the weakest.

When the frequency was 0.01~1.5 GHz, along with increasing frequencies of the applied electric field, the loss tangent values of 1 #, 2 #, 3 # and 4 # all showed an increasing trend, as well as the magnetic field produced in the coating. When the frequency of the applied electric field was 1.5 GHz, the loss tangent value peaked, and the attenuation ability of the magnetic field produced in the coating was the strongest. When the frequency was 0.01~1.5 GHz, with increasing frequencies of the applied electric field, the loss tangent value of 2 # was the largest, and the attenuation ability with respect to electromagnetic waves was the strong-

est, followed by 3 # and 1 #. When the frequency was 0.01~0.8 GHz, curves of 2 # and 4 # basically overlapped each other. Namely, when the frequency was 0.01~1.5 GHz, the loss tangent value of the coating with a thickness of 1 mm (2 mm) was the largest, and the absorbing-attenuation ability was the strongest, followed by coating with a thickness of 1.5 mm and 0.5 mm. The only variable of samples 1 #, 2 #, 3 # and 4 # was the coating thickness, where with increasing coating thicknesses, the loss tangent value of the coating showed a decreasing trend first and then an increasing one, and the attenuation ability of the coating with respect to electromagnetic waves first increased and then decreased.

Influence of coating thickness on the shielding properties of single-layer coated composites

In order to study the influence of the coating thickness on the shielding properties of single-layer coated composites, single-layer coated composites of four different thicknesses of the coating were prepared (0.5 mm, 1 mm, 1.5 mm and 2 mm) on plain cotton fabric, the specific process parameters of which are shown in *Table 5*.

Samples of coated fabric were prepared, and the shielding-attenuation value was tested, in which the testing scope was 100~150 MHz. Curves of the frequency-shield attenuation value drawn with Origin Pro are shown in *Figures 10* and *11* (the amplification for *Figure 10* is within the range of 30 MHz to 60 MHz).
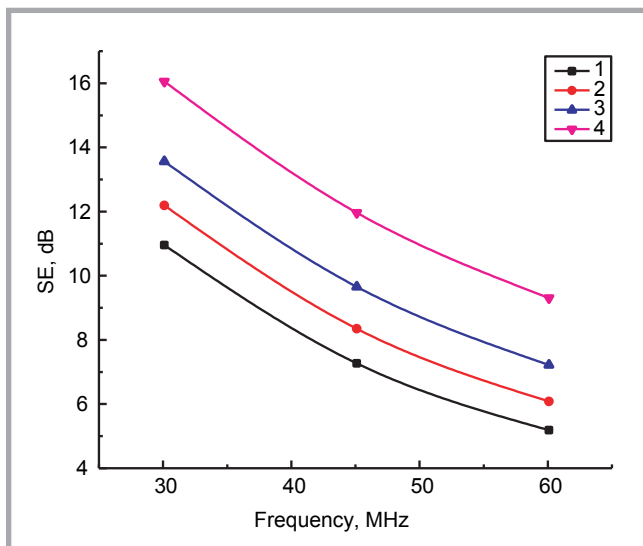
Figure 11. *Influence of the thickness of the coated fabric on shielding effectiveness.*
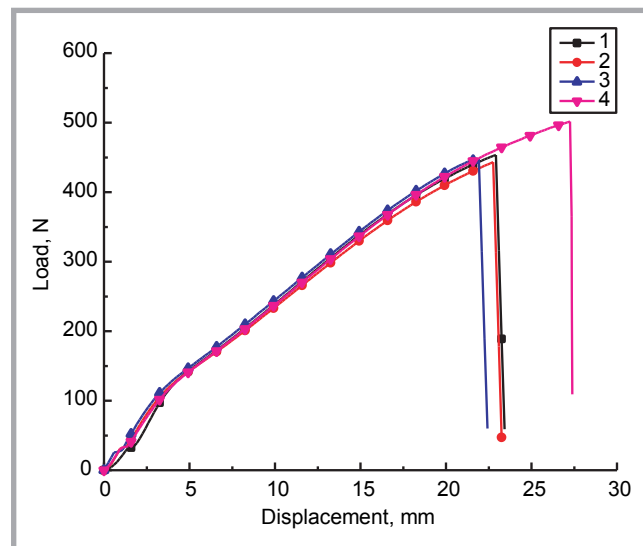

Figure 12. *Influence of the coating thickness on the tensile strength of coated composites with nickel powder.*

As can be seen from ***Figure 10***, when the frequency was 0.1~150 MHz, with increasing frequencies of the applied electric field, the shielding-attenuation value of the four samples decreased, with the size of the decrease speed being about the same. When the frequency was 60~150 MHz, the shielding-attenuation value of the four samples went on decreasing; however, the decease speed had obviously declined. When the frequency was 0.1~150 MHz, with increasing frequencies of the applied electric field, the shielding-attenuation value of 1 #, 2 #, 3 # and 4 # decreased gradually, as well as the shielding-attenuation ability with respect to electromagnetic waves. Thus, when the frequency was 0.1 MHz, the largest shielding-attenuation value was reached and the best shielding effect achieved. As can be seen from ***Figures 4-11***, when the frequency was 30~60 MHz, the shielding-attenuation value of 4 # was the largest, and the shielding-attenuation ability with respect to electromagnetic waves was the best, followed by 3 #, 2 # and 1#. When the frequency was 0.1~150 MHz, the shielding-attenuation value of the coating with a thickness of 2 mm was the largest, and its attenuation ability was the strongest,

followed by coating with a thickness of 1.5 mm, 1 mm and 0.5 mm.

Influence of the coating thickness on the mechanical properties of single-layer coated composites

In order to study the influence of the coating thickness on the mechanical properties of single-layer coated composites, single-layer coated composites of four different thicknesses of the coating were prepared (0.5 mm, 1 mm, 1.5 mm and 2 mm) on plain cotton fabric the specific process parameters of which are shown in ***Table 5***.

A test of the tensile properties using an Instron universal material testing machine was carried out, parameters of the mechanical properties of which are shown in ***Table 6***.

Samples of the coated fabric were prepared, and a displacement-load curve was drawn with Origin Pro, which is shown in ***Figure 12***. As can be seen, when the displacement was 0~5 mm (d – displacement), the displacement-load curve of 1 #, 2 #, 3 # and 4 # showed a nonlinear change; and when the displacement

was 5~30 mm, with increasing displacements, the load increased gradually, until the sample experienced fracture. When the load reached the maximum (also the maximum load displacement), the coated fabric experienced the failure, while with the increasing displacements, the load decreased gradually. When the displacement was 0~25 mm, with increasing displacements, 3 # first reached the maximum load, followed by 2 #, 1 # and 4 #. When the thickness was 1 mm, the coating had the smallest load value, while when the thickness was 2 mm, the coating had the largest load value.

◼ Conclusions

When the content of nickel powder was 0~20% and that of nickel powder relative to that of polyurethane was 20%, the real and imaginary parts of the dielectric constant of the coating were the largest, and its polarising ability and loss ability with respect to electromagnetic waves were the strongest. When the content of nickel powder relative to that of polyurethane was 15%, the loss tangent value of the coating was the largest, and its absorption and attenuation ability with respect to electromagnetic waves was the strongest.

When the coating thickness was 0.5 mm~2 mm, the real and imaginary parts of the dielectric constant of the coating with a thickness of 1 mm were the largest, and the polarising ability and loss ability with respect to electromagnetic waves were the strongest. The loss

Table 6. *Related parameters of mechanical properties of different thicknesses of the coating.*

Number	Maximum load, N	Maximum load displacement, mm	Tensile stress value of maximum load, MPa	Elasticity modulus (MPa)
1	453.28937	22.92321	9.03158	74.05085
2	443.1842	22.75668	8.86368	65.77975
3	447.80304	21.92326	8.95606	66.91876
4	501.67773	27.25653	10.03356	60.60886

tangent value and shielding-attenuation value of the coating with a thickness of 2 mm were the largest, and the absorbing-attenuation ability and shielding-attenuation ability with respect to electromagnetic waves were the strongest.

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