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Influence of fabric density on shielding effectiveness of electromagnetic shielding fabric

Abstract: *In this paper, fabric density influence on the shielding effectiveness of electromagnetic shielding fabric is studied. A series of blended shielding fabrics are tested using a waveguide tube testing method to obtain the shielding effectiveness with different density. Experimental results show that the shielding effectiveness increases with the increase of fabric density, and there are two rapid increasing regions and one stable region. Then we propose a theory that the shielding effectiveness variation is described by adjacent form of yarns. This method can provide theoretical reference for the development of the electromagnetic shielding fabric and related theoretical research.*

Streszczenie. *W artykule opisano zagadnienie wpływu zwartości tkaniny oplotu ekranu na skuteczność ekranowania elektromagnetycznego. Wysunięto została teoria, że rodzaj stosowanej przędzy ma wpływ na zmianę skuteczności ekranowania. (**Wpływ zwartości tkaniny oplotu ekranu na skuteczność ekranowania elektromagnetycznego**)*

Keywords: Electromagnetic shielding fabric, Density, Shielding effectiveness, Influence.
Słowa kluczowe: tkanina oplotu ekranu elektromagnetycznego, zwartość, skuteczność ekranowania

Introduction

Various electromagnetic radiations exist in our modern life. Many researchers have proved that the electromagnetic radiation can produce adverse reaction, and even does harm to people's health [1]. The electromagnetic radiation has been listed as pollution and must be controlled by Human Environment Conference of United Nations, and many national governments have warned people against electromagnetic radiation [2]. Therefore, related theoretical research and application about electromagnetic shielding fabric have gradually become hot, and it has great significance to prevent people from electromagnetic radiation damage.

In order to shield electromagnetic waves, electromagnetic shielding fabric is obtained by adding metals and other methods [3]. However, the relationship between the shielding effectiveness (SE) and the fabric structure (fabric weave, fabric density, fabric thickness, yarn count, blended form of yarns) has not been clearly revealed at present. Therefore, there are scanty theoretical guidance for the manufacture and the design of the electromagnetic shielding fabric. In this paper, we will focus on the density factor and study the variation between the fabric density and the SE.

Until now there is little information about the relationship and influence between the density of the blended shielding fabric and its SE. it was briefly discussed when the model of the electromagnetic shielding fabric was constructed [4], the performance of the electromagnetic shielding fabric was studied [5], the shielding performance of the fiber was tested [6][7][8]. No literature studied the influence of the SE from the viewpoint of the density change and the variation mechanism.

In this study, according to the theoretical analysis of electromagnetic wave transmission, we test the blended shielding fabrics using waveguide tube, and we obtain the SE with different fabrics and different densities. By experimental analysis, the influence mechanism of the fabric density on the SE is described from microcosmic angle, and the relationship between the density and the SE is illustrated and the density function is given.

Theoretical analysis

According to the electromagnetic theory, the shielding way of the idea metal shield can be divided into reflection, multiple reflection and absorption, and most shielding relies on reflection[9]. Therefore, the SE of the fabric is determined by:

$$（1）\quad \boldsymbol{SE} = \boldsymbol{R} + \boldsymbol{A} + \boldsymbol{B} \qquad (\boldsymbol{dB})$$

Where, $\boldsymbol{R}$ is the reflection loss, $\boldsymbol{A}$ is the absorption loss, $\boldsymbol{B}$ is the multiple reflection loss, respectively. Suppose the plane wave is vertically incident to the fabric surface, the reflection loss is calculated as [10]:

$$（2）\quad \boldsymbol{R} = 168.16 - 10\boldsymbol{Lg}\frac{\mu_r \boldsymbol{f}}{\sigma_r}$$

The absorption loss is expressed as:

$$（3）\quad \boldsymbol{A} = 15.4\boldsymbol{t}\sqrt{f\mu\sigma} = 1.31\boldsymbol{t}\sqrt{\boldsymbol{f}\mu_r\sigma_r} \quad (\boldsymbol{dB})$$

Where, $\boldsymbol{t}$ is the thickness of fabric, μ_r is the relative permeability (H/m), σ_r is the relative conductivity (S/m), $\boldsymbol{f}$ is the frequency ($\boldsymbol{H}_Z$).

Therefore, the multiple reflection loss $\boldsymbol{B}$ can follow above principle, and it can be described as:

$$（4）\quad \boldsymbol{B} = 20\boldsymbol{Lg}(1 - \boldsymbol{e}^{2t/\delta}) = 20\boldsymbol{Lg}(1 - \boldsymbol{e}^{3.54\boldsymbol{t}\sqrt{f\mu\sigma}}) \ （\boldsymbol{dB})$$

Where, $\boldsymbol{t}$ is the thickness of fabric, δ is the skin depth, μ_r is the relative permeability (H/m), σ_r is the relative conductivity (S/m), f is the frequency ($\boldsymbol{H}_z$).

From Equation (1) to Equation (4), it can be seen that the SE of the shield is determined by its relative permeability and the relative conductivity. For electromagnetic shielding fabric, the relative permeability and the conductivity is proportional to the content of the conductive fiber [9]. The fabric density determines the content of the metal fiber, and also determines the relative permeability and the relative conductivity of the fabric, so the density of the fabric determines the SE of the fabric. To explore the law between the fabric density and the SE essentially is to explore the relationship between the content per unit area of the metal fiber and the SE.

Experiments

We test different electromagnetic shielding fabrics using a waveguide tube testing system. The waveguide tube testing system consists of the analyzer, the oscilloscope, the scanning signal source, the waveguide tube, and the waveguide coaxial converter [11]. This testing system can accurately test and calculate the SE of the fabric.

We make some blended samples with stainless fibers by small experimental loom, while the yarn count in these samples is same, the density and the weave structure are different. The warp and weft density of every sample are equal for convenient analysis, the stainless fibers' content in yarns is 15%. According to their fabric texture, these samples are divided into three groups: plain, twill, and satin. There are 20 samples in each group, their densities are from 60×60 (ends/10cm) to 250×250 (ends/10cm). Three round testing samples with 30(cm) ×30(cm) are produced from each sample.

Each of samples is placed in the middle of the waveguide tube, 2400 MHZ microwave is selected as emission source, and then the receiver will receive the signal and transmit to analyzer to calculate the SE. The distant between the emission source and the sample is 1.5m. Finally, the average value of the SE of three samples is calculated.

Results

When the sample is made, it is numbered. The density of each sample with same number is equal. The density is listed in Table 1.

Table 1 Density of sample with same number (end/10cm)

Number	1	2	3	4	5
Density	60/60	70/70	80/80	90/90	100/100
Number	6	7	8	9	10
Density	110/110	120/120	130/130	140/140	150/150
Number	11	12	13	14	15
Density	160/160	170/170	180/180	190/190	200/200
Number	16	17	18	19	20
Density	210/210	220/220	230/230	240/240	250/250

Figure 1 illustrates the SE of the sample in each group is changed with the fabric density.

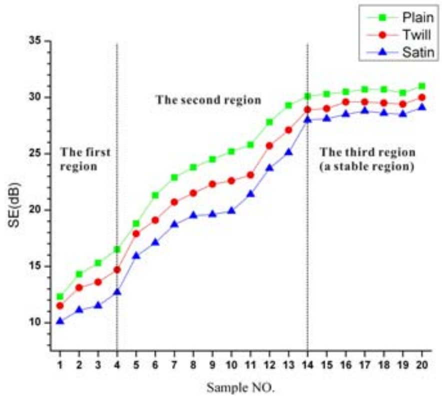

Fig.1 Variation of shielding effectiveness and density of different fabrics（2400MHz）

From Figure 1, we can notice that the fabric density is an effect factor on the SE whatever the sample textures are. The SE and the density present positive increasing relationship. The greater the density is, the closer the yarns in the fabric are, and the greater the SE is. The lower the density is, the bigger the interstices among yarns are, and the lower the SE is.

However, the increasing relationship is not a simple relationship in Figure 1. We also can observe that there are two rapid increasing regions ("the first region" and "the second region") and a stable region ("the third region"). In the rapid increasing region, the SE increases rapidly with the increase of the fabric density. In stable region, increase of the SE is not obvious with the increase of the fabric density.

In addition, as indicated in Figure 1, the SE of the plain fabric is the best, and the SE of satin fabric is the worst when the fabric density is same. Therefore, the texture of fabric is also influence the SE of the fabric.

Density influence analysis on the shielding effectiveness

After above analysis, we notice that two rapid increasing regions and one stable region in Figure 1 are determined by the state of the adjacent yarns in fabric.

Figure 2 shows the adjacent state of yarns. With the increase of the fabric density, the adjacent state of the yarns in fabric can divided into six states. Figure 2-a illustrates an interstice state of the yarn, yarns do not contact each other and there are obvious small interstices, the SE of the fabric is low in this yarn state. With the density increases, the yarn further close to each other, the hairiness of the yarns contacts each other and gradually fills the interstices. When the number of hairiness is small, a few interstices are filled, as shown in Figure 2-b. Here, the SE increases rapidly, it is the left boundary corresponding to the Figure 1. The contacting number and contacting surface of the hairiness increases rapidly in Figure 2-c, more small interstices are filled, and the SE also increases rapidly. When the density increases to some degree, the metal fiber in interstices of the yarns increases stable, as shown in Figure 2-d. Here, the SE also expresses a stable state, it starts to leave the first region corresponding to the Figure 1.

When the density further increases, yarns began to completely contact each other, as shown in Figure 2-e. The interstices are filled with the yarns, the SE increases jumpily, and it goes into the second region in Figure 1. Then the density further increases, yarns shows extruding state, the metal content per unit area increases, the SE increases rapidly too, it is in the second region corresponding to the Figure 1. When the yarn state shows as Figure 2-f, the extruding state reach to some trend. Here, even though the density increases, little change of the metal content of the yarn is, and the SE is stable, it has left from the second region and has went into the third region in Figure 1.

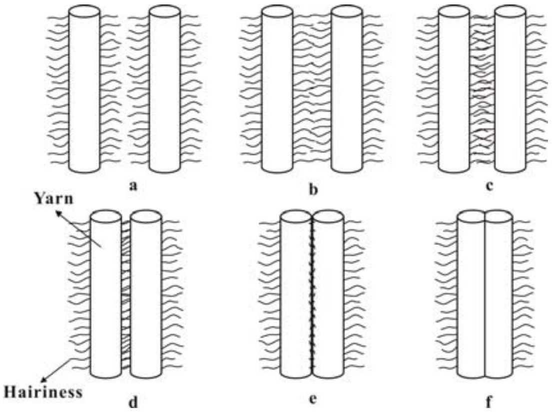

Fig.2 Adjacent states of the yarn

Left and right boundary values calculation of the first region and the second region

According to above analysis, we propose an algorithm which can calculate the boundary value of the first region and the second region by yarn count and the hairiness' thickness. This algorithm can provide a reference for the density selection in electromagnetic shielding fabric development.

Suppose the average diameter of yarn is d (mm), the thickness of hairiness is h（mm）, the weft density and warp density of left boundary in the first region are $D1_{w1}$ and $D1_{h1}$, the weft density and the warp density of right boundary in the first region are $D1_{w2}$ and $D1_{h2}$. The starting point of the left boundary and the right boundary in the first region is calculated as follows:

$$D1_{w1} = D1_{h1} = \frac{10}{d+2h} \tag{5}$$

$$D1_{w2} = D1_{h2} = \frac{10}{d+h} \tag{6}$$

Suppose the weft density and the warp density of left boundary in the second region are $D2_{w1}$ and $D2_{h1}$, the weft density and the warp density of right boundary in the first region are $D2_{w2}$ and $D2_{h2}$. The starting point of the left border and the right border in the second region is expressed as:

$$D2_{w1} = D2_{h1} = \frac{10}{d} \tag{7}$$

$$D2_{w2} = D2_{h2} = \frac{10}{d-h} \tag{8}$$

Where, the average diameter of yarn and the thickness of hairiness can be tested in experiments. There are many testing methods to select. Their values will be influenced by the yarn quality and the type of the fiber.

Stable value calculation of the SE

When the density is reach to some value, the SE no longer increases and expresses a stable value. We consider the SE value as stable value, as shown in the third region in Figure 1. This critical value is very important for production instruction. It can correctly design the density and reduce the material waste and the cost.

In Equation (8), the right boundary value of the second region, which is the starting value of the third region, is given. But this value is not the stable value of the third region. Because the yarn is extruded each other when the density is reach to this boundary value, the SE is not in a stable state. After experimental data analysis, the SE obtains a state value when the center distant between adjacent yarns reaches to $d-2h$; the SE obtains the stable value. Therefore, when the SE reaches to the stable value, the density can calculated as:

$$D3_{w1} = D3_{h1} = \frac{10}{d-2h} \tag{9}$$

Further verification

Above experiments and analysis is done on the basis that the weft density and the warp density of the sample are same, the metal content of the yarn and the yarn count are same, and the emission frequency keeps fixed.

From mechanism analysis in Figure 2, it is concluded that the SE of the fabric is related to the adjacent state of the yarn. Therefore, we can deduce that the change trend of the SE is consistent with that of the SE in Figure 1 when the warp density and the weft density are different. The left and right boundary value of the weft density and the warp density of each region can still be calculated by Equation (5) to Equation (8).

To verify above inference, we made different fabrics with different weft density and warp density to test their SE. we find that the change law is consistent with that of Figure 2. When the warp density and the weft density are different, the interstice form among yarns is not near a square. It will produce a phenomenon that fabric shielding against electromagnetic wave is uneven. Especially, when the electromagnetic wave is changed along a polarization direction, the difference of the SE is big. This phenomenon is verified by the electromagnetic theory and experiments [12]. Therefore, to avoid influencing of the SE by the polarization direction, the weft density and the warp density of the fabric and the yarn count keep consistent when we design electromagnetic shielding fabric.

Conclusions

1) There is a positive correlation between the SE and the density of the electromagnetic shielding fabric, and there are two rapid increasing regions and a stable region. In the rapid increasing region, the SE increases with the increase of the density. In the stable region, the SE did not increase obviously with the increase of the density

2) The SE essence of the electromagnetic shielding fabric is determined by the adjacent state of the yarn. The adjacent state is divided into six classifications: completely non-contact of the hairiness, initial contact of the hairiness, partial contact of the hairiness, completely contact of the hairiness, yarns adjacency and yarn extrusion. These different states determine the change trend of the SE.

3) The density value responding the left and the right boundary of the first region and the second region, and the stable value of the stable region are calculated by the diameter of the yarn and the thickness of the yarn hairiness. This calculation method can provide valuable reference for the electromagnetic shielding fabric design, and provide method to select the best density, reduce the cost and improve the SE of the electromagnetic shielding fabric.

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