Preparation Technique and EMI Shielding Evaluation of Flexible Conductive Composite Fabrics Made by Single and Double Wrapped Yarns

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ABSTRACT

Electronics products and communication equipment release electromagnetic (EM) waves in service. EM waves affect biological health and precision instrument accuracy. This study purposes to fabricate flexible conductive composite fabric which is made of complex yarn using metal (stainless steel, copper) fibers and PET filaments. Complex yarn is formed by a rotor twisting machine, at varying values of wrapped number (6.5-16 turns/cm) and lamination number (single-layer, double-layer). Results show that when the complex yarn was wrapped 16 turns/ cm, volume resistivity reached 2.9 Ohm-cm and conductivity reaches 0.408 S/cm. Four layers of conductive composite plied with 0°/90°/ 0°/ 90° resulted in the optimum electromagnetic shielding effectiveness, up to 47.7 dB.

Keywords: Composite fabric; conductive yarn; stainless steel; copper; electromagnetic shielding effectiveness.

INTRODUCTION

Electromagnetic (EM) waves jeopardize biological health, shorten product life, can affect the accuracy of precise instrument, and may cause safety issues. Due to increasing sensitivity of electronics, electromagnetic interference (EMI) becomes more and more of an issue.

One study reported that when exposed to a portable phone, mouse spermatoblasts had a higher probability of cell death and cell abnormalities, showing that portable phones could possibly have a negative effect on male reproductive function. [1]. In addition, other studies indicated that different frequencies of EM waves had different influences on different cells, and exposure duration and EM intensity both affected biological cells [2, 3].

Extremely low-frequency (ELF) EM waves led to cell death [4], and some studies proposed that ELF waves influenced deoxyribonucleic acid (DNA) repair mechanisms [5, 6]. Intermediate frequency (IF) waves effectively blocked cell growth [7] therefore, EMI shielding has become a critical research subject.

EMI shielding protective clothing is made by insertion of conductive materials such as metal fibers and carbon fibers into the fabrics, or by applying coating conductive layers such as polypyrrole on the surface of fabric to enhance the EMI shielding effect of composite fabrics [8, 9].

EMI shielding fabric can be used to protect the human body from EM radiation from mobile phones. By changing the fabric structure, metal coverage rate and metal content, different shielding levels of protective clothing can be produced. Ortlek et al [10] fabricated polyethylene terephthalate (PET) wrapped stainless steel (SS) complex yarn using a hollow spindle machine, and found that plain, twill and rib fabrics made from such yarns possessed different EMI shielding effects. Some studies focused on the influence of knitted structure and copper wires on EMI shielding properties, and found that use of double copper filament (Cu) exhibited improved EMSE [11-12]. Su and Chern [13] prepared wrap yarn, shell/core yarn, and plied twisting yarn and characterized the EMI shielding effects. Cheng et al used copper wire, stainless steel wire, carbon fiber and glass fiber as EMSE and ESD materials in the form of knitted fabrics, and hot-treated them into fabric-reinforced polymer composites for electromagnetic shielding [14–17].

This study compounds SS filament and Cu filament with PET filaments to fabricate high-level EMI shielding conductive composite fabrics. The fabrics were made from complex yarns in the laboratory using a rotor twisting machine and an electronic packaging machine. The effect of wrapped number on tensile tenacity, elongation and electrical conductivity as well as EM SE was determined. The influence of lamination angle and number on EM SE was also investigated.

EXPERIMENTAL

Materials

SS filaments (King Metal Fiber Technology Company, Taiwan) had diameters of 0.04 mm, 0.05 mm, and 0.08 mm. Cu filament offered by Floodlit Enterprise Company, Taiwan, had a diameter of 0.08 mm. A 75 D/72 f PET filament provided by Yi Jinn Industrial Co. Ltd, Taiwan with a diameter of 0.009 mm was used in the wrapped yarn. PET 1000 denier yarns supplied by Yi Jinn Industrial Co. Ltd, Taiwan were used to weaving the test fabrics.

Fabrication of the Yarns and Fabrics

Preparation of Wrapping Yarn

Two types of SS/PET and Cu/PET wrapping yarns were first fabricated into conductive complex yarns using a rotor twister machine. SS/PET wrapping yarn used 0.04 mm-diameter SS filament as the core and the 75 D PET filament as the sheath. Cu/PET yarn used 0.08mm-diameter as the core and 75 denier PET filaments as the sheath. The machine used to produce the metal/PET wrap yarns was designed, built and patented by Prof. Lin Jia-Horng. The schematic is shown in *Figure 1*. SS or Cu filament (core yarn) going through a thread eye (A) and the center of a rotor twister (C) was wrapped by the PET filament (wrap yarn) using the centrifugal force from a high-rolling rotor twister and coiling from a winding roller (F). The structure of metal/PET wrap yarn is shown in *Figure 2*. The wrap number of metal/PET yarns is 4 turns/cm.

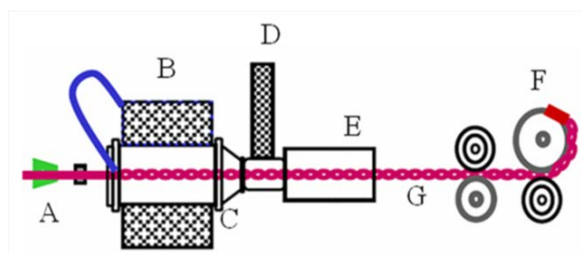

FIGURE 1. The configuration of the rotor twisting machine. A: thread eyes; B: PET yarn; C: a rotor twister; D: tangent belt driven by a motor; E: bearing; F: winding roller; and G: SS/PET complex yarn.

<u>Preparation of Single and Double Wrapped Complex Yarns</u>

SS/PET complex yarn or Cu/PET complex yarn used as the wrapping material, as well as SS filament or Cu filament used as core material were converted into conductive complex yarn using an electronic packaging machine (see *Figure 3*). SS filament is fed from the input through hollow spindle (D-a) and hollow spindle (D-b) and the conductive complex yarn is collected on the winding roller (K). When motor is started, yarn on the hollow spindle covers the core material along the direction of rotation, which also forms the twist direction as seen in *Figure 3*. Metal/PET wrap yarn is loaded on hollow spindles (D-a) and (D-b) and wrapped around the SS filament to form Metal/PET complex yarn. Two types of complex yarns were made-single and double wrapped. Single wrapped complex yarns were made by wrapping the wrap yarn made above around a Cu or SS filament. Double wrapped complex yarns were made by wrapping an inner wrap yarn around a filament and wrapping a second wrap in the opposite twist around the filament and inner wrap yarn. Yarns with 6.5, 8, 10, 12, 14 and 16 wraps per cm were produced.

Preparation of Conductive Composite Fabrics

Single and double wrapped complex yarns (*Table I*) as weft yarn and 1000D PET filaments as warp yarn were woven into different kinds of conductive composite fabrics using a rapier loom. These woven fabrics have a plain structure.

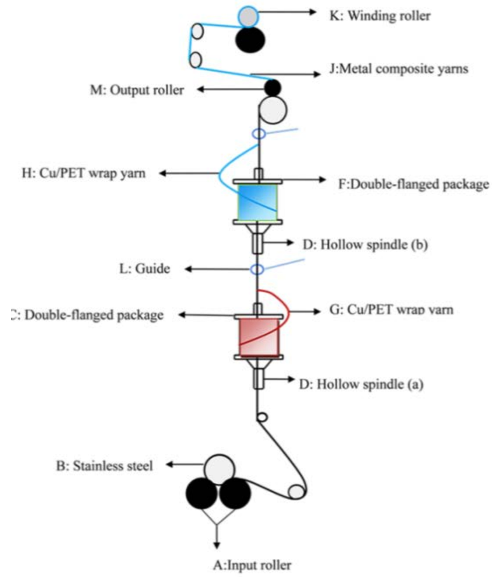

FIGURE 3. Spinning diagram of single and double wrapped complex yarn.

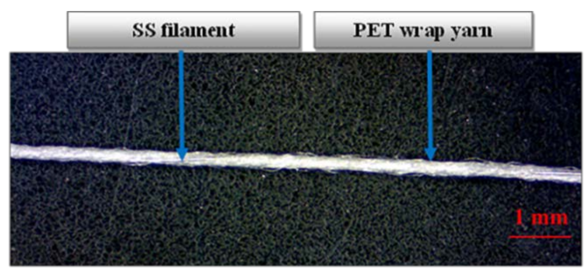

FIGURE 2. Stereomicroscopic observation of SS/PET wrapping yarn. (SS diameter: 0.04 mm, wrap number: 4 turns/ cm, rotor twisting speed: 8000 rpm).

TABLE I. Name codes of single and double wrapped complex yarns.

Code	Lamination number	Wrapped number (turns/cm)	Rotor speed (rpm)	Twist direction (inner)	Twist direction (outer)	Core Material	Inner wrap yarn	Outer wrap yarn
s-6.5	single	6.5	8000	Z	-	SS	SS/PET	-
s-8	single	8	8000	Z	-	SS	SS/PET	-
s-10	single	10	8000	Z	-	SS	SS/PET	-
s-12	single	12	8000	Z	-	SS	SS/PET	-
s-14	single	14	8000	Z	-	SS	SS/PET	-
s-16	single	16	8000	Z	-	SS	SS/PET	-
d-6.5	double	6.5	8000	Z	S	SS	SS/PET	SS/PET
d-8	double	8	8000	Z	S	SS	SS/PET	SS/PET
d-10	double	10	8000	Z	S	SS	SS/PET	SS/PET
d-12	double	12	8000	Z	S	SS	SS/PET	SS/PET
d-14	double	14	8000	Z	S	SS	SS/PET	SS/PET
d-16	double	16	8000	Z	S	SS	SS/PET	SS/PET
cucu005ss	double	16	8000	Z	S	Cu	Cu/PET	005SS/PET
cucu008ss	double	16	8000	Z	S	Cu	Cu/PET	008SS/PET
sscucu	double	16	8000	Z	S	SS	Cu/PET	Cu/PET

Name Codes of the Samples

The name codes of single and double wrapped complex yarns are displayed in *Table I*. For s-6.5, s stands for single wrapped complex yarn, and 6.5 stands for wrap number; the wrapped direction is Z-twist. For d-6.5, d stands for double wrapped complex yarn, and 6.5 stands for wrap number; inner and outer yarn is in a opposite twist, Z-twist and S-twist respectively. Cucu005ss indicates a double wrapped complex yarn made by first wrapping the Cu/PET inner yarn around the 0.05-mm diameter Cu filament and then wrapping a second 005SS/PET wrap yarn around the filament and wrap yarn. Cucu008ss represents double wrapped complex yarn wrapped around a second 008SS/PET wrap yarn. Sscucu indicates a double wrapped complex yarn made by first wrapping Cu/PET inner yarn around 0.08 mm-diameter SS filament and then a wrapping a second Cu/PET yarn around the inner yarn and filament.

The name codes and fabric parameter of composite fabrics are displayed in *Table II*. Composite fabrics used 1000D PET filaments as the warp yarns and used the single and double wrapped complex yarns as the weft yarn.

TABLE II. Name codes of conductive woven fabrics.

Name code	Warp yarn	Weft yarn	Density (ends*picks)	Area weight (g/m^2)	Thickness (mm)	Cover factor
8	1000D PET filament	d-8	20*36	378	0.55	18.7
10		d-10	20*36	387	0.55	18.9
12		d-12	20*36	394	0.55	19.2
14		d-14	20*36	400	0.55	19.4
16		d-16	20*36	413	0.55	19.8
cucu005ss		cucu005ss	20*36	454	0.7	20.2
cucu008ss		cucu008ss	20*36	628	0.75	21.6
sscucu		sscucu	20*36	549	0.75	20.5

Test Methods

Yarn Strength and Elongation

According to CNS-11263, the maximum breaking strength and breaking elongation of wrap yarns were measured using a Yarn Strength Tester (Textechno statimat, Germany). The distance between the fixtures was 250 mm. The tensile speed was 300 mm/min, and the preload was 0.057 g/denier. Twenty samples were measured and mean values calculated.

Fabric Conductivity Measurements

Conductivity of woven fabrics was measured using a four-point probe tester. The sample size was 90 mm×90 mm. The sheet resistance *(R_s)*, volume resistance (ρ_v) and conductivity (σ_s) of fabrics are respectively expressed as:

$$R_s(\Omega/cm^2) = R \cdot C_{F1} \cdot C_{F2} \quad (1)$$

Where R is specific resistance, C_{F1} is a correction parameter for fabric thickness and C_{F2} is a correction parameter for fabric area. Then

$$\rho_v(\Omega \cdot cm) = R_s \cdot t \quad (2)$$

where ρ_v is *volume resistance*, R_S *is sheet resistance*, t *is sample thickness,* and finally

$$\sigma_s\,(\mathrm{S/cm}) = 1/\rho_v \quad (3)$$

where σ_s *is* conductivity, ρ_v is volume resistance.

EMI Shielding Test

Electromagnetic shielding effectiveness was performed according to ASTM 4935-2010 using specified standard samples placed in a shielding effectiveness test sample holder (EM-2107A). The scan frequency range varied from 300k to 3G Hz, and the electromagnetic field was far-field plane-wave. EMI shielding effectiveness of a reference specimen is marked as $SE_{Ref;}$ that of the load specimen is marked as SE_{Load} (see *Figure 4*). The determined EMI shielding effectiveness of the test sample is SE_{Load} subtracted from SE_{Ref}.

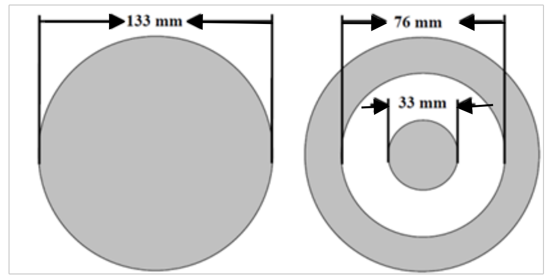

FIGURE 4. Sample holder dimensions for EMI testing [17].

RESULTS AND DISCUSSION

Maximum Tensile Strength and Elongation of Conductive Complex Yarn

Effects of Wrapped and Laminations Number on Tensile Strength of Conductive Complex Yarns

Figure 5 shows the influence of the wrapped and lamination numbers on the tensile strength of complex yarns. When the wrap number increases from 6.5 to 8 turns/ cm, the tensile strength rises accordingly. Increasing the wrapped number increases the cohesion force increase between the inner and outer yarns, resulting in higher tensile strength. When the wrapped number exceeds 8 turns/cm, the outer wrap yarn generates high-density entanglements and cannot produce effective stress transmission. The beam is then subjected to the entire stress resulting in stress concentration and faster failure [18]. The inner wrap yarn and the second wrap yarn in the double-wrapped complex is twisted in the opposite direction- Z-twist and S-twist. The result is higher strength, decreased leakage of metal filaments and more stable twist compared to single wrapped complex yarn.

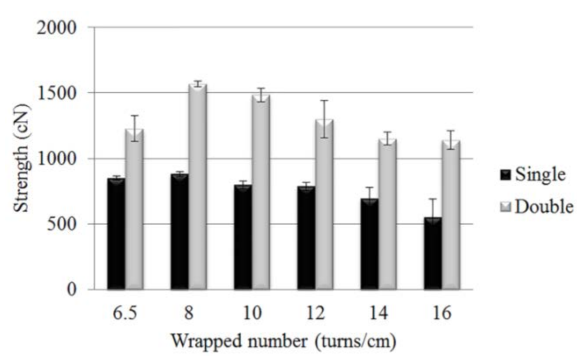

FIGURE 5. Effects of wrapped number and lamination number on tensile strengths of single and double wrapped complex yarns.

Effects of Wrapped and Lamination Numbers on Tensile Elongation of Conductive Complex Yarn

Figure 6 shows that the elongation of double wrapped complex yarn steadily increases with the number of wraps. The elongation of single wrapped complex yarn increases slightly from 6.5 to 8 turns/cm, and then decreases from 8 to 16 turns/cm for single-wrapped complex yarns. The elongation change between 8 turns/cm and 16 turns/cm is significant (**p<0.01). The similarity in the trends of tenacity and elongation of the single wrapped complex yarn suggest that there is a work-to-break mechanism involved. For double wrapped complex yarn, elongation increases significantly and then remains constant between 6.5 and 16 turns/cm. Double complex yarn wrapped at 6.5 turns/cm shows significantly different elongation from that wrapped at other wrapped numbers (8, 10, 14, 16 turns/cm), but the elongation among 8, 10, 14, 16 turns/cm is insignificant (p>0.05) due to wrap yarn slippages in the longitudinal direction- the applied force on the complex yarns cannot be dispersed, resulting in fracture points [19].

Overall, the single and double wrapped complex yarns display different elongational behaviors. This is because for double wrapped conductive yarn, the outer-layer PET wrap yarn produces better binding force to the inner-layer yarn. Hence, when the conductive complex yarn is subjected to tensile force, increased interactions between the inner and outer layers occur, dispersing the external force [20]. The breaking elongation of double wrapped complex yarn is higher than that of single wrapped yarn at the same wrapped number because the double wrapped yarn contains more outer wrap yarn, thus higher deformation energy is required to produce tensile fracture [20].

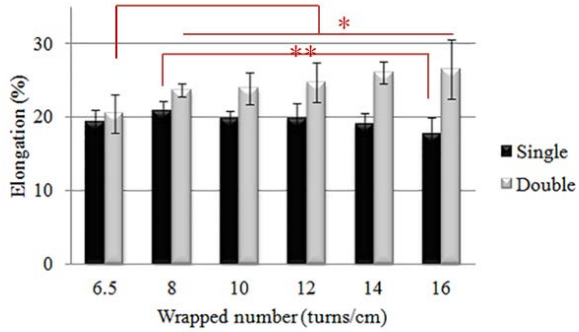

FIGURE 6. Effects of wrapped number and lamination number on tensile elongation of single and double wrapped complex yarns.

<u>Conductivity of Woven Fabrics</u>

Effect of Wrapped Number on Woven Fabric Conductivity

Figure 7 shows the relationship between wrapped number on sheet resistance, volume resistance and conductivity of composite fabrics. The constitution of complex yarn is an SS filament is core wrapped by SS/PET complex yarn. As shown in *Figure 7(a)*, sheet resistance of conductive fabric decreases with an increase in the wrapped number of the complex yarn. An increase in the amount of SS/PET conductive yarn results in an increase in the amount of SS filament per unit length of outer layer. As the wrapped number increases from 8 turns/cm to 14 turns/cm, the sheet resistance decreases from 1.38×10^{7} to 173 Ω/cm^2, about five orders of magnitude. A similar tendency is displayed in *Figure 6(b).* As wrap level increases from 8 turns/ cm to 14 turns/ cm, the volume resistance sharply decreases from 5.93×10^{5} Ω-cm to 1.04 Ω-cm, about four orders of magnitude. $J=\sigma E$, where J is current density ($1/R$); σ is conductivity and R is resistance. Therefore, conductivity quickly rises from 1.53 $\times10^{-6}$ to 9.83 $\times10^{-2}$ as wrapped number increases from 8 turns/cm to 14 turns/cm in *Figure 7(c).* Through the above evaluation, it is found that when wrapped at 14 and 16 turns/ cm, the sheet resistance is 173 Ω/cm^2 and 48.4 Ω/cm^2 respectively, which both satisfy the EMI shielding requirements. The conductive properties affect EMI shielding effectiveness. When the complex yarn is wrapped at 16 turns/ cm, the conductivity of composite fabrics reaches 0.127 S/cm. Fabrics used in subsequent studies will consist of yarns wrapped at 16 turns/cm in order to maximize conductivity.

EMI Shielding Property of Conductive Woven Fabric

Effects of Wrapped Number of Weft Yarn, Number of Layers, and Plied Orientation on EMI Shielding Effectiveness (SE)

Figure 8 shows effect of number of layers and plied orientation on EMI SE of conductive fabrics. *Figure 8(a)* shows that when the conductive fabrics are plied with the same orientation, the SE difference between the layers is less than 5dB. This is likely to due to the same orientation of metal fibers and the consistent conductive networks. This results in fewer circuits per unit area and less effective shielding of electromagnetic waves. Therefore, when the plied orientation between fabrics was changed, EM SE obviously increased.

Yarns containing Cu will provide better EMI shielding because Cu is 45 times more conductive than SS. High-frequency EM waves penetrate into the thin conductive layer, and transmission thickness decreases as the incident frequency of EM waves increase. Therefore, increased conductive properties tend to enhance the EMI SE of the shield.

Figures 9-14 show the effects of number of layers (2-6 layers), weft material (cucu005ss, cucu008ss, sscucu) and plied orientation (0°/0°/0°/0°/0°/0°,0°/45°/90°/-45°/0°/45° and 0°/90°/0°/90°/0°/90°) on EMI shielding effectiveness of composite fabrics at an incident frequency of 300 k-3GHz. EMI SE improves as number of layers increases. This is because a change in plied orientation results in a denser conductive network and more circuits per unit area than a change in the number of layer change.

For conductive fabrics plied from the same layer and weft material (cucu008ss), *Figure 11* shows that plying at 0°/45°/90°/-45°/0°/45°and 0°/90°/0°/90°/0°/90° results in higher EMI SE than 0°/0°/0°/0°/0°/0°, with levels between 20~40 dB. At 1800 MHz, four layers of conductive fabrics plied at 0°/45°/90°/-45°/0°/45° and 0°/90°/0°/90°/0°/90° have better EMI SE- the value reaches 47.7 dB and 35.5 dB, which results in shielding of 99.9983% and 99.9972% of EM waves, respectively. Therefore, increasing the number of layers and changing fabric orientation can promote multi-reflection of EM waves in the shield and thus achieve attenuating EM wave intensity. When the frequency exceeds 2000 MHz, the incident waves become short enough to easily penetrate through the slit on the shield. This results in leaky wave phenomenon and decreases EMI SE [21-23].

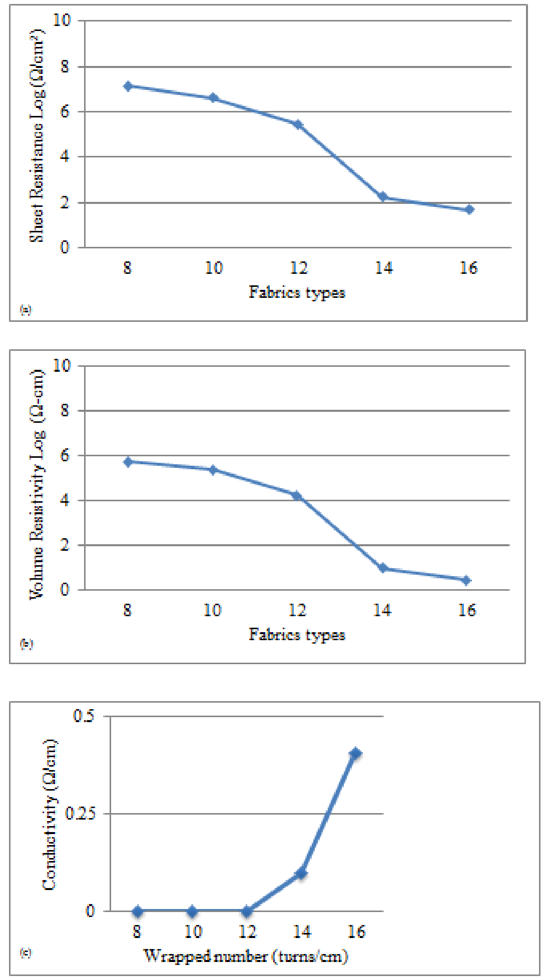

FIGURE 7. Effect of wrapped number on surface resistance (a), volume resistance (b) and conductivity (c) of composite fabrics.

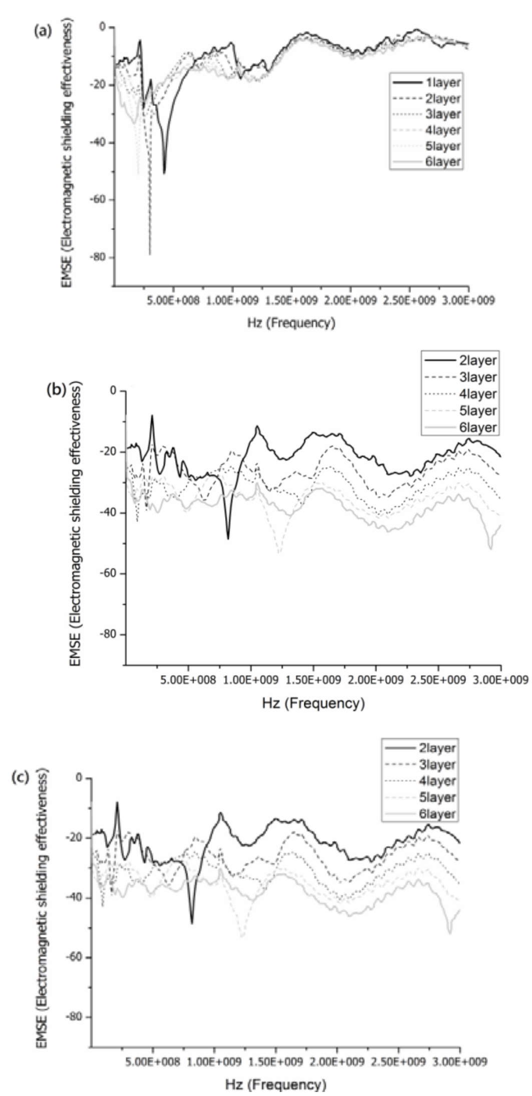

FIGURE 8. Effect of number of layers on EMSE of composite fabrics plied with 0°, 45°, and 90° orientations (wrapped number: 16 turns/cm).

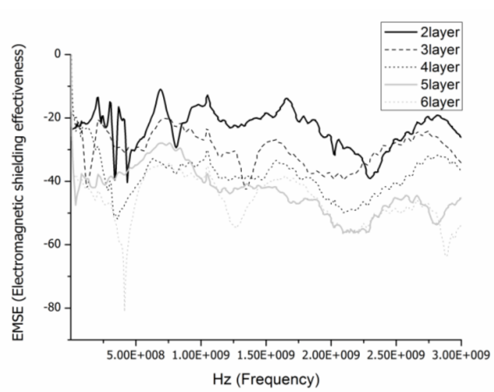

FIGURE 9. Effect of number of layers on EMSE of composite fabrics plied with 0°/45°/90°/-45°/0°/45°(weft yarn: cucu005ss).

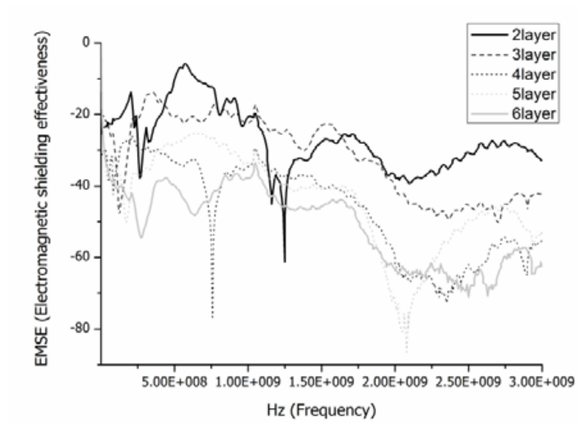

FIGURE 10. Effect of number of layers (2~6 layers) on EMSE of composite fabrics plied with 0°/ 90°/ 0°/ 90°/ 0°/ 90° (weft yarn: cucu005ss).

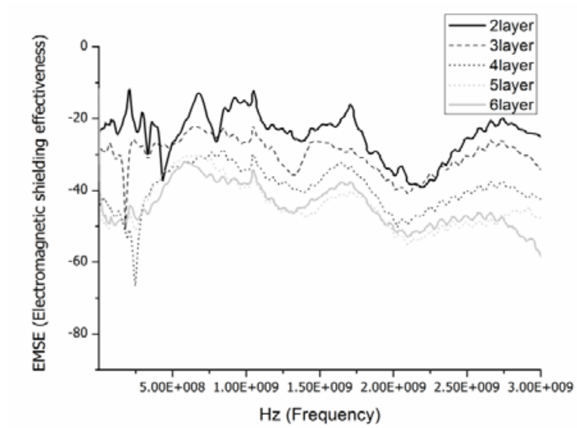

FIGURE 11. Effect of number of layers (2~6 layers) on EMSE of composite fabrics plied with 0°/ 45°/ 90°/ -45°/ 0°/ 45° (weft yarn: cucu008ss).

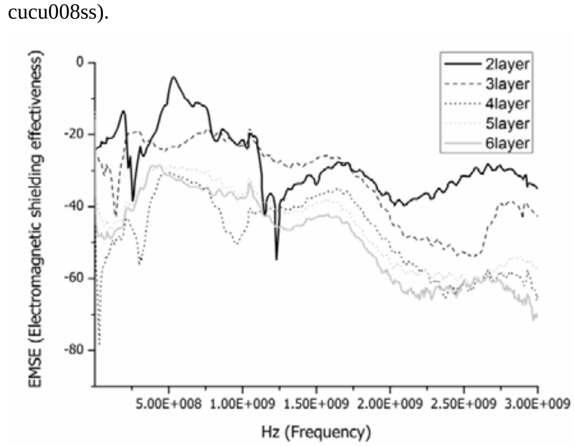

FIGURE 12. Effect of number of layers (2~6 layers) on EMSE of composite fabrics plied with 0°/ 90°/ 0°/ 90°/ 0°/ 90°(weft yarn: cucu008ss).

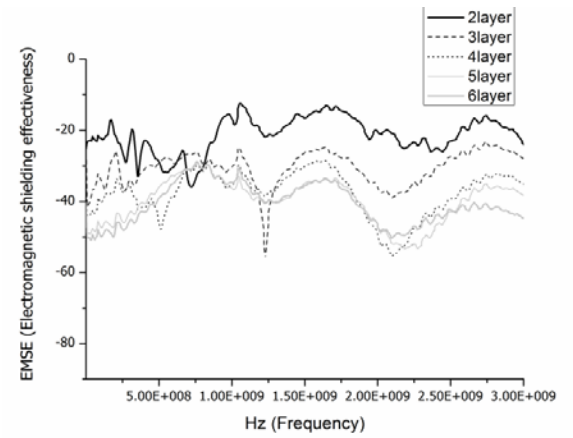

FIGURE 13. Effect of number of layers (2~6 layers) on EMSE of composite fabrics plied with 0°/ 45°/ 90°/ -45°/ 0°/ 45° (weft yarn: sscucu).

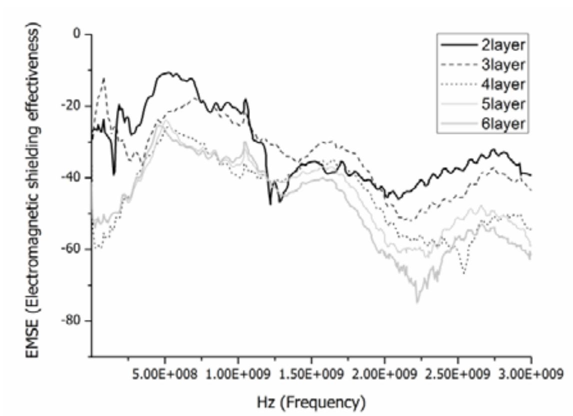

FIGURE 14. Effect of number of layers (2~6 layers) on EMSE of composite fabrics plied with 0°/ 90°/ 0°/ 90°/ 0°/ 90° (weft yarn: sscucu).

CONCLUSION

This study successfully employs SS, Cu and PET filaments to fabricate different complex yarns with varying wrapped number (6.5-16 turns/cm) and lamination number (single, double) using a rotor twisting machine and an electronic packaging machine. Yarns were woven into flexible composite fabrics using a rapier loom. Single wrapped complex yarn with 8 turns/cm has the highest tensile strength, reaching 881.5 cN/dtex, and double wrapped complex yarn reaches 1569.3 cN/dtex. Double wrapped complex yarn with 16 turns/cm has the maximum tensile elongation, 26.48%. As wrapped number increases from 8 turns/cm to 14 turns/cm, volume resistance of conductive fabrics rapidly decreases from 5.93×10^5 to 10.4 Ω-cm, about four orders of magnitude. With the same layers and the same weft yarn (cucu008ss), EMI shielding effectiveness of composite fabrics plied with 0°/ 45°/ 90°/ -45°/ 0°/ 45° is higher than that of plied with 0°/ 0°/ 0°/ 0°/ 0°/ 0° by 20~40 dB. These flexible EMI shielding materials will be useful for protection of precision instruments from EM waves.

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