Indian Journal of Fibre & Textile Research
Vol. 34, June 2009, pp. 149-154

Electromagnetic shielding effectiveness of copper core yarn knitted fabrics

R Perumalraj [a]
Department of Textile Technology, Bannari Amman Institute of Technology, Sathyamangalam 638 401, India
and
B S Dasaradan
Department of Textile Technology, P.S.G. College of Technology, Peelamedu, Coimbatore 641 004, India

Received 30 July 2008; accepted 25 September 2008

A study on electromagnetic shielding effectiveness of copper core yarn knitted fabrics through Taguchi design and ANOVA has been reported. The copper is selected as the conductive filler to produce copper yarns for making knitted fabric. The electromagnetic shielding effectiveness of these knitted fabrics has been measured in the frequency range 20-18000 MHz using network analyzer equipment. It is observed that with an increase in tightness factors, wale density and course density, the shielding effectiveness increases. The interlock knitted fabric has better electromagnetic shielding effectiveness than rib and plain knitted fabrics. With an increase in copper wire diameter, a decrease in shielding effectiveness is observed.

Keywords: Conductive filler, Copper yarn knitted fabrics, Electromagnetic inference, Electromagnetic wave, Network analyzer

1 Introduction

During the last decade, concerns have increasingly grown on electromagnetic interference (EMI) and effect of electromagnetic wave radiation from electronic and telecommunication devices on the human body[1]. Human tissues may be accidentally or intentionally exposed to electromagnetic sources such as radar, microwave oven and industrial microwave equipment. The effect of electromagnetic wave exposure on the human body is still unclear. In the case of industrial applications, electromagnetic shielding materials are used to exclude the unwanted electromagnetic radiation or signals, for example to carry out sensitive electrical measurements or to prevent malfunctioning of equipment's confidential data from being interrogate, TEMPEST protection is used. It is also used to provide protection against the electromagnetic pulse, which can disrupt neighboring equipment such as computers. Electromagnetic shielding provides protection by reducing signals to levels at which they no longer affect equipment or can no longer be received. This is achieved by reflecting and absorbing the radiation. Polymeric composites are extensively used as passive and active elements in some electrical circuit components in different technological applications[2,3] due to their light weight, easy processibility, flexibility, corrosion resistance and cost-effectiveness. But elastomers and plastics contain very low concentrations of free charge carriers. They are electrically non-conductive and transparent to electromagnetic radiation. To provide conductivity and shielding from EMI, incorporation of fillers of high intrinsic conductivity such as particulate carbon blacks, carbon and graphite fibres, or metal powder to the polymer matrix is required[4,5]. The amount of electrically conductive filler required to impart high electrical conductivity to an insulating polymer can be dramatically decreased by the selective localization of the filler in one phase, or best at the interface of a continuous two-phase polymer blend[6-11]. Unfortunately, most polymer composites used for household electrical and electronic devices are electrically insulating and transparent to electromagnetic radiation and electrostatic discharge (ESD). The potential health hazards (e.g. cancer) associated with exposure to electromagnetic fields[12-17] are also the matter of concern. To shield and limit against EMI and ESD, conductive polymer composites started replacing coated materials for various shielding applications in the electrical and

[a]To whom all the correspondence should be addressed.
E-mail: raj134722002@yahoo.com

electronic industries, especially for electronic household materials. This trend has been driven mainly because of the better characteristics of these polymers in terms of ESD, shielding from EMI, thermal expansion, density, and chemical (corrosion and oxidation resistance) properties[18-22]. However, conductive polymers have rigid characteristics owing to their chemical conformation of benzene rings, making their formation difficult. A few studies have reported conductive knitted fabrics reinforced composites as electromagnetic shielding effectiveness (EMSE) and ESD materials. Previously, Cheng *et al.*[23-26] fabricated some knitted fabric reinforced polypropylene composites for use as EMSE and ESD materials, and indicated that the knitted fabric reinforced polymer composites are suitable for making complex shaped components and application in electromagnetic shielding. In this work, the electromagnetic shielding effectiveness of the conductive knitted fabrics made of copper filament with varying structure, tightness factor, thickness and diameter of copper wire has been studied. The aim of this study is to develop conductive knitted fabric with desirable EMSE and ESD properties. Copper has been selected as the shielding material mainly because of its superior electrical properties compared to other metals. Moreover, copper exhibits high absorption and low reflection to electromagnetic energy. The absorption loss is defined as the product of conductivity and permeability. It has been reported[27] that the materials with high absorption loss and low reflection loss are highly effective in shielding the electromagnetic energy. Copper is also less expensive as compared to other materials. Hence, copper has been chosen as the conductive filament[28]. The desired level of the EMSE for usage in high end applications such as in military applications, electronic enclosures, and others is around 50-70 dB. The development of fabrics with such shielding effectiveness would be a handy tool for safeguarding electronic appliances from EMI.

2 Materials and Methods

Copper wire with diameter 0.1, 0.11 and 0.12 mm was used as conductive filler for producing copper core yarn. Cotton fibre was used as sheath material. Different copper core yarns were produced using ring spinning machine with core attachment. From the produced copper core yarn, different types of plain, rib and interlock knitted fabrics were produced (Table 1).

2.1 Experimental Design

Taguchi method was applied to identify the optimum level of fabric parameters for electromagnetic shielding effectiveness performance characteristic individually. Taguchi method replicates each experiment with the aid of an outer array that deliberately includes the sources of variation that a product would come across while in service. Such a design is called a minimum sensitivity design or a robust design. The robust design method is called Taguchi method. To achieve the optimum design factor setting, Taguchi advocated a combination of two stage process. First step is related to the selection of robustness seeking factors and the second step is related to the selection of adjustment factors to achieve the desired target performance. Various stages in the experimental design have been dealt by many researchers in the past. In other experimental designs, uncontrollable factors are kept under observation during experimentation, whereas Taguchi methods include those factors in the experimentation to make the design a robust one in the form of signal-to-noise ratios (S/N). In robust design, one minimizes sensitivity to noise by seeking combinations of design parameter settings. The most appropriate S/N ratio can be selected depending upon the properties of interest (Table 2) for both scaling factors and adjusting factors. The experiments using the controlled and uncontrolled variables at different levels (Table 1) were carried out randomly to avoid the systematic errors. The selection of appropriate orthogonal array (OA) is a critical step

Table 1—Controlled and uncontrolled variables

Factor	Notation	Controlled variable			Uncontrolled variable	
		Level 1	Level 2	Level 3	Noise level 1	Noise level 2
Copper wire diameter, mm	A	0.1	0.11	0.12	-	-
Knitted fabric structure	B	Plain	Rib	Interlock	-	-
Tightness factor	C	12.99	13.13	15.22	-	-
Thickness, mm	D	0.79	0.85	0.90	-	-
Frequency, MHz	E	-	-	-	N1(High)	N2 (Low)
RH %	F	-	-	-	N3 (High)	N4 (Low)

in Taguchi's experimental design. The OA selected should satisfy the following criterion:

Degrees of freedom (DOF) of OA $\geq$ Total DOF required

Therefore, L_9 Taguchi orthogonal array and 3 levels were selected to assign various columns. The experiments were conducted according to the trial conditions specified in L_9 OA. A total of 36 experiments (three repetitions at each trial condition) was conducted.

Using Taguchi analysis and analysis of variance (ANOVA), the optimal performance parameters were determined and the optimal values were predicted. The average values of performance characteristics at each level and against each parameter were calculated and are given in Table 3.

2.2 Electromagnetic Shielding Effectiveness Test

The EMSE of the conductive fabric was calculated by following ASTM D4935-99 test methods. Shielding effectiveness (SE) of EM enclosures is well defined and can be easily understood. It is the ratio of the signal received from a transmitter without the shield to the signal received with the shield; or in terms of the insertion loss when a shield is placed between the transmitting antenna and the receiving antenna.

The basic characteristic of the conductive fabric is its attenuation property. Attenuation of the electromagnetic energy is a result of the reflection, absorption and multi-reflection losses caused by a specific material inserted between the source and the receptor of the radiated electromagnetic energy.

Table 2—Signal-to-noise (S/N) ratio and its significance

Case	S/N ratio
Target is the best	S/N (θ) = 10 $\log_{10}(\tau^2 / s^2)$
Small-the-better	S/N (θ) = -10 $\log_{10}(y_i^2 / n)$
Larger-the-better	S/N (θ) = 10 $\log_{10}[(1/yi^2) / n]$
Binary scale (GO/NO-GO)	S/N (θ) = 10 $\log_{10}(p/1\text{-}p)$

y_i ,τ —Response variable, s—dependant, p—proportion of good products and n—number of trials of experiments.

Attenuation caused by a material is characterized, depending on the measuring method used, by the two quantities, namely shielding effectiveness (SE), and insertion loss (*A*).

2.2.1 Shielding Effectiveness

Shielding effectiveness (SE) is defined as the ratio of electromagnetic field strength measured without (E_0) and with (E_1) the tested material when it separates the field source and the receptor, as shown below:

$$SE = E_0 / E_1$$

In decibels,

$$SE_{dB} = 20\log E_0 / E_1$$

This depends on the distance between the source and the receptor of electromagnetic energy. In the far field zone, it characterizes the attenuation of the electromagnetic wave. The measurement carried out in the near field zone characterizes the attenuation effectiveness for the electric or magnetic field component only.

2.2.2 Insertion Loss

Insertion loss (*A*) is a measure of the losses (or attenuation) in a transmitted signal caused by the tested material being inserted into the measuring channel. The insertion loss can be measured using the following relationship:

$$A = U_0 / U_1$$

In decibels,

$$A_{dB} = 20 \log (U_0 / U_1)$$

Table 3—Experimental test setup for optimization of electromagnetic shielding effectiveness

Expt. No.	Copper wire diameter	Knitted fabric structure	Tightness factor	Thickness	N1 N3	N2 N3	N1 N4	N2 N4	S/N ratio
1	0.1	Plain	12.99	0.79	34	44	36	58	32.13
2	0.1	Rib	13.13	0.85	36	46	38	61	32.59
3	0.1	Interlock	15.22	0.90	37	49	39	63	32.89
4	0.11	Plain	13.13	0.90	32	41	35	46	31.46
5	0.11	Rib	15.22	0.79	35	40	38	59	32.18
6	0.11	Interlock	12.99	0.85	36	41	34	52	31.87
7	0.12	Plain	15.22	0.85	31	39	33	47	31.15
8	0.12	Rib	12.99	0.90	33	37	35	44	31.28
9	0.12	Interlock	13.13	0.79	34	39	35	45	31.50

where U_0 is the channel output voltage without the tested material and U_1, the same voltage with the tested material.

A spectrum analyzer with coaxial transmission equipment was used to measure the EMSE of the copper core conductive fabric at frequencies ranges 20– 200MHz, 200 MHz – 1GHz and 1−18GHz.

2.3 Test Procedure

The tests were carried out in an anechoic chamber in which no acoustical reflections or echoes exist. The floor, walls and ceilings of the chamber are lined with a metallic substance to prevent the passage of electromagnetic waves. Radio frequency signal is generated by a signal generator and it is transmitted through an antenna outside the chamber. Signal from the signal generator is measured by spectrum analyzer with antenna inside the chamber. The first measurement (calibration) was carried out without the test fabric. The tests in the different frequency ranges are conducted.

3 Results and Discussion

Higher shielding effectiveness value indicates the better electromagnetic shielding effectiveness from copper knitted fabric and hence "larger the better" signal to noise is employed to optimize the fabric parameters. Table 3 shows the orthogonal array of the experimental setup followed by shielding effectiveness and the relevant signal-to-noise ratios. Figure 1 shows the effect of copper knitted fabric parameters on shielding effectiveness values in terms of S/N ratio. The shielding effectiveness appears to be highly influenced by knitted fabric structure and copper wire diameter as compared to tightness factor and thickness of developed conductive knitted fabric.

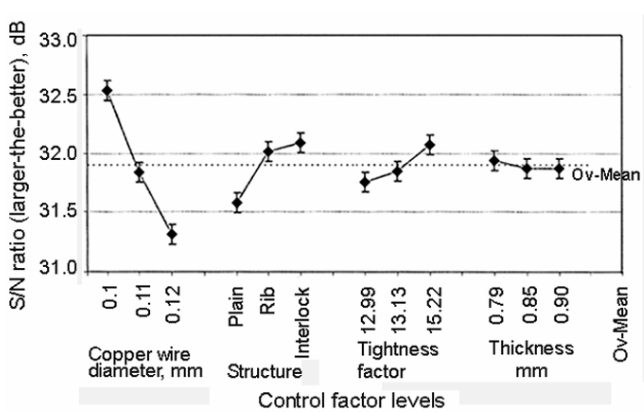

Fig. 1—Signal-to-noise ratio of electromagnetic shielding effectiveness of copper knitted conductive fabric

3.1 Effect of Copper Wire Diameter on EMSE

The copper wire diameter has a significant influence on shielding effectiveness of the fabric. Figure 1 shows the effect of wire diameter with constant course and wales densities of copper knitted fabric. With an increase in wire diameter, a general decrease in shielding effectiveness is observed. Since copper is a rigid material compared to polymeric textile material, it offers resistance to bend while knitting the fabrics. With the increase in diameter, the bending of copper thread becomes more difficult, resulting in openness in the knitted fabric structure, thereby providing less shielding effectiveness as compared to the other samples.

3.2 Effect of Knitted Fabric Structure on EMSE

Figure 1 shows the effect of knitted fabric structure on EMSE of the copper core knitted fabric samples with incident frequency from 20 MHz to 18000 MHz. Interlock knitted structures show better EMSE at low frequency to higher frequency range (20-18000 MHz) than the plain and rib structures, as due to their interlocking of two copper core yarn they offer grouping of yarn, thereby reducing the porosity of the fabric. The interlock and rib knitted structures have 46-63 dB shielding effectiveness between the frequency range 750 MHz and 1000 MHz.

3.3 Effect of Thickness on EMSE

It can be understood that the increase in the shielding effectiveness of the knitted fabric with the decrease in thickness is due to the presence of increased copper content per square meter of the fabric. Figure 1 shows the effect of thickness of knitted fabric on EMSE of copper knitted fabric. It is observed that the thickness of knitted fabrics shows negligible influence on electromagnetic shielding effectiveness at low to higher frequency level. The ANOVA carried out for electromagnetic shielding effectiveness of fabric shows the neutral / negligible effect on thickness.

3.4 Effect of Tightness Factor on EMSE

It can be understood that the increase in the shielding effectiveness of the knitted fabric with the increase in courses and wales densities is due to the presence of increased copper content per square meter of the fabric. Figure 1 shows the effect of tightness factor of knitted fabric on EMSE of copper knitted fabric. It is observed that the fabrics with higher tightness factor have good shielding effectiveness

Table 4—ANOVA – factor effects and *F* values of response variables for electromagnetic shielding effectiveness

Design factor	Degree of freedom	Factor effect, %	*F* value (Before pooling)	Empty or pooled *F*=<1.5	*F* after pooling	Dominant or significant or neutral/negligible	Optimum level
Copper wire diameter, mm	2	79	39	No	218	Dominant	0.1
Knitted fabric structure	2	16	8	No	44	Dominant	Interlock
Tightness factor	2	6	3	No	15	Significant	15.22
Thickness, mm	2	0	0	Pooled	-	Neutral/Negligible	-

than lower tightness factor fabrics at low to higher frequency level. This is due to the more number of threads per unit area in the knitted fabric.

ANOVA carried out for the signal-to-noise ratio of various combinations of the design and noise factors shows the predominant controlling nature of knitted fabric structure, copper wire diameter, tightness factors and thickness as shown in the Table 4. ANOVA also shows the dominant effects of copper wire diameter and fabric structure as compared to tightness factors and thickness.

Effect of individual variables in terms of their average S/N ratio along with the % factors effects and *F* values (pooled and unpooled) again confirm the dominant nature. Confirmation tests in the Taguchi methods supplements assure validity of the results obtain in the experimental designs and orthogonal array selected in the study and various levels of the design parameters and their interaction. Confirmation test carried out with optimum parameter for the response variable shows the closer results to that of original results and does not show any significant difference at 95% confidence levels. The values obtained in confirmation tests along with the original values for response variables considered in the study are given below:

Original results	:	63
Confirmation results	:	62
Significance at 95% confidence level	:	No
Scaling factors	:	A1, B3
Adjustment factor	:	C3

4 Conclusions

The conductive fabric produced from copper core yarn knitted fabric provides an attenuation of 30-63 dB at the medium frequency range 700-1000 MHz. Hence, these fabrics can be used to shield the house-hold appliances, such as FM/AM radio, wireless phone, cellular phone, computers, buildings, secret rooms and various electronic gadgets that operate up to 1000 MHz frequency. The following observations have been made in this study:

4.1 With an increase in walse density, course density and tightness factors, an increase in shielding effectiveness is observed from low frequency to higher frequency range (20-18000 MHz).

4.2 Interlock fabric structure has higher EMSE at low frequency to higher frequency range (20-18000 MHz) than the plain and rib structures.

4.3 An increase in copper wire diameter shows a general decrease in electromagnetic shielding effectiveness. Since copper is a rigid material compared to polymeric textile material, it offers resistance to bend while knitting the fabrics. With the increase in diameter, the bending of copper thread becomes more difficult, resulting in openness in the knitted fabric structure, thereby providing less shielding effectiveness.

4.4 The ANOVA carried out for electromagnetic shielding effectiveness of knitted fabric shows the neutral/ negligible effect on thickness.

The variation in the shielding effectiveness of the fabric can be contributed to the fact that the electrical property of the material varies depending upon the frequency. Hence, it is suggested to use the fabric at the frequencies where higher attenuation is obtained.

Industrial Importance: These fabrics can be used to shield the industrial appliances, such as industrial electronic gadgets, power lines, mobile radio, TV broadcast and receiver, cardiac pacemakers, automotive electronic equipment, inadvertent detonation of explosive devices, electronic control systems of airlines, cooling systems for telecommunication applications, voltage regulation of synchronous generators, wireless communications, military secret room, military tents, etc.

References

1 Hombach V, Meier K, Burkhardt M, Kuhn E & Kuster N, *IEEE Trans, Microwave Theory Technology,* 44 (1996) 1865.

2 Clauser H R, *Industrial and Engineering Materials* (Mac Graw-Hill, New York), 1975.

3 Masi J V, Dixon D S & Avoux M, *Proceeding, IEEE International Symposium on EMC* (IEEE Atlanta) 1987, 183.

4 Bigg D M, *Polym Eng Sci,* 19 (1979) 1188.

5 Lipatov S, Mayunyia Y P, Gladyreva N A & Lebedev Y V, *Polym Sci USSR*, 25 (1983) 714.

6 Sumita M, Sakata K, Asai S, Miyassaka K & Nakagaw H *Polym Bull* 25 (1991) 265.

7 Asai S, Sakata K, Sumita M & Miyassaka K, *Polymer,* 24 (1992) 414.

8 Ponomarenko A T, Shevchenko V G & Enikolopyan N S, *Polym Sci*, 96 (1990) 125.

9 Sircar A K, *Rubber Chem Technol*, 54 (1981) 820.

10 Gubbels F, Jerome R, Teyssie Ph, Vanlathem E, Deltour R, Caldero A, Parente V & Bredas J L, *Macromolecules*, 27 (1994) 1972.

11 Soares B G, Gubbels F, Jerome R, Teyssie Ph, Vanlathem E & Delto R, *Polym Bull*, 35 (1995) 223.

12 Kasevich R S, Cellphones, radars, and health, *IEEE Spectrum*, 39(8) (2002) 15-16.

13 Habash R W, Electromagnetic-the uncertain health risks, *IEEE Potentials*, 22(1) (2003) 23-26.

14 Stuchly M A, Health effects of exposure to electromagnetic fields, *Proceedings*, *Applications Conference in Aerospace*, Vol. 1 (Aspen, Co.), 1995, 351-368.

15 Williams T, The health effects of electromagnetic radiation, electromagnetic compatibility in heavy power installations, *IEE Colloquium*, 23 (1999) 5/1-5/6.

16 *NIEHS Report on Health Effects from Exposure to Power-line Frequency Electric and Magnetic Fields* (National Institute of Health, NC 27709), 1999.

17 Stuchly M A, Electromagnetic fields and health, *IEEE Potentials*, 12(2) (1993) 34-39.

18 Greshham R M, EMI/RFI shielding of plastics, *Plastic Surface Finishing*, 75(2) (1988) 63-69.

19 Hoeft L O & Tokarsky E W, *Measured electromagnetic shielding characteristics of fabric made from metal clad aramid yarn and wire, Principles of electromagnetic compatibility*, paper presented at the IEEE International Symposium on EMC, Washington DC, USA, 1988.

20 Barry C, Electroless copper/nickel shielding: high-performance solution to electromagnetic interference, *Plastic Surface Finishing*, 12 (1989) 30-33.

21 Huang C Y & Pai J F, Studies on processing parameters and thermal stability of ENCF/ABS composites for EMI shielding, *J Appl Polym Sci*, 63(1) (1997) 115-124.

22 Diaz A F & Kanazawa K K, Electrochemical polymerization of pyrrole, *J Chem Soc Chem Commun*, 18 (1979) 635-637.

23 Cheng K B, Ramakrishna S & Lee K C, Development of Conductive Knitted- fabric-reinforced Thermoplastic Composites for Electromagnetic Shielding Applications, *J Thermoplastic Compo Mater,* (5) (2000) 378-399.

24 Cheng K B, Lee K C, Ueng T H & Mou K J, Electrical and impact properties of the hybrid knitted inlaid fabric reinforced polypropylene composites, *Composite Part A,* 33(9) (2002) 1219-1226.

25 Cheng K B, Ramakrishna S & Lee K C, Electromagnetic shielding effectiveness of copper/glass fiber knitted fabric reinforced polypropylene. composites, *Composite Part A*, 31(10) (2000) 1039-1045.

26 Chen H C, Lee K C & Lin J H, Electromagnetic and electrostatic shielding properties of co-weaving-knitting fabrics reinforced composites, *Composite Part A*, 35(11) (2004) 1249-1256.

27 Clayton R P, *Introduction to Electromagnetic Compatibility* (John Wiley & Sons, Inc., USA), 1992, 632-650.

28 Ramson S, Metalloplastics: High conductivity materials, *Polym News*, 8 (1982) 124-125.