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Mechanical properties of copper/cotton core-spun yarns produced by siro and ring spinning methods

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Copper/cotton core-spun yarns have been produced using siro and conventional ring methods, and their mechanical properties and cover factor are analyzed. The results indicate that the cover factor and tensile properties of copper/cotton core-spun yarns decrease with an increase in copper core diameter. Nevertheless, the siro copper/cotton core-spun yarns exhibit higher tensile properties as compared to conventional ring copper/cotton core-spun yarns.

Keywords: Bending rigidity, Copper/cotton core-spun yarn, Copper filament, Cover factor, Electromagnetic shielding effectiveness, Siro spinning, Ring spinning, Tensile properties

1 Introduction

The growth of the electronic industry and using electronic devices in communications, computations, automations, biomedicine, space, and other purposes have led to a new form of pollution known as noise or electromagnetic interference (EMI)[1-3]. Thus, it is necessary to reduce, or completely eliminate destructive and adverse effects of the electromagnetic waves by using conductive surfaces. For this purpose, flexible protective fabrics with conductive core spun yarns are very effective.

There are several different methods to produce conductive yarns including twisting such as ring, siro, and friction spinning systems[4-19]. Twisting conductive metal filament with another filament like polyester or spun yarn is prevalent for producing hybrid conductive yarns. In a study, several kinds of stainless steel (SS) hybrid yarns were produced, in which SS filaments were twisted with other filaments and/or polyester spun yarns[4]. In other studies, a ring machine was applied for producing cotton/copper yarns with different diameter of copper filaments (0.1, 0.11 and 0.12 mm)[5,6]. Soyaslan *et al.*[7] used the yarn-folding machine to produce conductive yarns from copper wire (0.1 and 0.15 mm in diameter) and cotton yarn. In another study, Schwarz *et al.*[8] produced electro-conductive hybrid yarns using hollow spindle spinning system. They found that the hybrid yarn's tensile rupture is caused by the breakage of the wrapped metal monofilament. When the wrapped yarns are multifilament or staple yarns, core yarn breakage led to tensile failure of the hybrid yarn. Ceken *et al.*[9] produced conductive knitted fabrics with conductive copper and stainless steel wires wrapped with acrylic yarns and also SS/cotton core yarns. In a further study, Tezel *et al.*[10] produced conductive yarns by twisting stainless steel or copper wires with cotton yarn on a hollow spindle twisting machine. Yu *et al.*[11], by using hollow spindle spinning machine, produced the hybrid conductive yarn in which stainless steel wire filament is wrapped in a criss-cross-section form by polyester and antibacterial nylon yarn. In a recent study, Lou *et al.*[12] used metallic wires, stainless steel (SS) wires and copper (Cu) wires as the core and polyester (PET) fibres as the wrap material to form the metal/PET wrapped yarns. Results showed that the tenacity and elongation of the SS/PET and Cu/PET wrapped yarns slightly increase with the wrapping turns from 8 to 12 turns/cm.

There are several research studies producing conductive spun yarns. In a study, Cheng *et al.*[13], manufactured blended ring-spun yarns from stainless steel and polyester staple fibres to investigate electromagnetic shielding effectiveness (EMSE) of different woven fabrics. Perumalraj *et al.*[14] used copper wires with diameter 0.09 and 0.1 mm as conductive filler for producing copper/cotton core-spun yarn by using DREF 3 spinning machine. In another study, Bedeloglu *et al.*[15], manufactured

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metal/cotton core-spun yarns with the core of copper and stainless steel on ring spinning machine. The results showed that yarn characteristics were influenced by wire types and diameters, and roving count. When wire diameter decreased and roving count increased, in general the breaking length strength (RKM), breaking force, elongation, and hairiness decreased. Yarns produced with coarser roving generally showed higher elongation and tenacity compared to others. In a further study, Bedeloglu *et al.*[16] investigated the bending rigidity of these yarns using a weighted ring-loop method. The results showed that the increase in diameter of metal wire increased the bending rigidity of yarns. In another study, Ortlek *et al.*[17] produced stainless steel/cotton core-spun yarn by using siro spinning system for investigating EMSE of knitted fabrics. They applied a V-shaped, metal wire guiding roller for controlling SS filament position in the yarn structure.

It is noted that in most of the studies, a relative coarse stainless steel or copper wire was used and twisted with other filaments or spun yarns. Thus, conductive metallic wire was wrapped around the non-conductive yarn component, in which the conductive wire cannot be properly positioned in the produced yarn core. In this study, fine copper filament wires were applied to produce conductive copper/cotton core-spun yarns using ring and siro spinning systems. The conductive component pre-tension and its position was carefully controlled in order to be arranged in the conductive yarn center and hence completely covered by sheath fibres. Thus, the core-spun yarn cover factor and yarn mechanical properties of produced yarns were analyzed and compared.

2 Materials and Methods

2.1 Materials

Combed cotton roving with linear density of 716 tex was used as sheath material. The tensile strength and elongation of cotton fibres used in this study were 28.2 cN/tex and 7.1% respectively. The copper wires (diameter 0.06, 0.07 and 0.08 mm) were taken as core materials. Mechanical properties of copper filaments were measured on an Instron 5566 tensile tester. For each copper filament, 8 samples were tested. Cross-head speed was set in such a way that the breaking time remains 20±3 s. The gauge length of each sample was 25 cm. Mechanical properties of copper filaments are shown in Table 1.

Table 1 — Mechanical properties of copper filaments

Diameter mm	Tensile stress Mpa	Tensile strain %	Tenacity, cN/tex
0.06	1541.65 (0.52)	2.53 (1.65)	2.17 (0.21)
0.07	1900.74 (0.76)	2.22 (1.42)	2.46 (0.22)
0.08	2567.27 (1.02)	1.99 (1.29)	2.93 (0.23)

Values in parentheses are standard deviation.

2.2 Methods

2.2.1 Yarn Production Method

In this study, copper/cotton core-spun yarns were prepared using two different methods, namely conventional ring spinning, and siro spinning.

In the first method, to produce core-spun yarn, a Saco-Lowell ring spinning machine was modified. The copper wire was withdrawn from the package and fed through a disk tensioner and was guided to the nip of front rollers using a porcelain guide [Fig. 1(a)]. This guide was able to move horizontally and vertically in order to set the position and angle of copper wire at the back of front rollers. The feeding angle of copper wire was kept constant 60°. The roving was fed into the roving guide similar to conventional ring spinning system. The nominal yarn count for sheath part was kept as constant 40tex for all 3 yarn samples. To manufacture core-spun yarn, the core component was kept under a specific pre-tension value. Pre-tension values for 0.08, 0.07 and 0.06 mm copper filament wires were 33, 30 and 20 g respectively. The twist was set at 500 turns/m (TPM). The spindle speed was 8484 rpm and yarn delivery speed was 17 m/min. The traveller weight for yarns with 0.08, 0.07 and 0.06 mm copper filament was 180, 160 and 140 mg respectively.

In the siro spinning method, to produce core-spun yarn, a Saco-Lowell ring spinning machine was modified [Fig. 1(b)]. The copper wire was withdrawn from the package, fed through a disk tensioner and guided to the nip of front rollers using a porcelain guide. The condition of porcelain guide was similar to that of former method. Two 716 tex rovings were fed separately into the drafting zone through a roving condenser at a strand spacing of 5 mm. For condensing the rovings, another condenser was set behind the front rollers. The nominal yarn count for sheath part was kept as constant 20 tex for all 3 yarn samples. In siro spinning method, similar to ring spinning method a specific pre-tension value was required for core component. Pre-tension values for 0.08, 0.07 and 0.06 mm copper filament wires were 33, 30 and 20 g respectively. The twist was set at 500 turns/m. The traveller weight for yarns with 0.08, 0.07

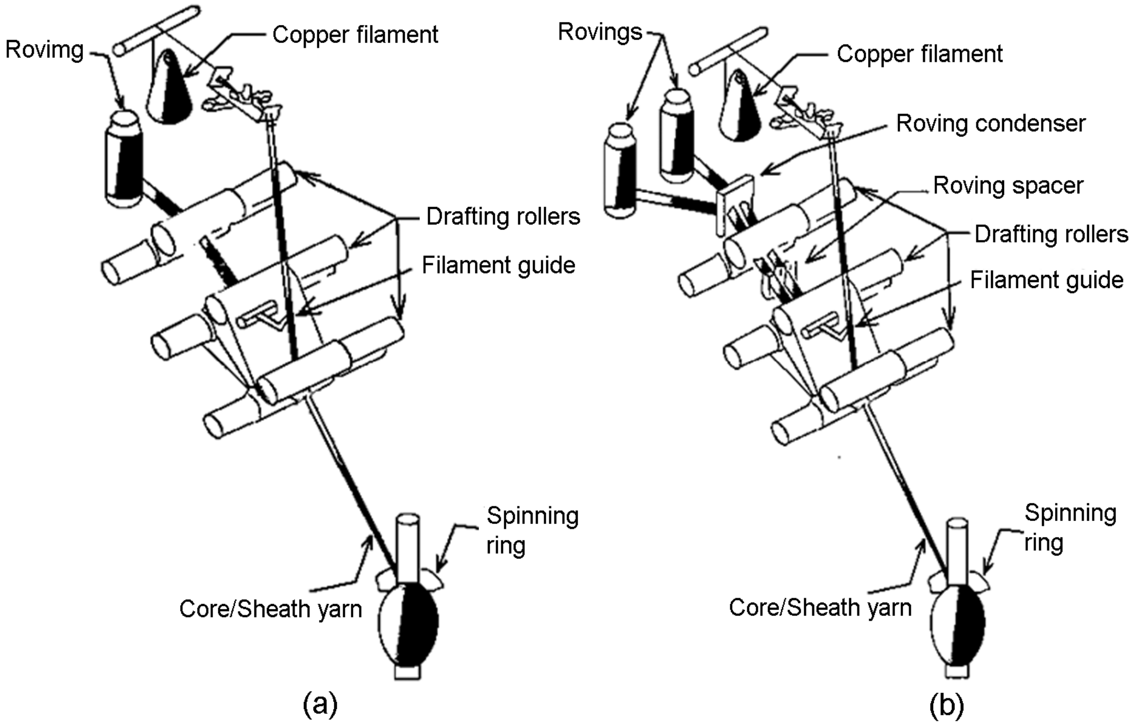

Fig. 1 — Schematic diagram of experimental set-up to produce (a) conventional ring-spun, and (b) siro core-spun copper/cotton yarns

and 0.06 mm copper filament was 180, 160 and 140 mg respectively. Table 2 shows the specifications of core-spun yarns produced on ring and siro spinning systems.

2.2.2 Yarn Properties Testing

For determining the yarn diameter, longitudinal view of yarn samples was obtained by Projectina microscope. The diameter of 50 different parts of each yarn was measured and the average values were reported as the yarn diameter. Tensile properties of samples were measured on an Instron 5566 tensile tester. For each yarn, 15 samples were tested. Cross-head speed was set in such a way that breaking time remains 20±3 s. The gauge length of each sample was 25 cm. All the tests were carried out under the standard conditions (20±2° C and 65±2% relative humidity). Bending rigidity of samples was estimated using the following equations:

$$\text{Bending rigidity} = EI \quad \ldots (1)$$

$$I = \frac{\pi d^4}{64} \quad \ldots (2)$$

where I is the second moment of area; d, the diameter of yarn; and E, the tensile elastic modulus of yarn.

It is noted that the cross-section shape of yarn was assumed as circle. Thus, the tensile elastic modulus of samples was obtained based on the following equations:

Table 2 — Specification of copper/cotton core-spun yarn

Sample code	Roving count tex	Copper wire diameter mm	Wire count tex	Yarn count tex	Yarn diameter mm	Spinning method
C06	716	0.06	25	65	0.33	Conventional ring
C07	716	0.07	34	74	0.40	Conventional ring
C08	716	0.08	45	85	0.45	Conventional ring
S06	716	0.06	25	65	0.34	Siro
S07	716	0.07	34	74	0.37	Siro
S08	716	0.08	45	85	0.40	Siro

$$\sigma = \frac{F}{A} \quad \ldots (3)$$

$$E = \frac{\sigma}{\varepsilon} \quad \ldots (4)$$

where σ is the stress; F, the force; A, the cross section area; E, the tensile elastic modulus; and ε, the strain.

2.2.3 Yarn Cover Factor Measurement

To determine the cover factor of yarns, at first 8 pieces of each yarn sample of 20 cm length were randomly chosen and then they were placed on a black card under a constant load of 2g for all samples. A typical image of yarn sample (S06) is shown in Fig. 2(a). After that, all samples were scanned with a flatbed scanner with 300 DPI. The obtained yarn images were analyzed using a program under MATLAB software. By using some filter toolboxes, the protruded fibres from yarn body were eliminated and then the RGB images were converted to indexed images. Figure 2(b) depicts the yarn image (sample S06) after using MATLAB program. The pixel points including copper pixels and yarn body pixels were calculated. Following equation was applied for the calculation of yarn cover factors (CF)[18]:

$$\mathrm{CF} = \left(1 - \frac{\text{Sum of copper pixels in image}}{\text{Whole pixels of yarn}}\right)\times 100 \qquad \ldots (5)$$

3 Results and Discussion

The mechanical properties and cover factor values of produced conductive copper/cotton core-spun yarns with siro and conventional ring spinning systems are demonstrated in Table 3. Because of the accurate controlling copper filament position, both spinning methods provide very high cover factor in which the largest cover factor is for sample C06 and the lowest cover factor is for sample S08. The increase in core diameter of all samples decreases the cover factor of yarns. Cover factor (CF) of copper/cotton core-spun yarns produced on conventional ring spinning system is about 5% higher than those produced on siro spinning system. Experimental observations of Mohammadi[18] showed that the copper wire was twisted with one of cotton strands during siro spinning processing. For this reason, the copper component was not completely covered by sheath fibres as compared to that in ring spinning system.

Figure 3 shows the stress-strain diagram of produced copper/cotton core-spun yarns. As observed, the tensile stress and tensile strain of siro samples are approximately two times greater than the respective conventional ring copper/cotton core-spun yarns presumably, because of better contribution of material constituents in the yarn structure. By increasing diameter of core part in produced yarn, the ratio of copper component to cotton increases, and hence the tensile strain and stress of all samples decrease.

The yarn tenacity variation against copper diameter is represented in Fig. 4(a). As observed, increasing the diameter of core copper component led to a decrease in yarn tensile strength. Similar results were also obtained by Bedeloglu *et al.*[15]. They showed that by increasing diameter of copper component, breaking force and breaking work of copper/cotton core-spun yarns decrease. Also, Ramachandran *et al.*[19] observed that the increase in core contribution in the yarn structure decreases the breaking tenacity values.

This result can be attributed to the less cohesion of core component to sheath fibres for coarser copper component. It is deduced that for finer copper wire due to lower torsional and bending rigidity the copper

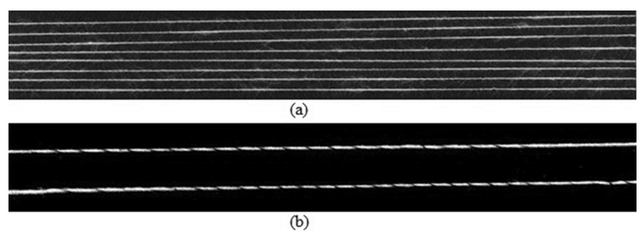

Fig. 2 — Yarn images for (a) typical S06 sample and (b) S06 samples after using MATLAB program

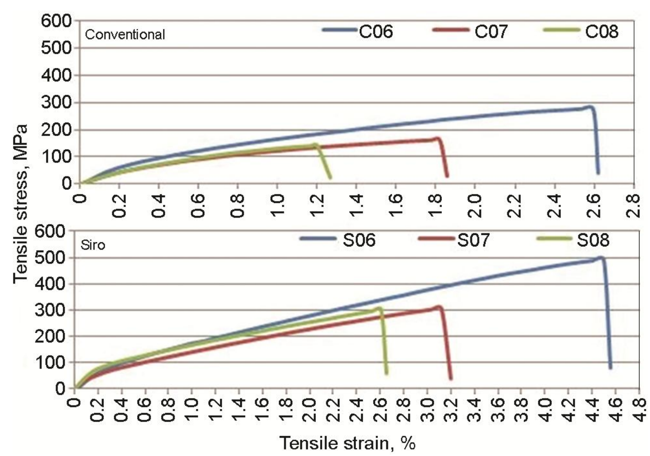

Fig. 3 — Stress-strain of copper/cotton core-spun yarns

Table 3 — Mechanical properties and cover factor of samples

Sample code	Tensile stress Mpa	Tensile strain %	Tenacity cN/tex	Elastic modulus Gpa	Bending rigidity N.mm^2	Cover factor %	Breaking work cN.cm
C06	275.65(1.78)	2.6 (0.30)	3.68 (0.43)	3.22 (0.21)	1.88 (0.25)	91.52	100.69 (0.33)
C07	161.72 (0.92)	1.9 (0.20)	2.78 (0.26)	2.36 (0.14)	2.97 (0.22)	90.68	61.59 (0.26)
C08	133.32 (1.02)	1.3 (0.13)	2.26 (0.24)	2.07 (0.23)	4.17 (0.18)	89.33	41.50 (0.19)
S06	489.95 (2.61)	4.6 (0.44)	6.94 (0.56)	3.31 (0.51)	2.17 (0.23)	86.40	302.48 (0.39)
S07	315.27 (1.69)	3.05 (0.29)	4.64 (0.37)	3.24 (0.39)	3.04 (0.19)	85.95	157.75 (0.28)
S08	261.66 (1.78)	2.3 (0.36)	3.94 (0.33)	3.20 (0.25)	4.15 (0.17)	85.27	147.14 (0.21)

Values in parentheses are standard deviation.

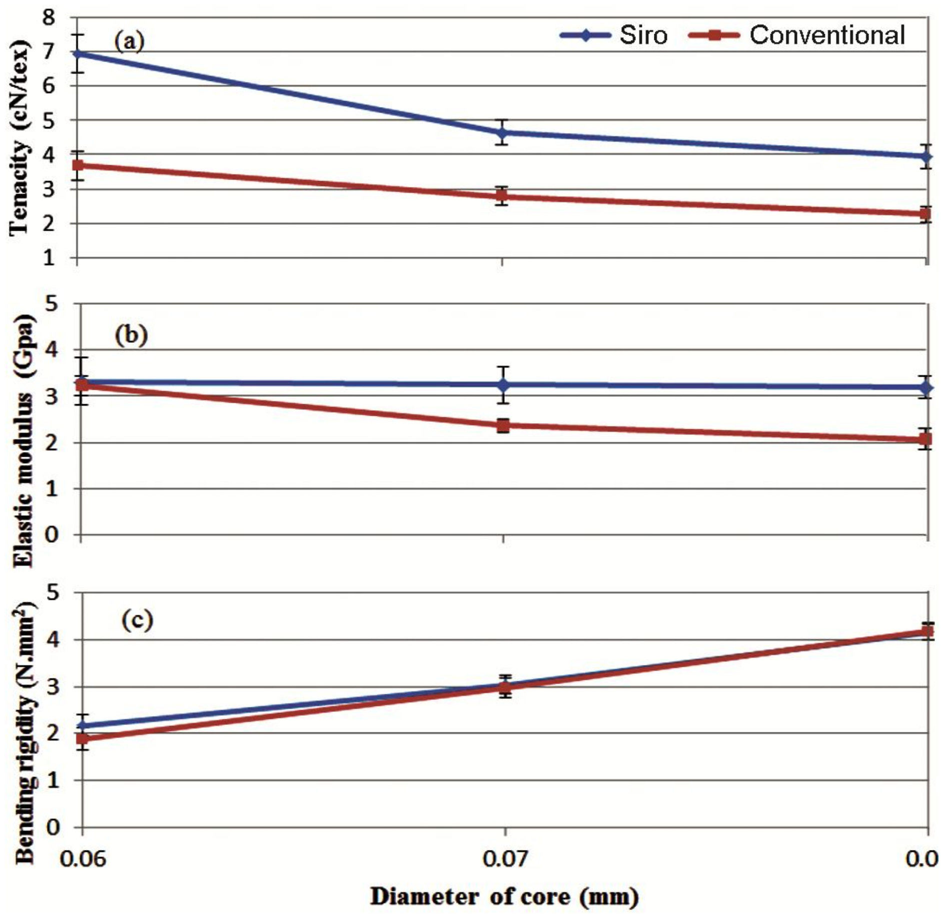

Fig. 4 — Copper/cotton core-spun yarns (a) tenacity, (b) elastic modulus and (c) bending rigidity against copper diameter

filament can efficiently twisted with cotton fibres and hence increases the cohesion between the two components. This results in an increase in yarn tensile strength. It is found that the tenacity of siro yarn is much higher than that of ring yarn, and statistical analysis at 95% confidence limit confirms this difference.

The tensile elastic modulus of copper/cotton core-spun yarns is shown in Fig. 4(b). The difference between yarn elastic modulus values in both spinning methods is increased with copper diameter. However, samples C06 and S06 have similar elastic modulus. It is also found that the increase in copper diameter for siro core-spun yarns does not represent significant effect on yarn elastic modulus. Nevertheless, increasing copper diameter sharply decreases the ring-spun copper/cotton core yarn elastic modulus.

Bending rigidity of siro and conventional sing copper/cotton core-spun yarns against copper diameter is demonstrated in Fig. 4(c). The results indicate that the increase in yarn diameter and copper core wire leads to increase in bending rigidity of copper/cotton core-spun yarns. According to Eqs (1) and (2), bending rigidity is directly proportional to biquadrate of yarn diameter. As listed in Table 2, as copper diameter is increased the yarn diameter is also increased. For this reason, bending rigidity values of copper/cotton core-spun yarns increase with increase in copper diameter. It is also observed that the bending rigidity of siro copper/cotton core-spun yarn and conventional ring copper/cotton core spun yarn is almost similar. However, there is a slight difference between bending rigidity values of samples C06 and S06.

4 Conclusion

The results show that with the increase in copper core diameter the cover factor of copper/cotton core-spun yarns decreases in which the ring conductive yarns demonstrate higher cover factor than siro conductive yarns. The results also indicate that the elastic modulus of siro core-spun yarns is higher than that of conventional ring core-spun yarns. In addition, an increase in diameter of core part in conventional ring core-spun samples causes a sharp decrease in amount of elastic modulus. However, the elastic modulus of siro core-spun yarns remains unchanged with copper core diameter. The results also show that increasing the core copper diameter leads to a decrease in yarn tensile strength in which the siro copper/cotton core-spun yarns exhibit higher values than conventional ring copper/cotton core-spun yarns. Further studies are needed to investigate the electromagnetic shielding effectiveness of weft knitted fabrics produced from these core-spun yarns.

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