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Analysis of yarn properties in the superconducting magnetic bearing-based ring spinning process

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Abstract

The fundamental research work about the superconducting magnetic bearing (SMB) twisting system provides huge potential to eliminate the most important limitation of productivity, that is, the friction in the ring traveler system of the existing ring spinning process. As a continuity of the research work, the functionality of the SMB spinning has been carried out with different angular spindle speeds, yarn counts, and materials in order to determine the influence of the SMB technology. The current paper presents a comparative investigation of the yarn properties, such as yarn tenacity, yarn elongation, yarn evenness, microscopic views, etc., between conventional and SMB ring spun yarn. The intensive analysis confirms that the SMB system enables one to produce satisfactory yarn quality similar to that of conventional ring spun yarn up to 15,000 rpm. The influence of conventional and SMB spinning processes on yarn properties has been further analyzed statistically using an analysis of variance.

Keywords

superconducting magnetic bearing ring yarn, superconducting magnetic bearing, analysis of variance, yarn properties, yarn tenacity, yarn evenness, conventional ring yarn

About 84% of short staple yarn has been produced worldwide in ring spinning machines due to the best quality of yarn and the flexibility of the ring spinning technology. However, the productivity of the ring spinning is much lower in comparison to other spinning methods, such as rotor or air jet spinning processes.¹ In the ring spinning, a combination of ring and traveler has been used since 1830, where the traveler rotates on the ring to impart twist in the yarn. Although the productivity of ring spinning depends on the angular spindle speed, it is directly correlated to the rotational speed of the traveler. As the angular spindle speed increases, high contact pressure occurs between ring and traveler, which includes strong frictional forces and generates, in turn, heat. The main limitation of this twisting mechanism is thus the friction occurring between the ring and the traveler, which results in damages and wear of the ring and the traveler. This frictional heat deteriorates the yarn quality and process stability and causes end breakages, especially while spinning with thermoplastic materials (due to melting points). For this reason, the production of ring spinning is limited to

the maximum delivery speed of approximately 30 m/min, which is economically disadvantageous. For thermoplastic fibers, the productivity is even limited to 15 m/min, so that the optimal yarn quality can be assured. Therefore, the frictional problem of the existing ring/traveler system established for more than 100 years needs to be eliminated to increase productivity.

The passive magnetic bearing (superconducting magnetic bearing (SMB)) based on superconducting technology is an alternative to replace the existing twisting system in order to alleviate the present friction problem and thus allow one to increase the productivity of ring spinning to a great extent (up to 200–300%).

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This type of SMB possesses a self-stabilizing behavior without any necessity of expensive control and sensor units, which results in high stability even at a higher spindle speed. The most promising superconducting material is $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO), which displays excellent magnetic properties and has been used to construct the current SMB system.²⁻⁹

Within the framework of the research project, “Research of friction free twisting based on superconducting technology taking account into the yarn dynamics in textile processing machine”, the main objectives of the research work concern experimental analysis on the friction-free twisting element based on superconducting technology and its influence on spinning technology, which should make the basis for a further increment of productivity. As a continuity of the research work, the functionality of the SMB spinning has been carried out with different angular spindle speeds, yarn counts, and materials in order to determine the influence of the SMB technology.

Principle of ring spinning process with superconducting magnetic bearing (SMB) system

The SMB system consists of a permanent magnet (PM) ring (neodymium-iron-boron (NdFeB)), the superconductor ring (YBCO), and a cooling system. As shown in Figure 1 schematically, within the SMB system, the PM ring and the superconducting ring are arranged coaxially with respect to the spindle axis. After cooling the

superconductor below its transition temperature, the PM ring levitates and is free to rotate above the superconductor ring according to the principles of superconducting levitation and the “Flux pinning effect”. Each rotation of the PM ring imparts twist in the yarn similar to the traveler in the conventional ring/traveler system. The investigation of integrating a suitable SMB system to the existing ring spinning machine in place of the ring/traveler system has already proven its functionality as a new twisting system.¹⁰⁻¹⁹

In the SMB spinning process, the frictional heat occurring between the ring and the traveler has been eliminated with the SMB system. It is therefore important to explore the influence of spinning methods (i.e. conventional and SMB spinning) and the process parameters, such as yarn material, yarn count, and spindle speed on yarn properties, such as yarn tenacity, elongation, evenness, etc.

In this current paper, the produced yarns for various yarn materials, spindle speeds, and yarn counts both for conventional and SMB spinning processes have been tested and further investigated. The effects of spinning methods on different yarn properties have been then compared and analyzed statistically using an analysis of variance (ANOVA).

Experimental details

Materials

One hundred per cent cotton and polyester material were used for the analysis of yarn properties.

Figure 1. Principle of superconducting magnetic bearing-based ring spinning.¹³

The yarn has been produced with different yarn counts, such as 15, 20, and 30 tex, which are the mostly produced yarns in the ring spinning industry. The further process parameters are described in Table 1.

Plan of experiments

The ring yarns have been manufactured considering the parameters described in Table 1. Both the ring/traveler

Table 3. Factors and levels used for the analysis of variance

Factors	Levels	Values
Spinning methods	2	Conventional and SMB ring spinning
Yarn count [tex]	3	15, 20, 30 tex
Spindle speed [rpm]	3	5000; 10,000; 15,000

SMB: superconducting magnetic bearing.

Table 1. Process parameters used for the analysis of yarn properties

Process parameters	Material	
	100% Polyester (PES)	100% Cotton (CO)
Staple length	38 mm	28 mm
Fiber count	1.14 dtex	1.57 dtex
Roving count	499 tex	576 tex
Yarn count, m	15, 20 and 30 tex	15, 20 and 30 tex
Total draft	33.27; 24.95; 16.63	38.4; 28.8; 19.2
Break draft	1.14	1.14
Drafting settings:		
Main draft distance	50	50
Break draft distance	70	62
Spindle speed, n_s	5000; 10,000; 15,000 rpm	5000; 10,000; 15,000 rpm
Delivery speed, v	7.14; 14.30; 21.43 m/min	7.14; 14.30; 21.43 m/min
Yarn twist	470 (30 tex), 550 (20 tex), 630 (15 tex) TPM	570 (30 tex), 670 (20 tex), 750 (15 tex) TPM
Ring traveler	ISO No. 45, 63, 80	ISO No. 71
Ring diameter, a	45 mm	45 mm
Inner diameter of PM ring	45 mm	45 mm

PM: permanent magnet.

Table 2. Testing plan

Type of test	Testing device	Testing conditions	
Yarn tenacity (cN/tex)	Uster Tensorapid 3+	Testing standard:	DIN EN ISO 2062
Yarn elongation (%)	Uster Tensorapid 3+	Test principle:	Constant Rate of Extension (CRE)
		Test length:	250 mm
		Test speed:	250 mm/min
		Clamping material:	polyurethane
		Pretension:	0.5 cN/tex
		Test number:	25
Yarn evenness (CV _m %)	Uster Tester 3	Test length:	1000 m
		Test speed:	400 m/min
		Test number:	5
Microscopic yarn structure	Zeiss microscope AXIOImager.M1m	50× magnification	

and SMB twisting system have been integrated on a ring spinning tester (Dr. Fehrer AG, Austria) in order to produce yarns. Generally, synthetic yarns such as 100% polyester material cannot be spun at an

angular spindle speed higher than 15,000 rpm, due to the generation of the melting point by the frictional heat in the ring/traveler system. Although the 100% cotton material can be spun at an angular speed

Figure 2. Comparison of yarn tenacities between superconducting magnetic bearing (SMB) and conventional ring yarns with respect to different yarn counts and angular spindle speeds for 100% polyester (PES) and cotton (CO) materials.

higher than 15,000 rpm, the investigation has only been done up to 15,000 rpm, considering the average yarn quality. Moreover, the traveler masses in the case of the ring/traveler system have been selected for different yarn counts according to the recommendations of machine manufacturers.

Testing program

Before testing the different yarn properties using the ring/traveler and SMB twisting systems, the produced yarns were acclimatized for 24 hours in standard atmospheric conditions (temperature: $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and relative humidity: $65\% \pm 2\%$).

The yarn tenacity and elongation were measured with the Uster Tensorapid 3+ yarn strength tester. The measurement of yarn evenness was conducted with the Uster 3 evenness tester, which measures the yarn evenness based on a capacitive method. Furthermore, the yarn structures were examined with the Zeiss microscope AXIOImager.M1m. All the tests were conducted according to the standard norm. The testing plan and the test conditions are summarized in Table 2.

Analysis of variance

In order to analyze the effects of spinning methods and spinning parameters on the yarn properties, such as yarn tenacity, elongation, and evenness, the statistical method, that is, the multi-factorial ANOVA, has been applied. The ANOVA enables one not only to estimate the effects of individual factors on process quality, but also takes into account their interactions.^{20,21} The p -value (0–1) defines the probability of the extremity of the statistical results in the hypothesis testing with the ANOVA. The effect of statistical results is significant if the p -value is less than 0.05. Higher order interactions, that is, interactions between three and four factors, are neglected and combined into the error in

order to calculate the f -value and corresponding p -value at 95% confidence limits.

For the statistical analysis with the ANOVA, a three factor $2 \times 3 \times 3$ design has been used. The factors and levels used for the ANOVA are described in Table 3.

Results and discussion

Influence of spinning methods on yarn tenacity and yarn elongation

Yarn tenacity is one of the most important process parameters; it defines the spinning limits, such as the possibility of yarn end breakages, and thus allows one to estimate the maximum angular spindle speed. For the analysis of yarn strength, the conventional and SMB ring spun yarns have been produced with respect to different yarn counts and angular spindle speeds. The mean values of the yarn tenacity both for 100% polyester (PES) and cotton (CO) materials are illustrated in Figure 2 graphically. Generally, the SMB yarns possess a certain amount of higher strength in comparison to that of conventional ring yarn for both types of materials. The SMB system contributes to a uniform distribution of dynamic forces in the yarn path through the elimination of frictional forces occurred in the existing ring/traveler twisting system. However, it can be seen that the yarn strength decreases with respect to increased spindle speed for a constant yarn count.

The statistical results of the ANOVA using the values of yarn tenacities are further shown in Table 4 exemplarily in the case of 100% cotton material. Since the p -values of these three factors are significantly higher than 0.05, it can be concluded that spinning method and yarn count do not have any significant influence on the yarn tenacity.

On the other hand, the ANOVA results described in the Appendix 2 for 100% polyester yarns show that the yarn strengths are influenced by spinning methods,

Table 4. Analysis of variance results for yarn tenacity in the case of 100% cotton materials

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-values	P-value
A: Spinning methods	0.26889	1	0.26889	4.44	0.103
B: Yarn count [tex]	0.39000	2	0.19500	3.22	0.147
C: Spindle speed [rpm]	0.09333	2	0.04667	0.77	0.521
A–B interaction	0.38778	2	0.19389	3.20	0.148
A–C interaction	0.03111	2	0.01556	0.26	0.785
B–C interaction	0.36667	4	0.09167	1.51	0.349
Residual (error)	0.244222	4	0.06056		
Total	1.78000	17			

angular spindle speeds, and yarn counts, although the differences in tenacity for different spinning methods in the case of 100% polyester yarns are not significant according to Figure 2.

In order to check the quality of produced yarns for different spinning methods, the values of yarn tenacity have been compared to that of USTER® *STATISTICS*,

which provides the yarn quality reference values for yarn producers. The USTER® *STATISTICS* percentiles express how many spinning mills worldwide are able to produce at the specified level or better. For example, if a spinning mill reaches the 5% value, it means that only 5% of spinning mills worldwide are able to produce a yarn, roving, or sliver at this quality level or better.²²

Figure 3. Comparison of yarn tenacity of the produced conventional and superconducting magnetic bearing (SMB) ring spun yarns with USTER® *STATISTICS* (yarn count: 30 tex and angular spindle speed: 15,000 rpm).²² PES: polyester.

According to Figure 3, the USTER reference values in case of the produced SMB ring yarns correspond to 15% and 40% for 100% polyester and cotton materials, respectively. The drafting settings can be

attributed to the average quality of yarn tenacity, especially in the case of 100% cotton materials.

Furthermore, the yarn elongations of conventional and SMB ring yarn have been analyzed from the yarn

Figure 4. Comparison of yarn elongation between superconducting magnetic bearing (SMB) and conventional ring yarns with respect to different materials, yarn counts, and spindle speeds. PES: polyester; CO: cotton.

tenacity results (Figure 4). It can be observed that the elongation of the SMB yarn is higher than that of the conventional yarn.

The reason for the higher elongation in the case of the SMB spinning system lies in the dynamic force equilibrium of the yarn path of the SMB system. A constant mass of the PM ring has been used in this case to spin yarn with different yarn counts and angular spindle speeds, which may contribute to the increase of yarn elongation both in case of 100% polyester and cotton materials.

The stress–strain curves are further shown exemplarily in Figure 5 for a defined yarn (30 tex) from 100% polyester material, which exhibit similar force diagrams both in the case of conventional and SMB ring yarns.

Moreover, the statistical results of the ANOVA using the mean values of elongation are summarized in Table 5, which determine the influence of different

process parameters on yarn elongation. By comparing the p -values (less than 0.05) of the three factors in Table 5, it becomes apparent that spinning methods (conventional and SMB ring spinning), yarn counts, and spindle speeds have a significant influence on the yarn elongation for 100% cotton material. A similar tendency has also been observed after analyzing the elongation values in the case of 100% polyester material (Appendix 4).

Influence of spinning methods on yarn evenness and structure

As a part of further analysis of yarn properties, the yarn evenness and yarn structure have been analyzed both in the case of conventional and SMB ring yarns.

From Figure 6, it can be observed that the values of yarn evenness ($CV_m\%$) in the case of SMB ring yarn

Figure 5. Stress–strain curves of conventional and superconducting magnetic bearing (SMB) ring yarn (yarn count 30 tex and material 100% polyester).

Table 5. Statistical analysis using the analysis of variance for yarn elongation in the case of 100% cotton material

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-values	P-value
A: Spinning methods	0.18402	1	0.184022	419.29	0.000
B: Yarn count [tex]	1.03743	2	0.518717	1181.89	0.000
C: Spindle speed [rpm]	0.36760	2	0.183800	418.78	0.000
A–B interaction	0.02154	2	0.010772	24.54	0.006
A–C interaction	0.01338	2	0.006689	15.24	0.013
B–C interaction	0.01587	4	0.003967	9.04	0.028
Residual (error)	0.00176	4	0.000439		
Total	1.64160	17

Figure 6. Comparison of yarn evenness between superconducting magnetic bearing (SMB) and conventional ring yarns with respect to different spindle speeds and yarn counts for 100% polyester (PES) and cotton materials.

decrease to approximately 2–5% of the relative values in comparison to that of conventional ring yarn both for 100% PES and CO materials. The elimination of frictional heat and the stable running of the SMB system cause the improvement of yarn evenness in the case of SMB ring yarn.

Furthermore, the results of the ANOVA for yarn evenness are presented in Table 6 exemplarily in the case of 100% cotton material.

By comparing the *p*-values of the three factors mentioned in Table 6, it is apparent that spinning method, yarn count, and spindle speed have a significant

Table 6. Statistical analysis of yarn evenness with analysis of variance for 100% cotton material

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-values	P-value
A: Spinning methods	0.95681	1	0.956806	252.53	0.000
B: Yarn count [tex]	1.53934	2	0.769672	203.14	0.000
C: Spindle speed [rpm]	0.25021	2	0.125106	33.02	0.003
A–B interaction	0.05028	2	0.025139	6.63	0.054
A–C interaction	0.01141	2	0.005706	1.51	0.325
B–C interaction	0.04742	4	0.011856	3.13	0.148
Residual (error)	0.01516	4	0.003789		
Total	2.87063	17

Figure 7. Comparison of yarn evenness, CV_m , of conventional and superconducting magnetic bearing (SMB) ring yarn with USTER® STATISTICS (yarn count: 30 tex and angular spindle speed: 15,000 rpm). PES: polyester.

influence on yarn evenness. A similar tendency can be observed after analyzing the yarn evenness values for 100% polyester material (Appendix 6).

Unlike the yarn tenacity, the mean values of yarn evenness of conventional and SMB ring yarns have been compared with the reference values of USTER® *STATISTICS*. Figure 7 represents the yarn evenness (CV_m %) with the USTER reference values from 5% to 95% in the case of 100% polyester and cotton materials. The yarn evenness values of the produced yarns have been labeled in the graphs in order to indicate the yarn quality. For example, the USTER reference values of yarn evenness in the case of the SMB yarn (30 tex) is 15% and 20% for 100% polyester and cotton materials, respectively. The elimination of friction in the case of SMB yarn can be attributed to the improvement of yarn evenness.

The microscopic views for conventional and SMB ring yarns are illustrated exemplarily in Figure 8 with respect to different yarn counts (100% PES material) at the angular spindle speed of 15,000 rpm. According to Figure 8, there are more protruding fibers in the structure of conventional ring yarn, which are caused by the frictional heat generated in the ring/traveler system. As the ring/traveler has been replaced with the SMB system, fewer protruding fibers, that is, less hairiness, have been observed in the SMB yarn. Furthermore, the SMB ring yarns seem to be smoother and are twisted more uniformly in comparison to conventional ring spun yarns.

Furthermore, the microscopic views of SMB ring yarn were compared with regard to different angular spindle speeds from 5000 to 15,000 rpm for a defined yarn count (20 tex), as shown in Figure 9.

Figure 8. Comparison of microscopic yarn structures between superconducting magnetic bearing (SMB) and conventional ring yarns with respect to different yarn counts (100% polyester material) at the angular spindle speed of 15,000 rpm.

Figure 9. Comparison of superconducting magnetic bearing ring microscopic yarn structures (20 tex, 100% polyester) with respect to different angular spindle speeds.

The yarn structures of SMB yarn exhibit lower or similar hairiness in comparison to that of conventional ring yarn even at a higher angular spindle speeds. The smoother yarn guide at the PM ring in the SMB system causes this improvement, whereas the sharp edge of the heated traveler in the ring/traveler systems causes the hairiness of fibers during the contact between the yarn and the traveler in the conventional ring spinning process.

Conclusions and outlook

Within the current research work, the effect of different twisting systems (ring/traveler and SMB systems) on yarn quality have been investigated and compared with respect to different process parameters, such as different materials (100% cotton and polyester), yarn counts (15, 20, and 30 tex), and angular spindle speeds (5000, 10,000, and 15,000 rpm) on yarn quality. The SMB ring yarn shows a tendency to have higher strength to some extent in comparison to conventional ring yarn for specific angular spindle speed and yarn counts. However, a further statistical analysis of yarn properties with an ANOVA confirms that the SMB system does not affect the yarn strength significantly, especially in the case of 100% cotton material. Moreover, the complete elimination of frictional heat between the ring and the traveler and the uniform distribution of process forces in the SMB ring spinning contributes to the improvement of yarn evenness.

The results with implementing fully the new SMB system ensure that the yarn quality has not been negatively influenced, which provides vital information to proceed with the research work with higher spindle speeds. As the frictional problem of the existing ring/traveler system has been solved with the integrated SMB system, it is expected at least to double the productivity of the ring spinning machine with constant yarn properties. As a part of the research, the yarn will be further analyzed after modifying the ring spinning machine to be compatible with higher spindle speeds, such as 50,000 rpm.

Through the implementation of the SMB system, the productivity (angular spindle speed), especially in the case of thermoplastic materials such as polyester, can be raised from 15,000 to 50,000 rpm, which means an increment of the productivity up to three times in comparison to the conventional ring spinning machine. Currently, a research collaboration with a renowned international textile company has been started in order to develop an industry competent high-performance SMB ring spinning machine. A detailed study about the feasibility of the process for industrial use, especially for the cost factor, including implementation cost, energy consumption, etc., will be conducted after

the development of the industry competent SMB ring spinning machine.

Declaration of conflicting interests

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Appendices

Appendix 1: Measured values of the yarn tenacity

Spindle speed [rpm]	Yarn tenacity [cN/tex]											
	100% PES						100% Cotton					
	Ring yarn			SMB ring yarn			Ring yarn			SMB ring yarn		
	Yarn count [tex]											
	30	20	15	30	20	15	30	20	15	30	20	15
5000	36.49	35.8	35.5	36.8	36.2	35.8	18	17.7	17.5	18.3	17.9	17.8
10,000	35.6	35.3	35.1	36	35.8	35.6	17.8	17.5	17.3	18.2	17.8	17.7
15,000	35.2	35.1	34.9	35.8	35.7	35.5	17.6	17.3	17.2	18.1	17.7	17.8

PES: polyester.

Appendix 2: ANOVA results for the yarn tenacity for 100% PES

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-value	P-value
A: Spinning methods	1.08045	1	1.08045	346.67	0.000
B: Yarn count [tex]	0.91523	2	0.45762	146.83	0.000
C: Spindle speed [rpm]	1.59623	2	0.79812	256.08	0.000
A–B interaction	0.00723	2	0.00362	1.16	0.400
A–C interaction	0.08290	2	0.04145	13.30	0.017
B–C interaction	0.34713	4	0.08678	27.84	0.004
Residual (error)	0.01247	4	0.00312		
Total	4.04165	17			

Appendix 3: Measured values of the yarn elongation

Spindle speed [rpm]	Yarn elongation [%]											
	100% PES						100% Cotton					
	Conventional ring yarn			SMB ring yarn			Conventional ring yarn			SMB ring yarn		
	Yarn count [tex]											
	30	20	15	30	20	15	30	20	15	30	20	15
5000	12.50	12.37	11.2	12.7	12.47	11.3	7	6.7	6.5	7.1	6.9	6.6
10,000	12.6	12.4	11.5	13	12.6	11.7	7.2	6.8	6.6	7.37	7.1	6.75
15,000	12.75	12.7	11.8	13.4	13.1	12.3	7.4	6.9	6.75	7.6	7.3	6.95

PES: polyester; SMB: superconducting magnetic bearing.

Appendix 4: ANOVA results for the yarn elongation for 100% PES

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-value	P-value
A: Spinning methods	0.42014	1	0.42014	432.14	0.000
B: Yarn count [tex]	4.83023	2	2.41512	2484.12	0.000
C: Spindle speed [rpm]	1.05390	2	0.52695	542.01	0.000
A–B interaction	0.02861	2	0.01431	14.71	0.014
A–C interaction	0.11361	2	0.05681	58.43	0.001
B–C interaction	0.08147	4	0.02037	20.95	0.006
Residual (error)	0.00389	4	0.00097		
Total	6.53185	17			

Appendix 5: Measured values of the yarn evenness

Spindle speed [rpm]	Yarn evenness [CV _m %]											
	100% PES						100% Cotton					
	Conventional ring yarn			SMB ring yarn			Conventional ring yarn			SMB ring yarn		
	Yarn count [tex]											
	30	20	15	30	20	15	30	20	15	30	20	15
5000	10.5	11.4	12.73	10.2	11.2	12.59	12.8	13.37	13.7	12.4	13.1	13.2
10,000	10.7	11.6	12.8	10.3	11.3	12.38	13.2	13.5	13.8	12.6	13.12	13.3
15,000	10.8	11.7	13.1	10.2	11.1	12.5	13.4	13.6	13.9	12.7	13.3	13.4

PES: polyester; SMB: superconducting magnetic bearing.

Appendix 6: ANOVA results for the yarn evenness for 100% PES

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-value	P-value
A: Spinning methods	0.7041	1	0.70409	393.59	0.000
B: Yarn count [tex]	15.0978	2	7.54889	4219.88	0.000
C: Spindle speed [rpm]	0.0512	2	0.02562	14.32	0.015
A-B interaction	0.0035	2	0.00176	0.98	0.450
A-C interaction	0.1132	2	0.05662	31.65	0.004
B-C interaction	0.0478	4	0.01196	6.68	0.046
Residual (error)	0.0072	4			
Total	16.0248	17			