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Potential of High Performance Ring Spinning Based on Superconducting Magnetic Bearing

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Abstract**—**Due to the best quality of yarn and the flexibility of the machine, the ring spinning process is the most widely used spinning method for short staple yarn production. However, the productivity of these machines is still much lower in comparison to other spinning systems such as rotor or air-jet spinning process. The main reason for this limitation lies on the twisting mechanism of the ring spinning process. In the ring/traveler twisting system, each rotation of the traveler along with the ring inserts twist in the yarn. The rotation of the traveler at higher speed includes strong frictional forces, which in turn generates heat. Different ring/traveler systems concerning with its geometries, material combinations and coatings have already been implemented to solve the frictional problem. However, such developments can neither completely solve the frictional problem nor increase the productivity. The friction free superconducting magnetic bearing (SMB) system can be a right alternative replacing the existing ring/traveler system. The unique concept of SMB bearings is that they possess a self-stabilizing behavior, i.e. they remain fully passive without any necessity for expensive position sensing and control. Within the framework of a research project funded by German research foundation (DFG), suitable concepts of the SMB-system have been designed, developed, and integrated as a twisting device of ring spinning replacing the existing ring/traveler system. With the help of the developed mathematical model and experimental investigation, the physical limitations of this innovative twisting device in the spinning process have been determined. The interaction among the parameters of the spinning process and the superconducting twisting element has been further evaluated, which derives the concrete information regarding the new spinning process. Moreover, the influence of the implemented SMB twisting system on the yarn quality has been analyzed with respect to different process parameters. The presented work reveals the enormous potential of the innovative twisting mechanism, so that the productivity of the ring spinning process especially in case of thermoplastic materials can be at least doubled for the first time in a hundred years. The SMB ring spinning tester has also been presented in the international fair “International Textile Machinery Association (ITMA) 2015”.

Keywords**—**Ring spinning, superconducting magnetic bearing, yarn properties, productivity.

I. Introduction

Due to the best quality of yarn and the flexibility of the ring spinning technology, about 84% of short staple yarn has been produced worldwide in ring spinning machines, although the productivity is much lower in comparison to other spinning methods [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 angular spindle speed, it is directly correlated to the rotational speed of the traveler. The main limitation of this twisting mechanism is the friction occurring between ring and traveler, which results in damages and wears of ring and traveler. As the angular spindle speed increases, high contact pressure occurs between ring and traveler, which includes strong frictional forces and generates heat. This frictional heat deteriorates the yarn quality, process stability, causes end-breakages and thus stoppage of the machine, especially while spinning with thermoplastic materials (melting points). The investigation with the help of an infrared camera determines that the temperature increases sharply for example up to 300 °C within a very short time at a traveler angular speed of 20,000 rpm. 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 the thermoplastic materials, the productivity is even limited to 15 m/min, so that the optimal yarn strength can be assured. Therefore, the frictional problem of existing ring/traveler system established for more than 100 years needs to be eliminated to increase the productivity.

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II. State of the Art

In order to reduce or eliminate the ring/traveler system, there have been a number of research efforts using different topologies, material combinations, or special surface modifications of ring/traveler system. For example, the design of inclined “Orbit ring” ensures an optimal force distribution in ring/traveler system and improves the heat dissipation during spinning [2]. The travelers have also been enriched with steel structure with addition finish such as an electrolytic coating of nickel plating. These modifications of existing ring/traveler system with different topologies or coatings can only reduce friction to a certain amount to improve the service life of the travelers, but do little to increase productivity (maximum 10%). Further developments refer to eliminate the ring/traveler systems such as electrically controlled ring (US 5109659), rotating ring with air bearing (DE 184193) etc. Recently, an active magnetic bearing twisting system was invented (US 7205692), where repulsive magnetic forces are supplied to keep a permanent magnetic ring floating and thus eliminates the metal-metal friction of existing ring/traveler system. However, this type of bearing requires very expensive

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sensors to adjust and regulate the position of the rotating permanent magnet continuously, which is very complex and requires more space in twisting zone. Therefore, the passive magnetic bearing (SMB) based on superconducting technology can be a right alternative to replace the existing twisting system in order to alleviate the present friction problem and thus allow to increase the productivity of ring spinning to a great extent (up to 300%).

III. Objectives of the Research

Within the framework of the DFG projects, "Research of friction free twisting based on superconducting technology taking account into the yarn dynamics in textile processing machine", the main objectives concern with experimental analysis and intensive research on 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. A suitable concept of SMB system needs to be designed, developed and integrated in the spinning process replacing the existing ring/traveler system. Furthermore, a mathematical modeling considering the integrated SMB system has to be developed for the determination of the yarn tension distributions and the geometrical properties of the balloon. Thus, the numerical results and experimental investigations can explore and evaluate the interaction among the parameters of the spinning process and the superconducting twisting element and derive the physical limitation of the innovative twisting element. Subsequently, the yarn properties have to be investigated with different process parameters such as different materials, yarn counts, and spindle speeds. Thus, the research work provides enormous knowledge about the implementation of the new twisting system based on superconductivity for the high performance application in textile machines.

IV. Concepts of Superconducting Magnetic Bearing System in the Ring Spinning Process

The present work focuses on the innovative friction free SMB twisting system in the ring spinning process in combination with textile and superconducting technology as well as the theoretical modeling, simulation and metrological investigation by taking into account the dynamics of the yarn.

Within this research work, two suitable concepts of circular SMB are designed, constructed and manufactured as a twisting element in place of afflicted frictional ring/traveler twisting system in ring spinning machine (Patent: DE 112012000596A5) [3]-[7]. The main components of the SMB system consist of PM ring (Neodymium-Iron-Boron-NdFeB), the superconductor ring (YBCO-$YBa_2Cu_3O_{7-x}$), and a cryogenic system. As shown schematically in Fig. 1 (a), the Permanent magnet (PM) ring and the superconducting ring are arranged coaxially or coplanarly with respect to the spindle axis. By cooling the superconductor to -196 °C, e. g. with liquid nitrogen, the flux lines of the PM penetrating the superconductor are pinned by nano-crystalline defects within the superconductor, according to the "flux pinning effect". The PM ring is levitated for both concepts and free to rotate while the superconductor ring remains stationary. Each rotation of the PM ring imparts twist in the yarn.

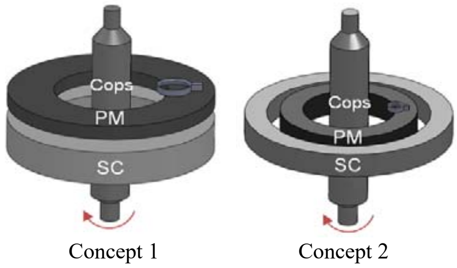


Fig. 1 (a) Concepts of SMB

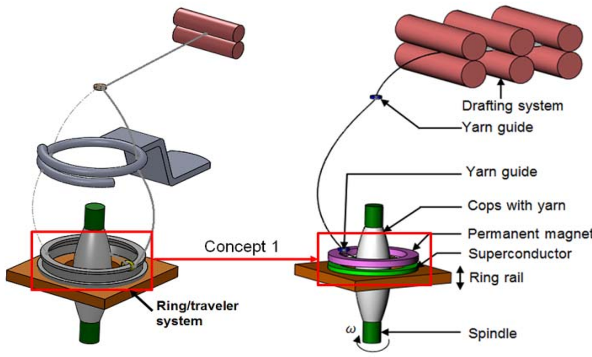


Fig. 1 (b) Schematic diagram for new concept of ring spinning process using SMB [4]

As the concept 1 has the advantage concerning dimension of cops in twisting zone in comparison to that of concept 2, it has been integrated and further investigated in the research work (Fig. 1 (b)).

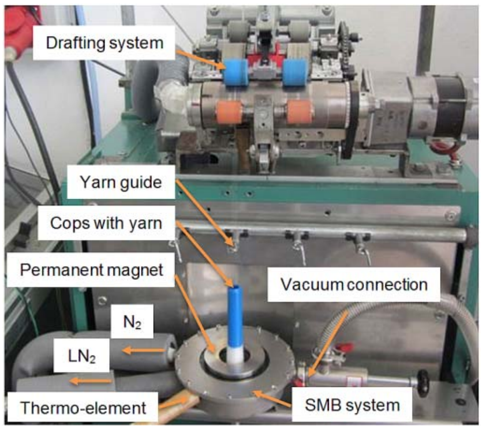
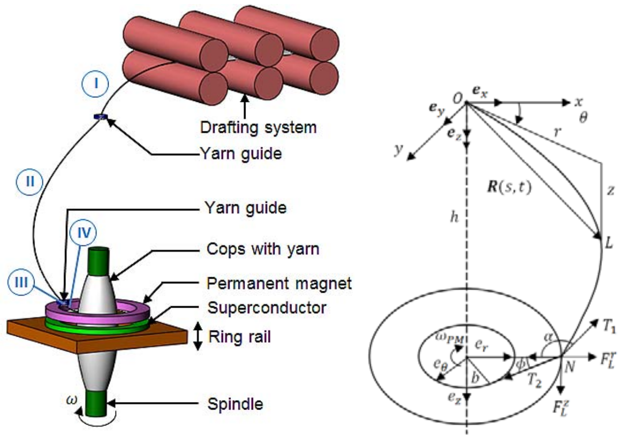


Fig. 2 Ring spinning machine with integrated SMB system

The functionality of integrated SMB system has already been tested in a 4-spindle ring spinning tester from Oerlikon AG (Fig. 2). The SMB ring spinning tester has also been presented in the international fair "International Textile Machinery Association (ITMA) 2015", Italy.

V. Mathematical Modeling of the Spinning Process with SMB System

The integration of high performance SMB-twisting element changes yarn tension distribution and balloon geometry, which differs considerably from that of conventional ring/traveler system. Therefore, a mathematical model of dynamic yarn path is established for different regions (I-IV), considering the newly integrated SMB (Fig. 3). As shown in Fig. 3, a rotating cylindrical coordinate system of $r(s)$, $\theta(s)$, $z(s)$ corresponding to the unit vectors $\boldsymbol{e_r}, \boldsymbol{e_\theta}, \boldsymbol{e_z}$ is described, which rotates with the angular speed of the spindle ($\omega = \omega \boldsymbol{e_z}$).



(a) (b)

Fig. 3 (a) Yarn path of SMB-spinning process [9]. Region I: between delivery rollers and yarn guide; II: between yarn guide and yarn guide at the permanent magnet (PM); III: yarn path through the yarn guide at the PM; IV: between yarn guide at the PM and winding point of cops and (b) Definition of coordinate system and yarn path in SMB-spinning process. F_L^z, F_L^r: Magnetic force. T_1 , T_2: Yarn tension

If a material point L is defined as position vector $\boldsymbol{R}(s,t) = r\boldsymbol{e_r} + z\boldsymbol{e_z}$, the equation of motion of yarn dynamics can be formulated as [8], [9]:

Region I: No dynamical forces occur.

Region II: $$m\{\mathfrak{D}^2\boldsymbol{R} + 2\omega\boldsymbol{e_z} \times \mathfrak{D}\boldsymbol{R} + \omega^2\boldsymbol{e_z} \times (\boldsymbol{e_z} \times \boldsymbol{R})\} = \frac{\partial}{\partial s}\left(T\frac{\partial}{\partial s}R\right) \quad (1)$$

Region III: $$\dot{\omega}_{PM}J + D\omega_{PM} = T_G^{\theta}(t)a_{iPM} \quad (2)$$

Region IV: $$T_2 = T_1 \cdot e^{\mu_y \alpha}. \quad (3)$$

wherein m is the linear yarn density, ω denotes the spindle's angular speed, $T(s,t)$ is the yarn tension at material point L, $\boldsymbol{F}$ is the air drag force, ω_{PM} is the angular speed of PM ring, $T_G^{\theta}(t)$ is the tangential yarn tension at the yarn guide of PM ring, J is moment of inertia, D is the damping constant of rotating PM ring, a_{iPM} is the inner radius of the PM, T_1 is the yarn tension at the yarn guide of the PM ring, μ_y is the frictional coefficient between yarn and yarn guide of the PM ring, and α is the wrap angle (Fig. 3).

The non-linear differential equation (1) has been integrated using Runge-Kutta method with the help of MATLAB program, considering the dynamics of SMB system in (2) and (3). As the numerical solutions are highly non-linearity and strongly dependent on the initial values, a sensitivity analysis is developed to efficiently and automatically find an optimal solution of the problem (Fig. 4). Thus, the numerical solution results in the yarn tension distribution in all regions (I-IV) and the corresponding balloon form with respect to the angular spindle speed. Fig. 5 describes the numerical results for 100% PES yarn (20 tex) using SMB system, where the yarn tensions at all regions increase with respect to angular spindle speed.

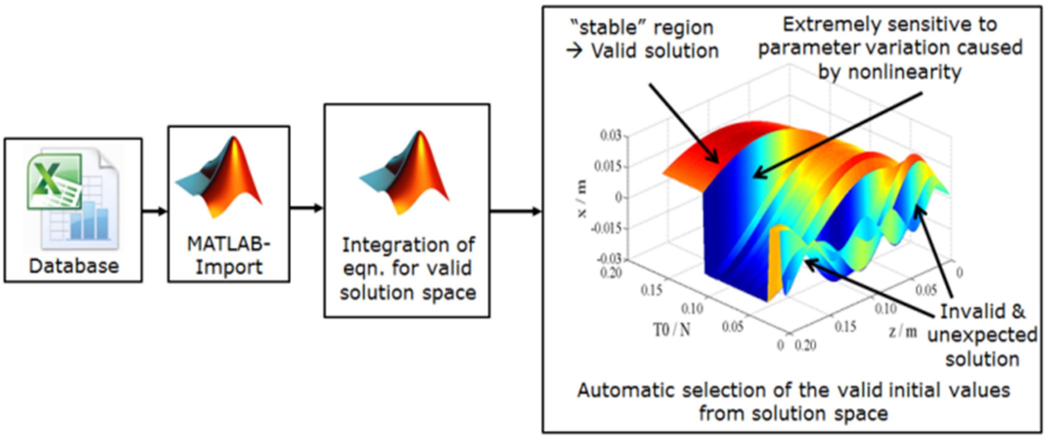
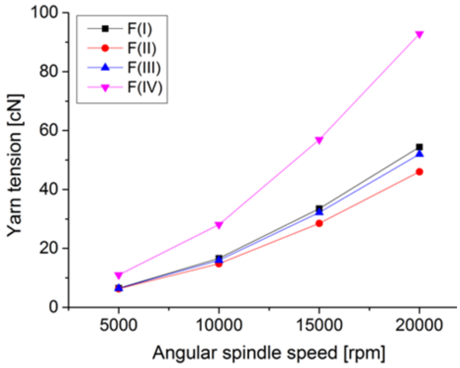
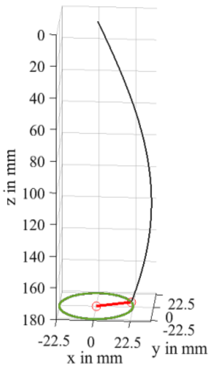


Fig. 4 Automated Sensitivity analysis [8]



(a)



(b)

Fig. 5 (a) Calculated yarn tension in region I-IV with different angular spindle speeds and (b) Calculated balloon form for the angular spindle speed of 20,000 rpm

In order to characterize the yarn tension and balloon form, in situ measurements of yarn tension at different regions of yarn path are conducted with modified or newly developed in situ measurement technologies [10]. Fig. 6 (a) shows a measurement setup of yarn tension in region IV between yarn guide of PM ring and cops. In this regard, a measuring ring (7) is mounted concentrically between PM ring (5) and the cops (8). The yarn path sliding over the measuring ring (7) deflects the leaf springs and stain gages mounted on a supporting ring (3). This deflection is measured with LabView data acquisition program. According to Fig. 6 (b), the yarn tension increases in relation to spindle speed from 5,000 to 20,000 rpm. Moreover, the measured mean yarn tensions of spinning systems, i.e. the ring/traveler and the SMB spinning system, have been compared at different regions with regard to angular spindle speeds as shown in Fig. 7. It can be observed from the Fig. 7 that the tension reduced with integrating SMB system, especially at higher angular spindle speed, which can be attributed to the elimination of the ring/traveler system and the belonging frictional force. As the polyester material cannot be spun higher than angular spindle speed of maximum 15,000 rpm due to the generation of heat using existing ring/traveler system, the measured results have been compared up to the 15,000 rpm.

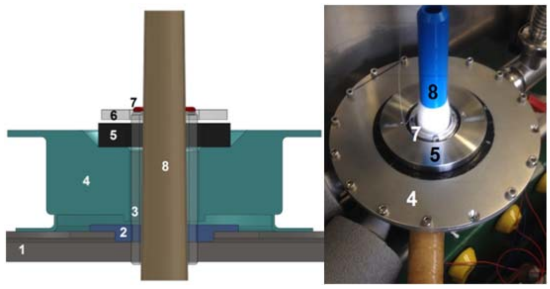


Fig. 6 (a) Setup for the measurement of yarn tension in region-IV between yarn guide of PM ring and cops [10]. 1: Ring rail 2, 3: Support for measuring ring, 4: Cryostat, 5: Superconductor, 6: Permanent magnet ring, 7: Measuring ring with Spring leaves and stain gages, 8: Cops

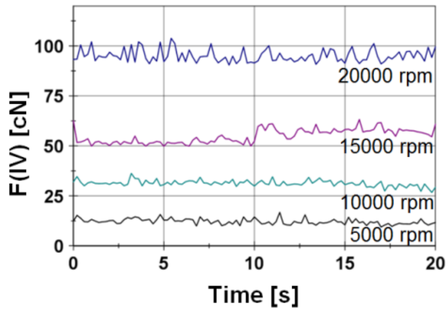


Fig. 6 (b) Measured mean values of yarn tension in region IV at different angular spindle speeds

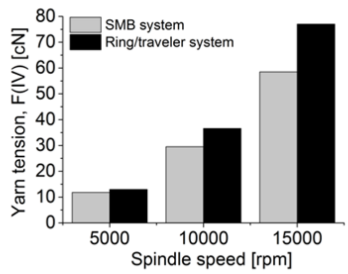


Fig. 7 Comparison of measured mean yarn tensions between conventional and SMB ring spinning in the region IV, i.e. between PM ring and Cops with respect to different angular spindle speeds

VI. Yarn Properties of SMB Ring Spinning Process

The yarn properties using the SMB-system have also been investigated for different yarn counts and angular spindle speeds and they remain nearly identical with those of conventional ring yarns. The properties such as microscopic appearance of the yarn, the yarn tenacity and yarn evenness have been investigated under standard atmospheric conditions both for 100% cotton and polyester material. The effects of spinning methods on different yarn properties are then compared and analyzed statistically. The SMB-ring yarn possesses comparable ring yarn quality regarding yarn strength and evenness. As shown in Fig. 8, the SMB-ring yarns show a tendency to have higher strength in comparison to conventional ring yarn for specific angular spindle speed.

The elimination of frictional forces occurred in the ring/traveler system also causes the improvement of the yarn evenness to some extent.

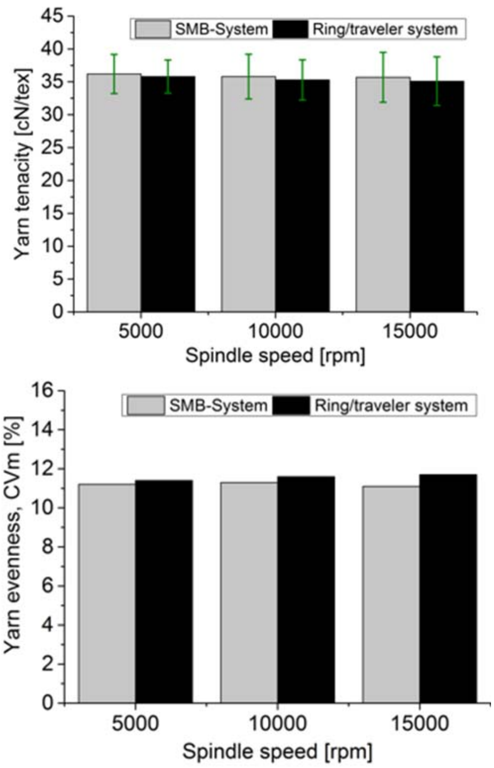


Fig. 8 Comparison of yarn properties (yarn count 20 tex) such as yarn tenacity and yarn evenness between SMB and conventional ring yarn with respect to different spindle speeds for 100% polyester material

VII. Advantages of the SMB Based Spinning Process

The main advantages of SMB system over conventional ring/traveler system can be summarized as follows:

- In SMB system, the PM ring rotates over superconducting ring friction free to impart twist in yarn, which allows to increase the productivity of ring spinning process, especially in case of spinning with synthetic yarns up to the angular spindle speed of 50,000 rpm, i.e. at least 200 % higher production rates.
- The bearing possesses a self-stabilizing behavior without any necessity of expensive control and sensor units, which results in high stability even at higher spindle speed.
- The SMB system can be simply constructed and integrated without any major modification of existing ring spinning machine.
- The yarn tension tends to significantly lower in comparison to that of conventional ring/traveler spinning at the same angular spindle speed, which enables to increase the productivity and ensures a gentle processing of fibers.
- The yarn properties after integration of SMB system show a satisfactory result with SMB system in comparison to that of conventional ring yarn.

VIII. Conclusion

The integration of the SMB twisting system ensures to eliminate the frictional heat still present in the existing ring/traveler system. The developed mathematical model and metrological investigation of the dynamic path confirm the reduced yarn tension in comparison to existing spinning processes at the same angular spindle speeds. The produced yarn with this spinning process features satisfactory ring yarn quality in comparison to conventional ring yarns. Thus, the research about the dynamic yarn behavior of SMB system presents the huge potential and a breakthrough (especially in case of thermoplastic materials) at least to double the productivity in comparison to existing spinning machines.

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 up to the angular spindle speed of 50,000 rpm. The detail study about the feasibility of the process for industrial use, especially for the cost factor including implementation cost, energy consumption etc. will also be conducted after the development of industry competent SMB ring spinning machine.

Acknowledgment

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