Statistical Modeling for the Effect of Rotor Speed, Yarn Twist and Linear Density on Production and Quality Characteristics of Rotor Spun Yarn

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ABSTRACT

The aim of this study was to develop a statistical model for the effect of RS (Rotor Speed), YT (Yarn Twist) and YLD (Yarn Linear Density) on production and quality characteristics of rotor spun yarn. Cotton yarns of 30, 35 and 40 tex were produced on rotor spinning machine at different rotor speeds (i.e. 70000, 80000, 90000 and 100000 rpm) and with different twist levels (i.e. 450, 500, 550, 600 and 700 tpm). Yarn production (g/hr) and quality characteristics were determined for all the experiments. Based on the results, models were developed using response surface regression on MINITAB®16 statistical tool. The developed models not only characterize the intricate relationships among the factors but may also be used to predict the yarn production and quality characteristics at any level of factors within the range of experimental values.

Key Words: Cotton, Twist; Rotor Speed, Productivity, Open-End Spinning.

1. INTRODUCTION

Ring spinning has been one of the most commonly used methods for producing textile yarns from staple fibers. As a matter of fact, almost all textile yarns from staple fibers were produced on the ring spinning system up till the early 1960s. Then it was realized that this versatile process had almost reached its practical limits with regard to productivity and quality. Therefore, in the following decades, research began for the development of newer spinning methods which could offer higher productivity in all yarn count ranges.

Several new ideas were put forward including rotor spinning and friction spinning systems showing promise as alternatives to the conventional ring spinning system in the coarse yarn count range. Rotor spinning system has already established its position and it accounts for more than 30% by weight of the staple fiber yarns produced in the world [1]. Over the last two decades, labour and production costs have steadily increased, and despite the progress made, ring spinning remains one of the most expensive processes for yarn manufacturing. Rotor spinning requires less number of workers and technicians, lower maintenance cost, less number of spare parts, reduced floor space and lower power cost because of less machinery involved in the yarn making process as compared to the ring spinning [2]. Furthermore, in rotor

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spinning, working conditions are generally cleaner and more pleasant which improve the efficiency as well as the health of workers. Moreover, about 2.5% less waste is generated in open-end rotor spinning as compared to the ring spinning for all yarn counts [3].

As far as quality parameters are concerned, rotor yarns are comparatively better with respect to count variation, evenness, and imperfections because drafting waves introduced by preparatory process are eliminated at the spinning operation. In addition, rotor spun yarn possesses higher elasticity than ring spun yarn [4]. Furthermore, end breakage rate per unit of production in rotor spinning process is lower which ultimately increases the quality of yarn as well as production. However, with equivalent twist levels, open-end yarn is weaker than ring yarn due to its structural difference. So higher twist level is used for rotor yarns in order to achieve the strength equivalent to that of the ring yarn. This high twist level and structural difference makes the rotor yarn harsher as compared to ring yarn [5].

Different researchers have studied various aspects of rotor yarns in the past. Lord, et. al. [6] found that open-end yarns have a larger diameter than ring yarns of the same count and twist, therefore they have better cover factor, good visual appeal and provide more fabric assistance than ring yarns. Candan, et. al. [7] stated that open-end yarns are more even, more extensible, bulkier, and weaker than ring yarns. Koc, et. al. [8] stated that yarn quality (irregularity and imperfections) tends to deteriorate as the rotor speed increases from 52,200-69,920 rpm. The yarn strength generally increased with the number of wrapper fibers. It was found that the number of belts per unit length increased with relatively smaller rotors. Gnanasekar, et. al. [9] concluded that higher rotor speeds generally decrease the yarn elongation for all the fibers due to the better consolidation of fibers in the rotor groove and thereby the avoidance of fiber slippage during tensile testing. Tao, et. al. [10] produced torque free single yarns from 100% cotton fibers. The spirality of single jersey knit fabric from these yarns was greatly reduced and in some cases completely eliminated. Sherma, et. al. [11] stated that open end yarns work quite satisfactorly in knitting and gives very acceptable fabrics in terms of dimensional and mechanical properties. Xu, [12] studied to improve the quality of rotor spinning yarn and analyzed the causes of breakages and neps, then put forward some ways to reduce yarn faults and improve the rotor spinning quality.

However, any model for predicting production and quality of rotor yarns has not been reported. Thus the aim of this study was to develop the statistical model for the effect of rotor speed and twist level of various yarn linear densities on the production and quality characteristics of the rotor spun yarn. By using such a model, optimum rotor speed and twist levels could be selected for different yarn counts in order to attain desirable productivity and quality levels of the resulting yarn for knitting.

2. MATERIALS AND METHOD

Cotton yarns of 30, 35 and 40 tex were produced on rotor machine (R40) by using Pakistani cotton with key characteristics given in Table 1. Carded sliver of 4 ktex was prepared by using Reiter blow-room line and card machine (C-51). These slivers were given two passages through drawing machine (RSB D 35) to get homogeneous and leveled sliver of 4 ktex. Actual linear density and mass variation of carded and drawn slivers are given in Table 2. Yarns of 30, 35 and 40 tex linear densities were produced by processing the drawn sliver through rotor machine (R-40) according to production parameters given in Table 3.

Rotor type (GB), rotor diameter (31mm), opening roller speed (8200 rpm), navel type (Grooved K4KR), and torque stop (ribbed w-3) were kept same for all the samples. Ten yarn cones were selected randomly from the lots of each yarn linear density and tested for their characteristics after conditioning at 20±2°C and 65±5% relative humidity for 48 hours.

Linear density of yarns was determined according to ISO 2060:1994 test method. Tensile properties of yarns were measured on Uster Tensorapid-4 in accordance with ISO 2062:1993 test method at a gauge length of 500 mm and an extension speed of 5000 mm/min. Twenty specimens per cone were tested and thus average tensile strength was determined from 200 entries. Similarly, Uster Tester-4 was used to determine CV_m%, total imperfections (thin places, thick places and neps) and hairiness at a speed of 400 m/min according to ISO 16549:2004 test method.

TABLE 1. HVI COTTON RESULTS

Property	Result
Upper Half Mean Length (mm)	28.04
Spinning Consistency Index (-)	134
Micronaire Value (micro-gram/inch)	4.70
Maturity Index (-)	0.90
Uniformity Index (%)	83.30
Short Fiber Index (%)	8.30
Strength (g/tex)	30.50
Reflectance (%)	74.70
Yellowness (degree)	8.90
Trash Count (number)	33

TABLE 2. QUALITY PARAMETERS OF SLIVER

Property	Carded Sliver	Drawn Sliver
Weight of Sliver (ktex)	4.05	4.0
Coefficient of Variation (%)	0.886	0.18
Mass Variation (CV_m %)	3.32	3.27

3 RESULTS AND DISCUSSION

3.1 Effect of Selected Variables on Yarn Production

Effect of RS, YT and YLD on yarn production was analyzed through response surface regression technique by using Minitab statistical software. All the three selected variables were found to have statistically significant effect on yarn production (p=0.000). The regression equation obtained from response surface regression coefficients is given as under:

Yarn Production (g/h) = 310.14+55.83*RS-70.24*YT+45.15*YLD+15.31*YT*YT-11.69*RS*YT+7.98*RS*YLD-9.39*YLD*YT

It is clear from the above equation that yarn production increased with increase in RS and YLD, while decreased with increase in YT. This is because yarn delivery speed is increased by increasing the RS while decreased by increasing YT. However, there is no change in delivery speed by increasing the YLD but production is increased due to increase in weight per unit length of the yarn. The coefficient of determination (R-Sq) for this regression equation is 100% which means that 100% variability in production can be explained by the terms included in the regression equation. There was significant squared effect of 'YT*YT' (p=0.000), which means that effect of YT is

TABLE 3. YARN PRODUCTION PARAMETERS

Process Parameter	Y_1					Y_2					Y_3				
Yarn Linear Density (tex)	30					35					40				
Total Draft	133.33					114.28					100				
Rotor Speed (000, rpm)	70	80	90	100		70	80	90	100		70	80	90	100	
Twist (tpm)	700	600	550	500	450	700	600	550	500	450	700	600	550	500	450

non-linear. Furthermore, there were significant interaction effects i.e. 'RS*YLD', 'RS*YT, and 'YLD*YT'. These interactions are evident in Fig. 1(a-c).

Fig. 1(a-c) depicts that the increase in production is very sharp when RS and YLD are increased simultaneously. It is also clear that this sharp increase in production is linear. Similarly, increase in production is sharp at the start when RS/YLD is increased and yarn twist is reduced simultaneously but this increase becomes steady after 600 tpm. However, this increase in production is not linear due to non-linear influence of twist.

3.2 Effect of Selected Variables on Yarn Quality Characteristics

Experimental results depicting the effect of different RSs and twist levels on quality characteristics of 40, 35 and 30 tex yarns are summarized in Tables 4-5. Effect of selected variables i.e. RS, YT and YLD on yarn quality was also

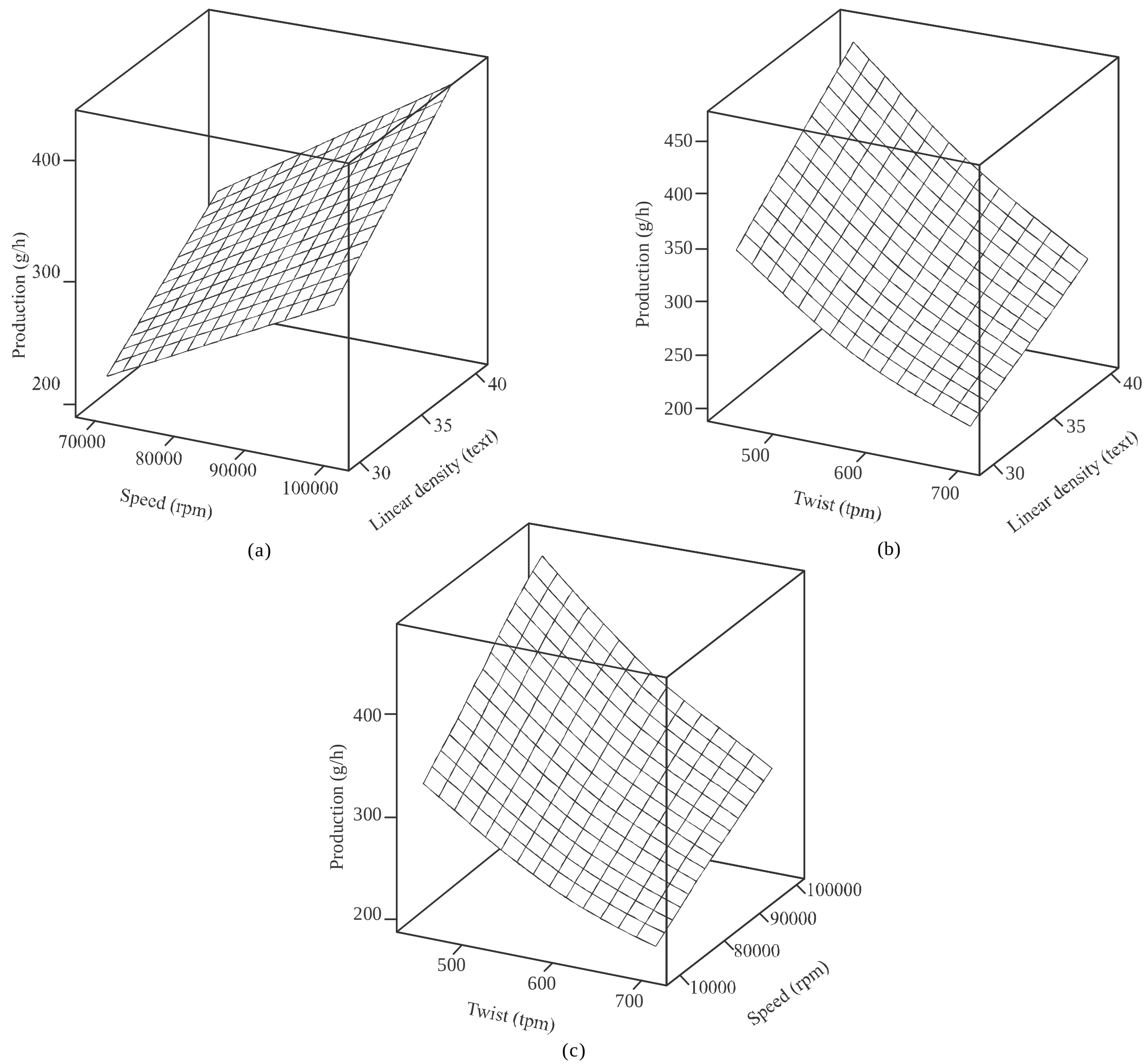

FIG. 1. INTERACTION EFFECTS OF (A) ROTOR SPEED AND YARN LINEAR DENSITY (B) YARN TWIST AND LINEAR DENSITY (C) YARN TWIST AND ROTOR SPEED ON YARN PRODUCTION

analyzed through response surface regression technique by using Minitab statistical software.

The coefficient of determination (R-Sq) for this regression equation is 98.8% which means that 98.8% variability in yarn strength can be explained by the terms included in the regression equation. As is clear from the above regression equation, yarn strength increases with increase in RS (Coef=12.78), YLD (Coef=85.01) and also in YT (Coef=55.66). There is significant squared effect of RS and YT (p=0.000), which means that effect of RS and YT is non-linear. Yarn strength increases with increase of RS due to increase in number of wrapper fibers per unit length which provide extra binding to the yarn but after 90,000 rpm, strength of yarn decreased due to major disturbance in the fiber arrangement along the yarn axis. At this stage, squared effect of rotor speed play its role and overall impact of speed increase becomes negative. Also, high rotor speeds reduced the fiber parallelization of the fiber ring in the rotor. However, this is not true for 40 tex yarn because of higher yarn diameter and number of fibers in the cross-section due to which it can withstand high yarn tension lead by high rotor speeds.

Furthermore, there is significant interaction effect between RS and YT. It is evident from Fig. 2(a) that yarn strength increases sharply at the start when RS and YT are increased simultaneously but this increase in strength becomes

TABLE 4. EFFECT OF ROTOR SPEEDS AND TWIST LEVELS ON CVm, T IPI AND HAIRINESS OF 40, 35 and 30 TEX YARNS

Rotor Speed (rpm)	Twist Levels (tpm)	Twist Factor (α)			CV_m (%)			Total IPI (Number)			H (-)		
		40 tex	35 tex	30 tex	40 tex	35 tex	30 tex	40 tex	35 tex	30 tex	40 tex	35 tex	30 tex
70000	700	140	130.90	121.24	12.75	13.13	13.00	78	64	84	5.51	5.21	4.93
70000	600	120	112.20	103.92	12.50	13.00	13.00	42	55	67	5.47	5.22	5.08
70000	550	110	102.85	95.26	12.38	13.00	13.00	32	54	56	5.47	5.15	5.13
70000	500	100	93.50	86.60	12.50	12.88	13.13	38	32	51	5.50	5.20	5.26
70000	450	90	84.15	77.94	12.50	12.75	-	28	30	-	5.53	5.31	-
80000	700	140	130.90	121.24	12.50	12.88	13.13	50	81	157	4.91	4.80	4.78
80000	600	120	112.20	103.92	12.13	12.88	13.50	30	65	146	4.80	4.83	4.97
80000	550	110	102.85	95.26	12.13	12.63	13.75	39	37	93	4.85	4.89	5.15
80000	500	100	93.50	86.60	12.38	13.38	13.38	22	100	76	5.09	5.25	5.22
80000	450	90	84.15	77.94	13.50	-	-	105	-	-	5.51	-	-
90000	700	140	130.90	121.24	11.88	13.00	13.00	72	77	79	4.47	4.60	4.48
90000	600	120	112.20	103.92	11.88	12.88	13.13	51	66	67	4.65	4.56	4.58
90000	550	110	102.85	95.26	11.75	12.63	12.88	21	58	55	4.69	4.65	4.44
90000	500	100	93.50	86.60	12.13	12.63	12.75	15	42	45	5.30	5.26	5.23
90000	450	90	84.15	77.94	12.38	12.50	0.00	12	43	-	5.24	5.28	-
100000	700	140	130.90	121.24	13.88	14.38	14.13	411	511	360	5.25	5.21	4.86
100000	600	120	112.20	103.92	13.75	14.38	14.38	333	362	391	5.37	5.03	4.95
100000	550	110	102.85	95.26	13.63	13.63	13.88	149	108	190	5.81	5.40	5.33
100000	500	100	93.50	86.60	13.63	-	14.38	112	-	229	5.78	-	5.33

steady after second step of RS and YT level. At 1st and 2nd steps, both the parameters play positive role by increasing the binding effect of fibers which is the reason of sharp increase but after that speed, fiber arrangement is disturbed and sharing of all fibers in yarn strength is reduced due to higher speed, which transfer the sharp increase segment to steady segment.

The regression equation for yarn elongation obtained from response surface regression coefficients is given as follows:

Yarn Elongation (%) = 6.0813-0.5714*RS+0.4592*YT+0.4732*YLD-0.2784*RS*RS-0.3885*RS*YT

The coefficient of determination (R-Sq) for this regression equation is 80.3% which means that 80.3% variability in yarn elongation can be explained by the terms included in the regression equation. Obviously, yarn elongation increases with increase in YT (Coef=0.4592) and YLD (Coef=0.4732), while it is decreased with the increase of RS (Coef =-0.5714). Actually, angle between the fiber spiral position and yarn axis is increased due to increase in twist which improves the springy behavior of fibers and is the source of higher elongation. Similarly, number of fibers per cross section is higher for the yarn with increased linear density which improves the cohesion force between the fibers and hence provides a better elongation. However, higher speed creates a permanent strain in the yarn due to

TABLE 5. EFFECT OF ROTOR SPEEDS AND TWIST LEVELS ON TENSILE PROPERTIES OF 40, 35 and 30 TEX YARNS

Rotor Speed (rpm)	Twist Levels (tpm)	Twist Factor (α)			SY Strength (cN)			Elongation (%)		
		40 tex	35 tex	30 tex	40 tex	35 tex	30 tex	40 tex	35 tex	30 tex
70000	700	140	130.90	121.24	526.10	452.50	366.85	7.46	7.19	6.34
70000	600	120	112.20	103.92	502.09	413.70	337.91	7.06	6.60	6.01
70000	550	110	102.85	95.26	471.41	406.35	314.97	6.70	6.36	5.82
70000	500	100	93.50	86.60	444.17	371.23	284.8	6.54	6.12	5.53
70000	450	90	84.15	77.94	407.52	329.69	-	6.20	5.40	-
80000	700	140	130.90	121.24	565.20	475.36	383.12	7.46	6.94	6.37
80000	600	120	112.20	103.92	536.46	443.57	349.02	6.95	6.54	5.73
80000	550	110	102.85	95.26	511.33	416.26	330.16	6.67	6.22	5.49
80000	500	100	93.50	86.60	472.81	396.06	304.2	6.26	5.49	4.66
80000	450	90	84.15	77.94	450.00	-	-	6.24	-	-
90000	700	140	130.90	121.24	539.03	484.00	397.94	6.67	6.66	6.28
90000	600	120	112.20	103.92	519.01	452.55	359.56	6.19	6.14	5.72
90000	550	110	102.85	95.26	507.81	428.76	343.81	6.06	5.97	5.67
90000	500	100	93.50	86.60	477.96	392.50	304.2	5.95	5.62	4.66
90000	450	90	84.15	77.94	460.09	350.71	-	5.53	5.44	-
100000	700	140	130.90	121.24	544.38	471.52	380.4	5.07	4.88	4.84
100000	600	120	112.20	103.92	525.11	442.05	352.3	4.89	4.75	4.50
100000	550	110	102.85	95.26	525.39	437.48	334.27	6.20	6.13	5.42
100000	500	100	93.50	86.60	490.95	-	308.19	5.87	-	4.46

higher spinning tension which in return reduces the elongation [8-9]. There is significant squared effect of 'RS*RS' ($p = 0.000$), which means that effect of rotor speed is non-linear. Furthermore, there is significant interaction effect between 'RS' and 'YT'. It is evident from Fig. 2(b) that yarn elongation increases sharply at the start when rotor speed and yarn twist are increased simultaneously. But this increase in elongation become steady at second step and after that, it is decreased steadily at third step and reduced sharply at last step of speed and twist. That means twist effect is dominant on the negative influence of higher rotor speed but after second step, influence of rotor speed becomes dominant on positive influence of twist and thus overall impact is reversed up-to highest level of rotor speed and twist.

The regression equation for yarn mass variation (CV_m) obtained from response surface regression coefficients is given as follows:

$$CV_m(\%) = 12.6643+0.4519*RS-0.3599*YLD + 0.7480*RS*RS$$

The coefficient of determination (R-Sq) for this regression equation is 66.5% which means that 66.5% variability in the coefficient of yarn mass variation can be explained by the terms included in the regression equation. It can be observed from the regression equation that, CV_m of yarn increases with increase in RS (Coef=0.4519) and decreases with increase of YLD (Coef=-0.3599) while the effect of yarn twist on CV_m was found to be insignificant ($p=0.83$ at 0.5 alpha). Actually, higher speed is a source of more number of wrapper fibers as shown in Fig. 3 (a-c) and disturbs the fiber arrangement in the groove of rotor so as a result, increase in irregularity is logical while higher yarn linear density improves the irregularity due to higher number of fibers per cross section [8]. There is significant squared effect of 'RS*RS' ($p=0.000$), which means that effect of rotor speed is non-linear.

The regression equation for total yarn imperfections (IPI) obtained from response surface regression coefficients is given as follows:

$$IPI\ (Numbers/km) = 53.73+93.25*RS+58.33*YT+103.03*RS*RS + 65.25*RS*YT$$

The coefficient of determination (R-Sq) for this regression equation is 73.9% which means that 73.9% variability in the IPI can be explained by the terms included in the regression equation. It is clear from the equation that the IPI increases with increase in RS (Coef=93.25) and YT (Coef=58.33). As discussed earlier, higher RS means more number of tight belts on the surface of yarn and hence observed by the evenness tester as imperfection. Similarly, higher twist makes the thin and thick places more prominent as can be seen in Fig. 3(a-c) and thus, these are counted as imperfections. The effect of YLD on the IPI was found

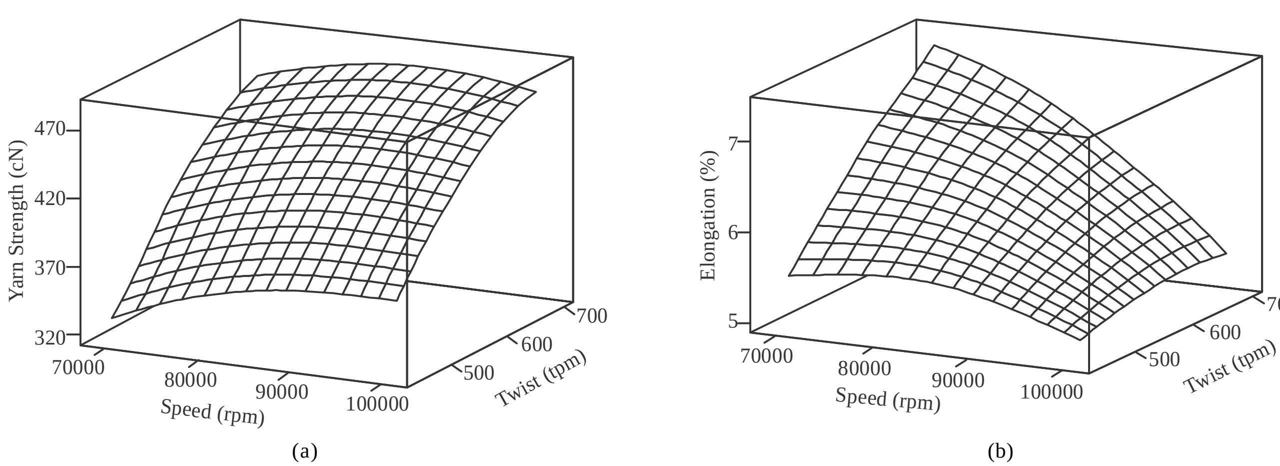

FIG. 2. INTERACTION EFFECT OF ROTOR SPEED AND YARN TWIST ON (a) YARN STRENGTH AND (b) ELONGATION

not to be statistically significant (p=0.117). However, there is significant squared effect of 'RS*RS' (p=0.000), which means that effect of RS is non-linear. Furthermore, there is significant interaction effect between 'RS' and 'YT'.

It is evident from Fig. 4(a) that IPI index increases with the increase in RS. However, at lower RS there is marginal decrease in IPI with the increase in YT while at higher RS; there is a large increase in IPI index with the increase in RS.

The regression equation for yarn hairiness index (H) obtained from response surface regression coefficients is given as follows:

$$\text{Yarn Hairiness } (-) = 4.7332-0.300*YT+0.0926*YLD+0.4869*RS*RS+0.1750*YT*YT-0.1582*RS*YT$$

The coefficient of determination (R-Sq) for this regression equation is 72.5% which means that 72.5% variability in the yarn hairiness can be explained by the terms included in the regression equation. It is evident from the equation that hairiness increases with increase in YLD (Coef=0.0926) and decreases with the increase of YT (Coef=-0.3001). More number of fibers per cross section, more protruding ends from yarn surface. Thus, higher YLD gives higher hairiness. Similarly, higher twist means more compactness of yarn which improves the quality of yarn with respect to hairiness. There are significant squared effects of 'RS*RS' (p=0.000) and YT*YT (p=0.011), which means that effect of RS and YT is non-linear. Furthermore, there is significant interaction effect between 'RS' and 'YT'. It is also evident from Fig. 4(b) that there is a marginal decrease in hairiness with the increase in twist at lower RS in comparison to large decrease in hairiness with the increase in YT at higher RSs. At lower yarn twist, there is a large increase in yarn hairiness with the increase in RS while at higher YT. There is a decrease in yarn hairiness with the increase in RS up-to certain point and beyond that there is increase in yarn hairiness with increase in RS. Actually, twist factor is dominant on the negative role of speed till the second last step and thus hairiness is decreased due to yarn compactness but at last step rotor speed factor becomes dominant on compactness factor and hence hairiness is increased due to higher disturbance in the fiber arrangement.

4. CONCLUSIONS

The effect of RS, YT level and YLD on production and quality characteristics of rotor spun yarn has been modeled using response surface regression. It has been found that the effect of these factors is not linear in all cases. There is significant squared effect and interactions among the factors studied in the models. Yarn production increases

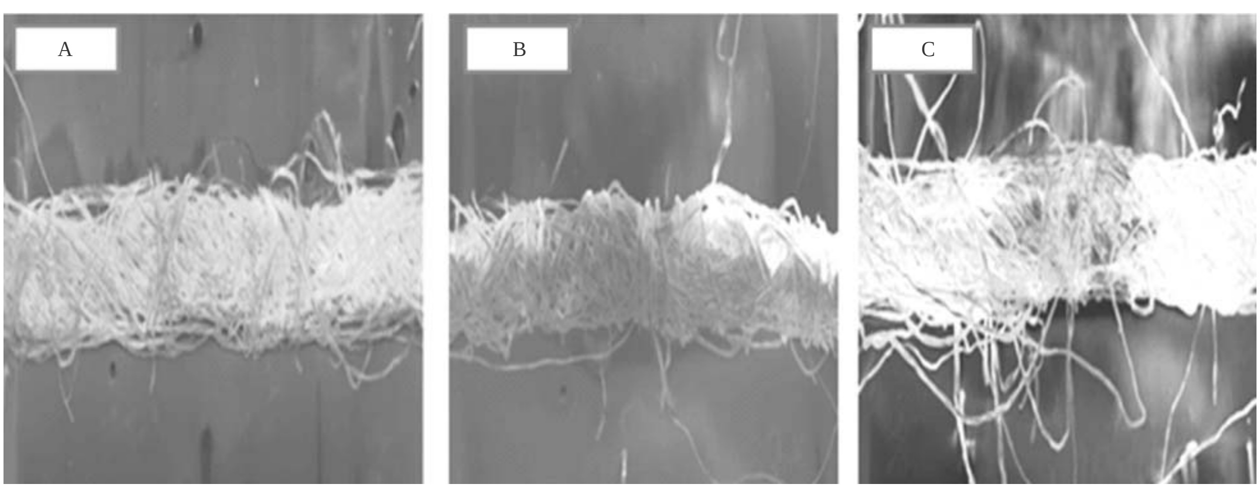

FIG. 3. SEM IMAGES TO SHOW DIFFRENCE IN YARN STRUCTURE (a) AT 70,000 RPM WITH 700 TPM, (b) AT 100,000 RPM WITH 700 TPM, (c) AT 70,000 RPM WITH 550 TPM

by increasing RS and YLD but decreases by increasing YT. Yarn strength increases sharply by increasing twist level and increases steadily by increasing RS at lower twist levels. Yarn elongation decreases by increasing RS at high twist levels while it increases by increasing twist level at lower rotor speeds. Total yarn imperfections (IPI) increase by increasing RSs and also by increasing twist levels at high rotor speeds. Yarn hairiness decreases by increasing twist levels while it first decreases by increasing rotor speed but increases by further increase in the rotor speed.

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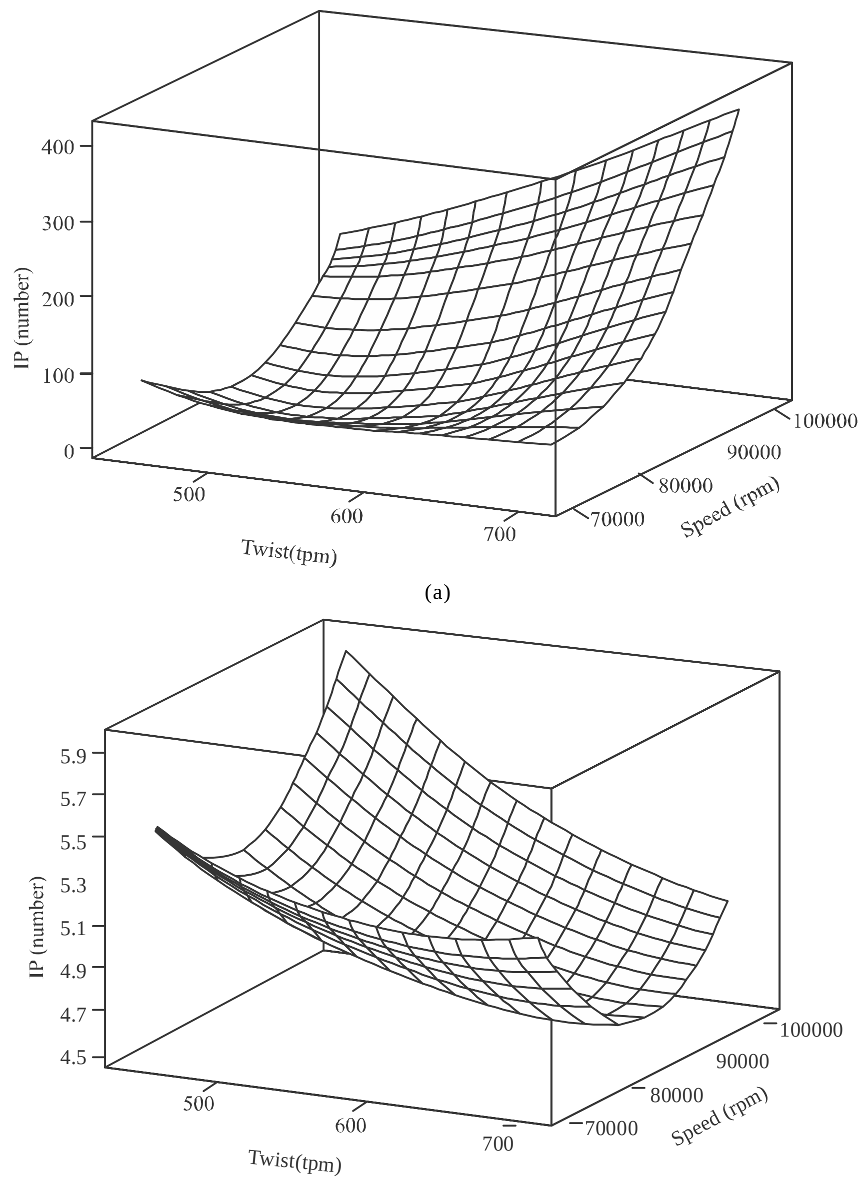

FIG. 4. INTERACTION EFFECT OF ROTOR SPEED/YARN TWIST ON (a) YARN IPI INDEX AND (b) HAIRINESS

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