# Effect of Key Process Variables on Mechanical Properties of Blended Vortex Spun Yarns

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Abstract

A study of significant factors and their interaction during vortex yarn spinning has been carried out to achieve desired mechanical properties of the polyethylene terephthalate (PET) /Cotton blended yarns which can offer process and performance advantages. The key significant factors i.e. feed ratio, air pressure and spindle size were varied in a mixed-level factorial design. The mechanical properties (count lea strength product, tenacity, and elongation at break) were studied and feed ratio was found to significantly affect the tenacity and elongation at break of spun yarns. A significant effect of these parameters was observed on the diameter and hairiness of the Muratec Vortex Spun (MVS) yarn.

**Key words**: vortex, yarn, spinning, mechanical, factorial

# Introduction

Although ring spinning is pre-dominantly used, other techniques of yarn manufacturing such as air-jet spinning have emerged owing to simplification of process, high production rate and lower cost. Vortex spun yarn, a variant of air-jet spun yarn (Oxenham, 2001), has gained acceptance in the spun yarn market since the last decade owing to its similarities to conventional ring spun yarn, in terms of appearance and tenacity values (Guldemet Basal & Oxenham, 2003; Nazan Erdumlu, Ozipek, &

Oxenham, 2012b). Vortex spun yarn is composed of an untwisted core of parallel fibres wrapped around by sheath fibres in a helical fashion (Soe, Takahashi, Nakajima, Matsuo, & Matsumoto, 2004). In terms of yarn structure, vortex spun yarns offer a unique structure, compared to ring and rotor spun yarns, as wrapper fibres start to twist from the centre axis of the yarn and move outwards. Muratec vortex spinning (MVS) machines dominate the market of vortex spinning.

The principles of vortex spinning and its modular assembly are shown in Figure 1 and Figure 2 respectively. The fibre strand delivered from the front roller nip enters the fibre guide with a needle tip at the bottom to guide the fibres into the hollow spindle. The fibre guide is covered by a nozzle from underneath having air jet orifices at defined angles to create air vortices around the hollow spindle tip. While the leading end of the fibres gets into the core, the trailing ends are under the influence of these vortices and get separated from the bundle, while passing through the air vortices zone, and fall around the spindle with subsequent wrapping around the untwisted core fibres (Murata Machinery Ltd., 2012). Downstream of the spinning assembly, a friction roller controls the winding tension as well as sets the feed ratio in reference to surface speed of the front rollers. An increase or decrease in feed ratio means a decrease and increase in linear speed of the front roller, respectively. It is this ratio which decides the amount of fibres fed into the nozzle chamber and subjected to the action of air vortices.

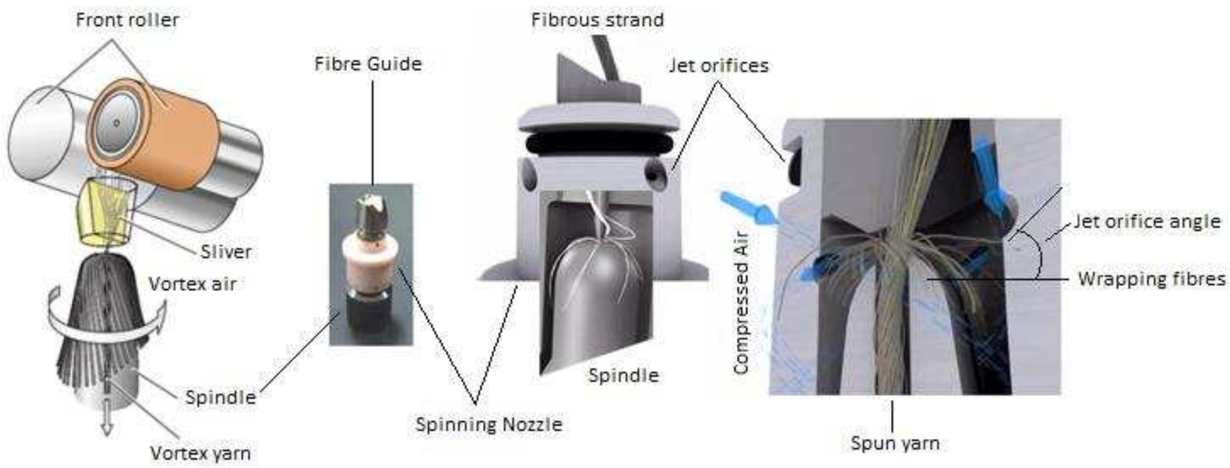



Figure 1: Description of principles of Vortex Spinning (Murata Machinery Ltd., 2012)

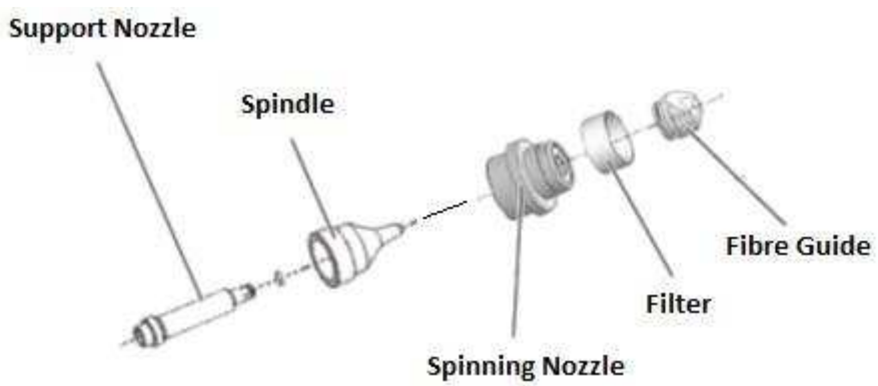



Figure 2: Schematic of Vortex Spinning Assembly (Murata Machinery Ltd., 2012)

The amount of wrapping fibres in vortex spun yarn is influenced by the type of raw material, fibre to fibre cohesion, number of fibres in fibrous strand, air pressure, feed ratio and yarn linear density. Fibre bundles with weak inter-fibre cohesion, or containing less number of fibres in the bundle (i.e. fine yarns) can't withstand the impact of air pressure and thus spread out from the main air stream(N Erdumlu, 2011; Nazan Erdumlu, Ozipek, & Oxenham, 2012a; Nazan Erdumlu et al., 2012b; Zheng, Zou, Shen, & Cheng, 2012). Due to the increased amount of wrapping fibres and their binding in the yarn structure, vortex yarn is more comparable to ring spun yarn in appearance than its predecessor i.e. air jet spun yarn. Furthermore, vortex spun yarn offers higher tenacity values, lower imperfection indices, lower hairiness and lower elongation compared to jet spun yarn, owing to close and regular packing of the fibres (Guldemet Basal & Oxenham, 2003). Higher production rates, low cost, low hairiness and higher fibre packing fractions offer advantages compared to ring spun and rotor spun yarn. However, a rigid parallel core restricted by wrapper fibres of MVS yarn is prone to cause higher stiffness, low compression, higher bending rigidity and low tenacity. (Soe et al., 2004).

Since the front end of wrapper fibres is bound inside the core and short (wild) fibres are eliminated through suction, hairiness of MVS yarn is much lower than ring spun yarn and consequently improved pilling behaviour of fabrics especially in knitted structures (Beceren & Nergis, 2008). The processing of 100% cotton on vortex spinning machine has had limited success for a narrow range of yarn linear densities while blends of cotton offer improved yarn evenness, strength and imperfection indices. The structure of MVS yarn varies with the yarn linear density since the ratio of wrapping fibres to core fibres increases as the yarn gets finer. A threshold is reached where the linear density is too low and results in frequent yarn breaks and the yarn formation becomes impractical (Nazan Erdumlu et al., 2012a).

The existing literature encompasses the analysis of yarn structure (Pei et al., 2012; Zheng et al., 2012; Zhuanyong Zou et al., 2009; Zhuanyong Zou, Cheng, Xi, Luo, & Liu, 2015), influence of process parameters on yarn structure and mechanical properties of yarn and fabric (G. Basal, 2006; Ortlek, 2005; Soe et al., 2004; Zeguang Pei & Chongwen Yu, 2011; Zhuanyong Zou et al., 2015). Zou et al. (Zhuanyong Zou et al., 2015) studied the influence of delivery speed, front roller nip to spindle tip distance, fibre length and yarn diameter on the yarn structure based on a theoretical model of fibre trajectory. The model has application to predict the yarn structure however the effect of aforementioned variables on the mechanical properties of yarns is not included. Ortlek (Ortlek, 2005) reported the effect of delivery speed, nozzle pressure and yarn diameter on yarn evenness, imperfections, hairiness and tensile properties. The spindle size and feed ratio are also key variables during the MVS process (G. Basal, 2006; Nazan Erdumlu et al., 2012b; Zeguang Pei & Chongwen Yu, 2011). Shang et al. (S. Shang, Sun, Yu, Chang, & Li, 2015) proposed an optimized design for the nozzle in an MVS machine. The proposed design exhibited improved yarn properties e.g. yarn CV%, imperfection index, tenacity and elongation at break values. However, the study was limited to a single count of viscose yarn. (Shanshan Shang, Hu, Yu, & Pei, 2016). Basal and Oxenham(G. Basal, 2006) followed a $2^5$ factorial split plot, with yarn speed and the nozzle pressure as main plots and the nozzle angle, the distance between the front roller and the spindle, and the spindle diameter as subplots. The shorter distance between the front roller and spindle and a high nozzle angle resulted in better yarn evenness. Furthermore, a high nozzle angle and pressure, low yarn delivery speed, shorter distance between the front roller and the spindle, and small spindle diameter reduced yarn hairiness.

This study aims to follow a systematic mixed-level factorial design and includes three key variables (spindle size, nozzle pressure and feed ratio) at various levels to study the non-linear effect. The main effect of various levels of spindle size (spindle tip opening in mm), nozzle pressure (air pressure in MPa) and feed ratio (the ratio of the surface speed of friction roller and that of the front drafting rollers) as well as their interactions on mechanical and dimensional properties of vortex spun yarns will be investigated. The right combination of variables can help to engineer yarns with desired dimensional and mechanical properties.

# Materials & Methods

A blend (52:48) of polyethylene terephthalate (PET, ICI Pakistan) and cotton (Pakistani variety MNH-93) fibres was employed to spin yarns (24 tex) on a Muratec vortex spinning machine (MVS-870). The properties of the cotton fibres (Table 1) were measured using HVI-Spectrum, Uster AFIS Pro-2 and Shirley trash analyser. The properties of the PET fibre (Table 1) were provided by the manufacturer. A mixed-level full factorial design resulted in eighteen (3 x 2 x 3) different combinations of variables (see Table 2) to produce the yarns.

**Table 1: Properties of Raw material**

| Cotton Fibre | | Polyethylene terephthalate (PET)Fibre | |
|---|---|---|---|
| Micronaire | 4.00 | Denier | 1.2 |
| Upper half mean length | 1.10 | Length | 38 mm |
| Degree of Reflectance (Rd.) | 73.83 | Colour | Semi dull |
| Degree of Yellowness (+b) | 8.30 | | |
| Moisture Regain % | 9.30 | Moisture Regain % | 0.65 |

| | | | |
|---|---|---|---|
| Tensile Strength (cN $Tex^{-1}$) | 29.14 | Tensile Strength (cN $Tex^{-1}$) | 70.6 |
| Elongation % | 6.00 | Elongation % | 8.7 |
| | | Crimps/in | 13 |
| Uniformity | 82.47 | - | - |
| Maturity | 0.87 | - | - |
| Short fibre index | 9.67 | - | - |
| Trash % | 6.14 | - | - |
| Neps/gm | 223.00 | - | - |

**Table 2: Design of experiment, mixed level full factorial design**

| Independent Variables | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Spindle size ($x_1$, mm) | 0.99 | 1.09 | 1.19 |
| Air Pressure ($x_2$, MPa) | 0.50 | | 0.55 |
| Feed Ratio ($x_3$) | 0.97 | 0.99 | 1.01 |

Count Lea Strength Product (CLSP) was determined through a lea strength tester (ASTM D-1578-93), yarn unevenness U%, CVm% (ASTM D1425-96), IPI (imperfection index, thick/thin/neps), Hairiness and diameter (Uster standard test method) by UT-4, Tenacity and elongation (ASTM D2256-02) by USTER® **Tensorapid 4**.

# Results and discussions

The linear density and evenness testing results are reported in Table 3.

**Table 3: Testing results for MVS yarn samples**

| Sample No | Spindle size ($x_1$, mm) | Air Pressure ($x_2$, MPa) | Feed Ratio ($x_3$) | Count (Tex) | Unevenness (U%) | CVm (%) | Imperfection Index IPI |
|---|---|---|---|---|---|---|---|
| 1 | 0.99 | 0.50 | 0.97 | 24.52 | 10.99 | 13.93 | 165.5 |
| 2 | 0.99 | 0.50 | 0.99 | 24.38 | 11.37 | 14.44 | 240.0 |
| 3 | 0.99 | 0.50 | 1.01 | 24.36 | 12.06 | 15.42 | 386.3 |
| 4 | 0.99 | 0.55 | 0.97 | 24.49 | 10.82 | 13.74 | 134.0 |
| 5 | 0.99 | 0.55 | 0.99 | 24.54 | 11.27 | 14.33 | 222.5 |
| 6 | 0.99 | 0.55 | 1.01 | 24.06 | 11.92 | 15.22 | 325.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | 1.09 | 0.50 | 0.97 | 24.38 | 11.79 | 14.98 | 235.0 |
| 8 | 1.09 | 0.50 | 0.99 | 24.45 | 12.30 | 15.59 | 284.0 |
| 9 | 1.09 | 0.50 | 1.01 | 24.47 | 12.27 | 15.65 | 378.0 |
| 10 | 1.09 | 0.55 | 0.97 | 24.56 | 11.73 | 14.90 | 214.4 |
| 11 | 1.09 | 0.55 | 0.99 | 24.54 | 12.17 | 15.47 | 276.0 |
| 12 | 1.09 | 0.55 | 1.01 | 24.75 | 12.17 | 15.51 | 392.0 |
| 13 | 1.19 | 0.50 | 0.97 | 24.52 | 11.12 | 14.12 | 180.0 |
| 14 | 1.19 | 0.50 | 0.99 | 24.27 | 11.45 | 14.54 | 225.9 |
| 15 | 1.19 | 0.50 | 1.01 | 24.66 | 12.06 | 15.39 | 376.5 |
| 16 | 1.19 | 0.55 | 0.97 | 24.75 | 11.09 | 14.08 | 160.5 |
| 17 | 1.19 | 0.55 | 0.99 | 24.34 | 11.40 | 14.49 | 196.5 |
| 18 | 1.19 | 0.55 | 1.01 | 24.15 | 11.95 | 15.23 | 336.5 |

## CLSP (Count Lea strength product)

The effect of all variables and their interactions on CLSP was found to be insignificant by analysis of variance (ANOVA) This is consistent with CLSP results plotted in Figure 3. CLSP is a product of lea strength and linear density. The decrease in feed ratio directly affects the linear density of the yarn and no significant change in the resultant CLSP indicates that strength decreased to keep the product of count and strength (i.e. CLSP) constant. However, the increase in feed ratio results in less fibre fed in to the spinning assembly, and at the same air pressure, higher twist is expected to be imparted in the fibre bundle. This again results in constant CLSP owing to lower linear density and higher strength combination. The tenacity and elongation of the spun yarns were studied further.

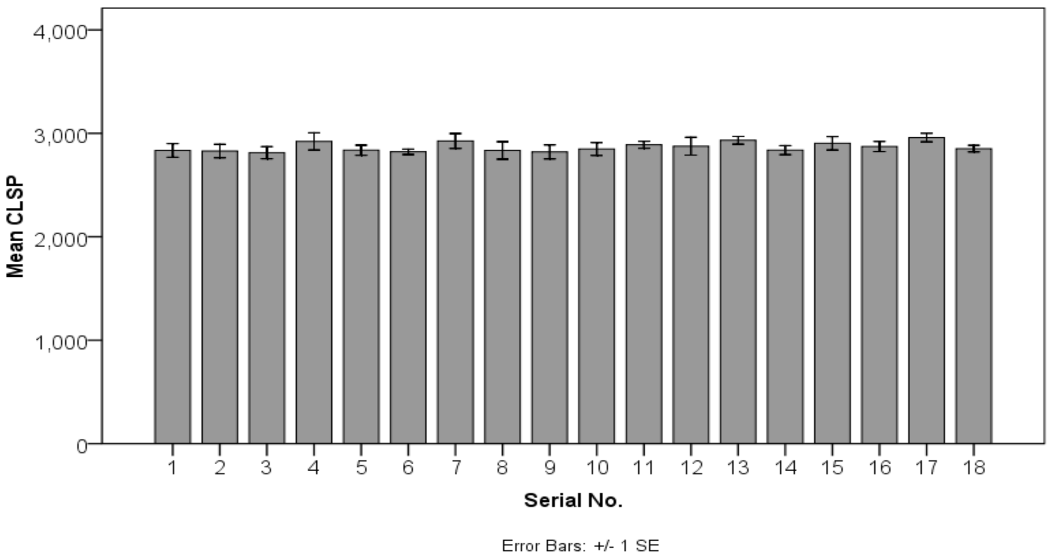



Figure 3: CLSP chart for various yarn samples (Table 3)

## Tenacity

**The feed ratio is the only factor that significantly affects the tenacity of yarn as observed from the ANOVA in** Table 4**.** The effect of the other two parameters i.e. air pressure and spindle size as well as all interactions were found to be insignificant. The results are consistent with previous studies, as the feed ratio influences the yarn strength directly in a significant way (Shanshan Shang et al., 2016; Z. Zou, Cheng, Xi, Luo, & Liu, 2015). The empirical analysis of data in Figure 4 and Figure 5 indicates that the samples at feed ratio 0.99 resulted in a higher mean tenacity (17.80 cN $Tex^{-1}$) compared to 0.97 (17.33 cN $Tex^{-1}$) and 1.01 (15.41 cN $Tex^{-1}$) . The main-effect plot of feed ratio is presented in Figure 5. The value of tenacity seems to exhibit little increase from 0.97 to 0.99 feed ratio and decreases with further increase to 1.01 feed ratio. The ratio of wrapper fibres to core fibres is likely to increase with increasing feed ratio. This decrease in number of core fibres results in less contribution of fibres to the overall tensile (uniaxial) strength of the yarns.

**Table 4: ANOVA table for Tenacity (cN $Tex^{-1}$)**

| Source | Sum of Squares | Df | Mean Square | F | P |
|---|---|---|---|---|---|
| Corrected Model | 116.953 | 17 | 6.880 | 3.662 | .000 |
| Intercept | 25542.242 | 1 | 25542.242 | 1.360E4 | .000 |
| Spindle Size | 1.333 | 2 | .667 | .355 | .703 |
| Air Pressure | 1.686 | 1 | 1.686 | .898 | .347 |
| Feed Ratio | 95.621 | 2 | 47.810 | 25.447 | .000 |
| Spindle size * Air Pressure | 7.785 | 2 | 3.893 | 2.072 | .133 |
| Spindle size * Feed ratio | 7.865 | 4 | 1.966 | 1.047 | .389 |
| Air pressure * Feed ratio | .713 | 2 | .357 | .190 | .828 |
| Spindle size * Air pressure * Feed ratio | 1.949 | 4 | .487 | .259 | .903 |
| Error | 135.273 | 72 | 1.879 | | |
| Total | 25794.469 | 90 | | | |
| Corrected Total | 252.226 | 89 | | | |

$R^2$ = 0.464 (Adj) $R^2$ = 0.337

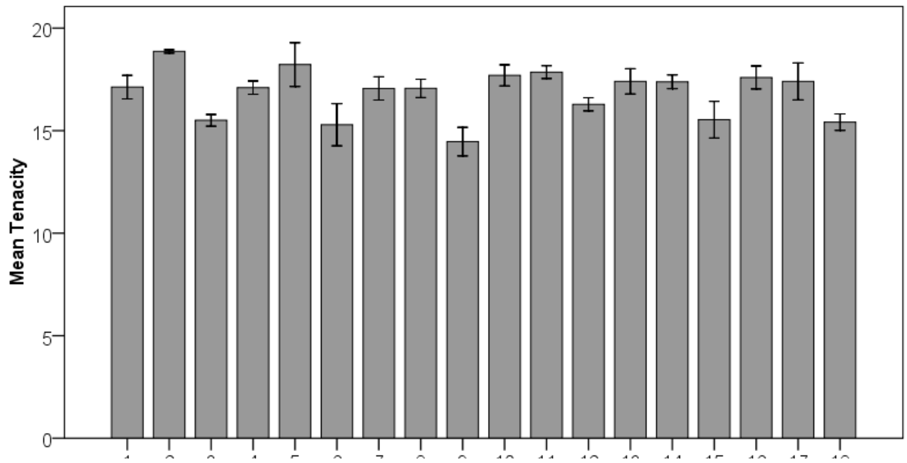



Figure 4: Tenacity (cN Tex-1) chart for various yarn samples (Sample IDs in Table 3)

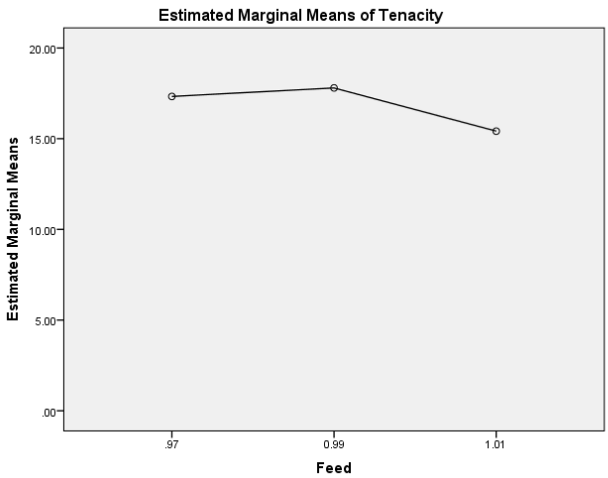



Figure 5:Main-effect plot between feed ratio and yarn tenacity(cN $Tex^{-1}$)

## Elongation at break

ANOVA (Table 5) exhibits that only the feed ratio has a significant effect on the breaking elongation of the yarn. According to Basal et al. (G. Basal, 2006) air pressure and spindle size has no significant effect on yarn elongation, which is consistent with this current study. However, the effect of feed ratio was not studied and was found significant in this current work. From the experimental values of breaking elongation (Figure 6), a feed ratio of 0.99 gives higher elongation. The higher the feed ratio, the lower will be the linear speed of the front roller and thus less fibre feed to the nozzle chamber, which in turn create a compact core-sheath yarn structure along with the influence of other variables. The effect is clearly visible in all cases of higher feed ratio levels that result in lower elongation values of the yarn owing to a relatively compact structure.

**Table 5: ANOVA for Yarn Elongation (%)**

Dependent Variable: Elongation

| Source | Sum of Squares | Df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 13.990 | 17 | .823 | 1.695 | .064 |
| Intercept | 3342.437 | 1 | 3342.437 | 6.883E3 | .000 |
| Spindle Size | .569 | 2 | .285 | .586 | .559 |
| Air Pressure | 9.000E-5 | 1 | 9.000E-5 | .000 | .989 |
| Feed Ratio | 10.389 | 2 | 5.195 | 10.697 | .000 |
| Spindle size * Air Pressure | 1.058 | 2 | .529 | 1.089 | .342 |
| Spindle size * Feed ratio | 1.525 | 4 | .381 | .785 | .539 |
| Air pressure * Feed ratio | .194 | 2 | .097 | .200 | .819 |
| Spindle size * Air pressure * Feed ratio | .254 | 4 | .063 | .131 | .971 |
| Error | 34.964 | 72 | .486 | | |
| Total | 3391.391 | 90 | | | |
| Corrected Total | 48.953 | 89 | | | |

$R^2$ = 0.286 (Adj) $R^2$ = 0.117

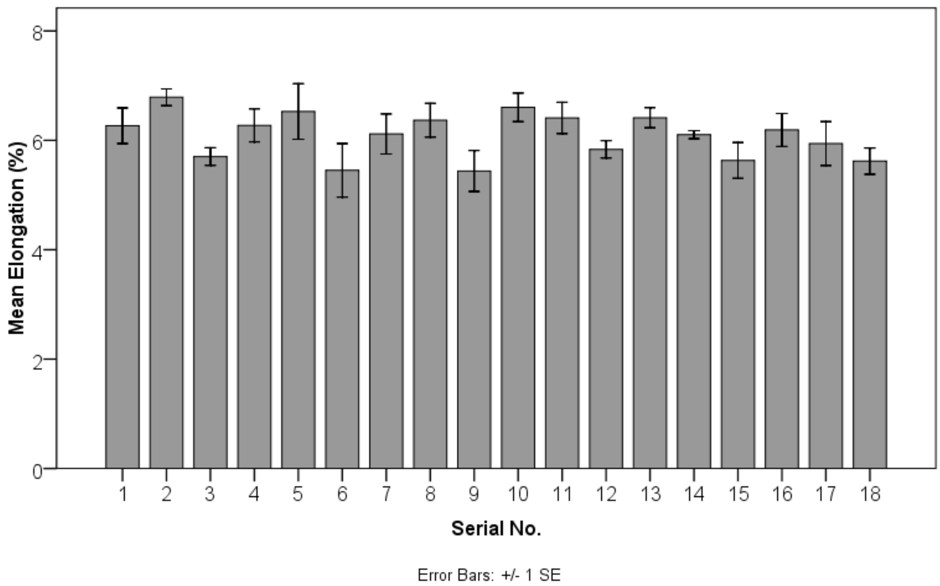



Figure 6 : Elongation (%) chart for various yarn samples (Sample IDs in Table 3)

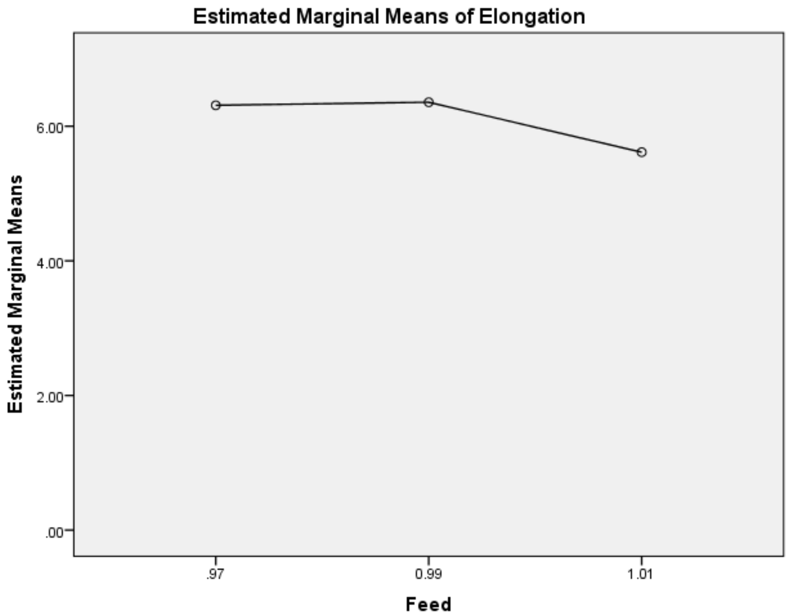



Figure 7: Main-effect plot between feed ratio and elongation (%)

The main-effect plot between feed ratio and elongation of the vortex yarn is presented in Figure 7. Yarn elongation is constant at 0.97 and 0.99 feed ratio and decreases at 1.01 feed ratio. The elongation of a vortex yarn depends upon the amount of wrapping fibres around the core and the tightness of the wrappings. An increase in feed ratio increases the amount of wrapped fibres and the resultant compression of fibres leading to relatively lower elongation.

## Mean diameter

ANOVA (Table 6) reveals a three-way interaction effect between the variables (Spindle size, air pressure and feed ratio). The yarn having greater spindle size and low air pressure results in a coarser yarn diameter as is obvious from samples 3, 14 and 15. The increase in spindle size allows a higher number of fibres to be wrapped around the core and low air pressure decreases the axial and tangential velocity which results in a lower twist level on the fibre bundles resulting in higher yarn diameter.

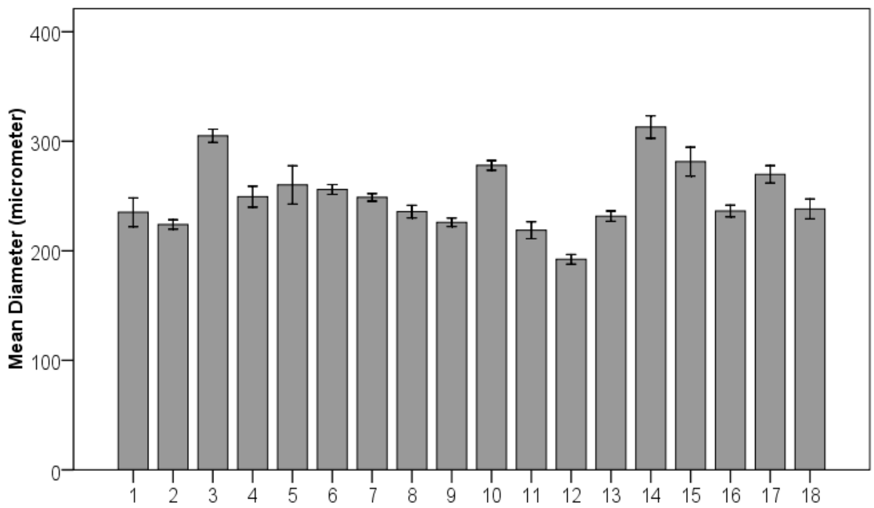


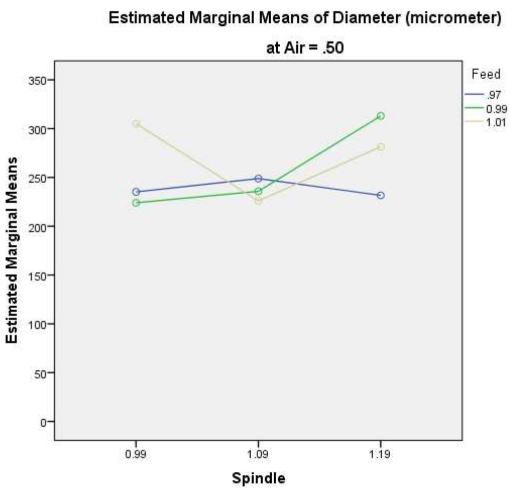

Figure 8: Diameter (micron) chart for various yarn samples

**Table 6: ANOVA table for yarn diameter (micron)**

Dependent Variable: Diameter (µm)

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 79737.789 | 17 | 4690.458 | 13.207 | .000 |
| Intercept | 5624500.011 | 1 | 5624500.011 | 1.584E4 | .000 |
| Spindle Size | 13270.289 | 2 | 6635.144 | 18.682 | .000 |
| Air Pressure | 2878.678 | 1 | 2878.678 | 8.105 | .006 |
| Feed Ratio | 743.622 | 2 | 371.811 | 1.047 | .356 |
| Spindle size * Air Pressure | 3060.556 | 2 | 1530.278 | 4.309 | .017 |
| Spindle size * Feed ratio | 40842.178 | 4 | 10210.544 | 28.749 | .000 |
| Air pressure * Feed ratio | 12767.356 | 2 | 6383.678 | 17.974 | .000 |
| Spindle size * Air pressure * Feed ratio | 6175.111 | 4 | 1543.778 | 4.347 | .003 |
| Error | 25571.200 | 72 | 355.156 | | |
| Total | 5729809.000 | 90 | | | |
| Corrected Total | 105308.989 | 89 | | | |

$R^2$ = 0.757 (Adj) $R^2$ = 0.700



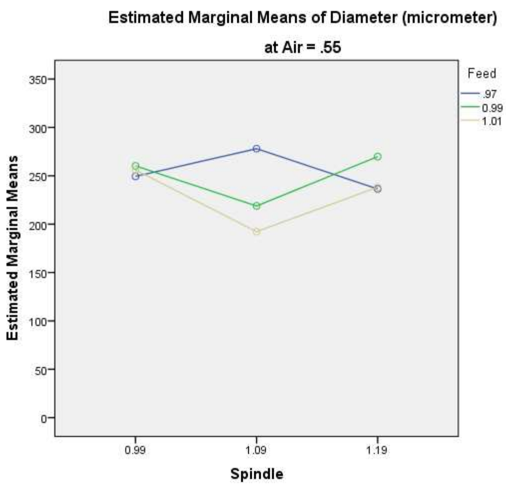



Figure 9: Feed Ratio-Spindle size interaction plot for mean diameter (µm) at 0.50 MPa Air pressure

Figure 10: Feed Ratio-Spindle size interaction plot for mean diameter (µm)at 0.55 MPa Air pressure

Figure 9 shows all three levels of spindle size and feed ratio at 0.50 air pressure and Figure 10 shows all three levels of spindle size and feed ratio at 0.55 air pressure. At both levels of air pressure, the plots for yarn diameter show non-linear behaviour of the yarn diameter with various levels of spindle size and feed ratio. Generally, it can be concluded that a higher spindle setting at a higher feed ratio value and lower air pressure setting results in a coarser yarn which is effectively a bulkier yarn with low packing fraction. A low air pressure will avoid yarn compactness and a wider spindle setting will provide more space for the fibres, resulting in loose wrapping of fibres.

## Hairiness

Figure 11 shows the hairiness chart of the yarn samples and Table 7 presents the ANOVA for hairiness, which shows a significant three-way interaction among the three process parameters.

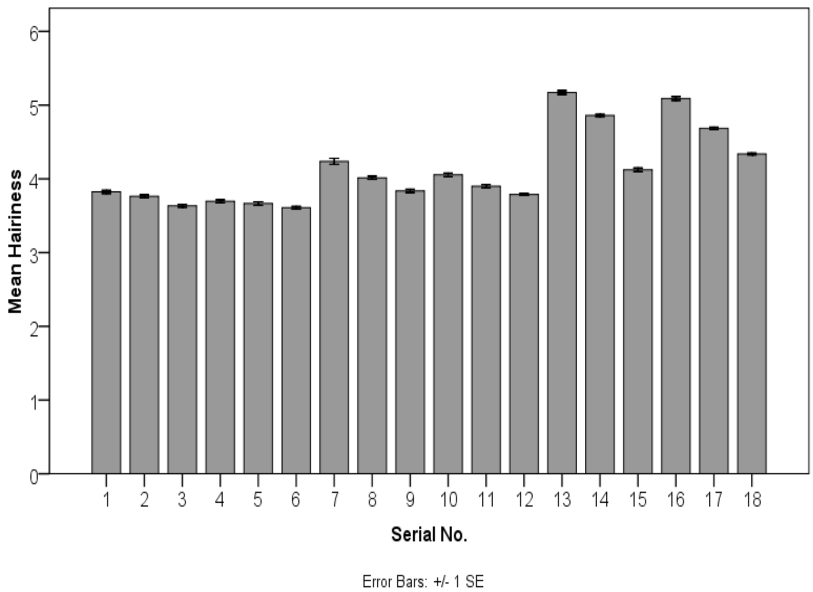


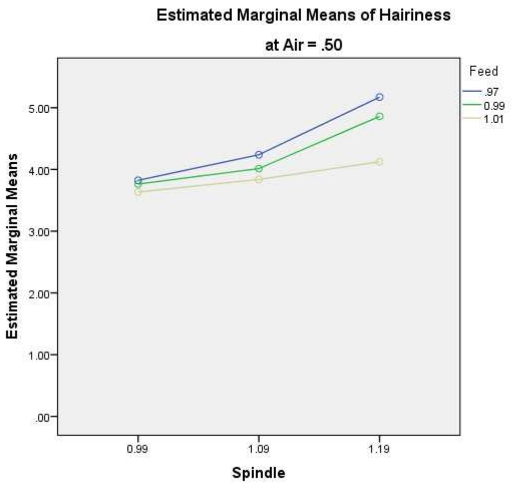

Figure 11: Hairiness chart for yarn samples

**Table 7: ANOVA table for Hairiness**

Dependent Variable: Hairiness

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 21.630 | 17 | 1.272 | 526.853 | .000 |
| Intercept | 1533.387 | 1 | 1533.387 | 6.349E5 | .000 |
| Spindle Size | 16.468 | 2 | 8.234 | 3.410E3 | .000 |
| Air Pressure | .113 | 1 | .113 | 46.819 | .000 |
| Feed Ratio | 3.157 | 2 | 1.578 | 653.525 | .000 |
| Spindle size * Air Pressure | .040 | 2 | .020 | 8.333 | .001 |
| Spindle size * Feed ratio | 1.610 | 4 | .403 | 166.694 | .000 |
| Air pressure * Feed ratio | .155 | 2 | .078 | 32.191 | .000 |
| Spindle size * Air pressure * Feed ratio | .086 | 4 | .022 | 8.918 | .000 |
| Error | .174 | 72 | .002 | | |
| Total | 1555.191 | 90 | | | |
| Corrected Total | 21.804 | 89 | | | |

$R^2$ = 0.992 (Adj) $R^2$ = 0.990



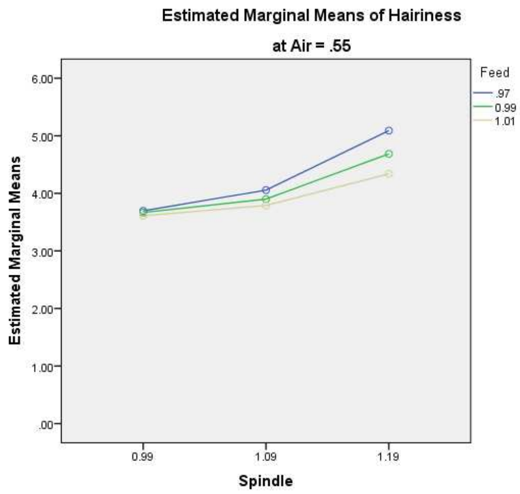




Figure 12: Feed Ratio-Spindle size interaction plot for yarn hairiness at 0.50 MPa Air pressure

Figure 13: Feed Ratio-Spindle size interaction plot for yarn hairiness at 0.55 MPa Air pressure

Figure 12 shows three levels of spindle size and feed ratio at 0.50 air pressure and Figure 13 shows three levels of spindle size and feed ratio at 0.55 air pressure. Generally, the higher pressure results in a relatively lower level of yarn hairiness, owing to higher twist insertion. At both levels of air pressure, the hairiness is increased at higher spindle size and lower feed ratio setting. Especially at s higher spindle size with both air pressure values, the effect of the feed ratio is more pronounced. However, the lower feed ratio at lower spindle size does not have a marked effect on yarn hairiness. It appears that a combination of higher pressure, lower spindle size and higher feed ratio results in lower values of hairiness. At a higher spindle size, the use of higher feed ratio and air pressure is more pivotal.

A narrow spindle size allows better fibre coherence with the yarn body owing to a compact structure with low hairiness and vice versa. The air pressure also affects the hairiness of the yarn by increasing lateral fibre ends wrapped around the main yarn structure more firmly. When the feed ratio is low, the feed from the front draft rollers will be high and a higher number of fibres come in to the nozzle chamber, or in other terms the same amount of fibres spend less time under the influence of air pressure and the formed yarn structure will be less compact resulting in high hairiness and vice versa for a higher feed ratio. Hence, the hairiness of vortex yarn is mutually dependent on all three factors. For lower hairiness, a narrow spindle size will accommodate fibres in an arranged fashion, a higher air pressure will facilitate their binding around the core and a higher feed ratio will compact available wrapping fibres (G. Basal, 2006; Nazan Erdumlu et al., 2012b).

# Conclusions

Vortex spinning is a high speed technique of manufacturing staple spun yarns. The effect of key process parameters of vortex spinning machine (the feed ratio, spindle size and air pressure) on the properties of yarn was studied. The combination of these important parameters in various possible ways can lead to the development of yarns with tailored mechanical properties for desired end uses. The count lea strength product was not affected by any of the variables and their interactions. Furthermore, where tenacity and elongation of the yarns were significantly affected by feed ratio.

For yarn diameter and hairiness, a three-way interaction of all variables was found significant. Hence, for similar values of CLSP, yarns with a range of different properties can be manufactured. Specifically; lower feed ratio, wider spindle size, and low air pressure can produce softer, and bulkier yarn suitable for knitting. On the other hand; higher feed ratio, narrow spindle size, and high air pressure can generate stiffer and compact yarn suitable for weaving.

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**Table 8: Properties of Raw material**

| Cotton Fibre | | Polyethylene terephthalate (PET)Fibre | |
|---|---|---|---|
| Micronaire | 4.00 | Denier | 1.2 |
| Upper half mean length | 1.10 | Length | 38 mm |
| Degree of Reflectance (Rd.) | 73.83 | Colour | Semi dull |
| Degree of Yellowness (+b) | 8.30 | | |
| Moisture Regain % | 9.30 | Moisture Regain % | 0.65 |
| Tensile Strength (cN $Tex^{-1}$) | 29.14 | Tensile Strength (cN $Tex^{-1}$) | 70.6 |
| Elongation % | 6.00 | Elongation % | 8.7 |
| | | Crimps/in | 13 |
| Uniformity | 82.47 | - | - |
| Maturity | 0.87 | - | - |
| Short fibre index | 9.67 | - | - |
| Trash % | 6.14 | - | - |
| Neps/gm | 223.00 | - | - |

**Table 9: Design of experiment, mixed level full factorial design**

| Independent Variables | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Spindle size ($x_1$, mm) | 0.99 | 1.09 | 1.19 |
| Air Pressure ($x_2$, MPa) | 0.50 | | 0.55 |
| Feed Ratio ($x_3$) | 0.97 | 0.99 | 1.01 |

**Table 10: Testing results for MVS yarn samples**

| Sample No | Spindle size (x1, mm) | Air Pressure (x2, MPa) | Feed Ratio (x3) | Count (Tex) | Unevenness (U%) | CVm (%) | Imperfection Index IPI |
|---|---|---|---|---|---|---|---|
| 1 | 0.99 | 0.50 | 0.97 | 24.52 | 10.99 | 13.93 | 165.5 |
| 2 | 0.99 | 0.50 | 0.99 | 24.38 | 11.37 | 14.44 | 240.0 |
| 3 | 0.99 | 0.50 | 1.01 | 24.36 | 12.06 | 15.42 | 386.3 |
| 4 | 0.99 | 0.55 | 0.97 | 24.49 | 10.82 | 13.74 | 134.0 |
| 5 | 0.99 | 0.55 | 0.99 | 24.54 | 11.27 | 14.33 | 222.5 |
| 6 | 0.99 | 0.55 | 1.01 | 24.06 | 11.92 | 15.22 | 325.0 |
| 7 | 1.09 | 0.50 | 0.97 | 24.38 | 11.79 | 14.98 | 235.0 |
| 8 | 1.09 | 0.50 | 0.99 | 24.45 | 12.30 | 15.59 | 284.0 |
| 9 | 1.09 | 0.50 | 1.01 | 24.47 | 12.27 | 15.65 | 378.0 |
| 10 | 1.09 | 0.55 | 0.97 | 24.56 | 11.73 | 14.90 | 214.4 |
| 11 | 1.09 | 0.55 | 0.99 | 24.54 | 12.17 | 15.47 | 276.0 |
| 12 | 1.09 | 0.55 | 1.01 | 24.75 | 12.17 | 15.51 | 392.0 |
| 13 | 1.19 | 0.50 | 0.97 | 24.52 | 11.12 | 14.12 | 180.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14 | 1.19 | 0.50 | 0.99 | 24.27 | 11.45 | 14.54 | 225.9 |
| 15 | 1.19 | 0.50 | 1.01 | 24.66 | 12.06 | 15.39 | 376.5 |
| 16 | 1.19 | 0.55 | 0.97 | 24.75 | 11.09 | 14.08 | 160.5 |
| 17 | 1.19 | 0.55 | 0.99 | 24.34 | 11.40 | 14.49 | 196.5 |
| 18 | 1.19 | 0.55 | 1.01 | 24.15 | 11.95 | 15.23 | 336.5 |

**Table 11: ANOVA table for Tenacity (cN $Tex^{-1}$)**

| Source | Sum of Squares | Df | Mean Square | F | P |
|---|---|---|---|---|---|
| Corrected Model | 116.953 | 17 | 6.880 | 3.662 | .000 |
| Intercept | 25542.242 | 1 | 25542.242 | 1.360E4 | .000 |
| Spindle Size | 1.333 | 2 | .667 | .355 | .703 |
| Air Pressure | 1.686 | 1 | 1.686 | .898 | .347 |
| Feed Ratio | 95.621 | 2 | 47.810 | 25.447 | .000 |
| Spindle size * Air Pressure | 7.785 | 2 | 3.893 | 2.072 | .133 |
| Spindle size * Feed ratio | 7.865 | 4 | 1.966 | 1.047 | .389 |
| Air pressure * Feed ratio | .713 | 2 | .357 | .190 | .828 |
| Spindle size * Air pressure * Feed ratio | 1.949 | 4 | .487 | .259 | .903 |
| Error | 135.273 | 72 | 1.879 | | |
| Total | 25794.469 | 90 | | | |
| Corrected Total | 252.226 | 89 | | | |

$R^2$ = 0.464 (Adj) $R^2$ = 0.337

**Table 12: ANOVA for Yarn Elongation (%)**

Dependent Variable: Elongation

| Source | Sum of Squares | Df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 13.990 | 17 | .823 | 1.695 | .064 |
| Intercept | 3342.437 | 1 | 3342.437 | 6.883E3 | .000 |
| Spindle Size | .569 | 2 | .285 | .586 | .559 |
| Air Pressure | 9.000E-5 | 1 | 9.000E-5 | .000 | .989 |
| Feed Ratio | 10.389 | 2 | 5.195 | 10.697 | .000 |
| Spindle size * Air Pressure | 1.058 | 2 | .529 | 1.089 | .342 |
| Spindle size * Feed ratio | 1.525 | 4 | .381 | .785 | .539 |
| Air pressure * Feed ratio | .194 | 2 | .097 | .200 | .819 |
| Spindle size * Air pressure * Feed ratio | .254 | 4 | .063 | .131 | .971 |
| Error | 34.964 | 72 | .486 | | |
| Total | 3391.391 | 90 | | | |
| Corrected Total | 48.953 | 89 | | | |

$R^2$ = 0.286 (Adj) $R^2$ = 0.117

**Table 13: ANOVA table for yarn diameter (micron)**

Dependent Variable:Diameter (Diameter)

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 79737.789 | 17 | 4690.458 | 13.207 | .000 |
| Intercept | 5624500.011 | 1 | 5624500.011 | 1.584E4 | .000 |
| Spindle Size | 13270.289 | 2 | 6635.144 | 18.682 | .000 |
| Air Pressure | 2878.678 | 1 | 2878.678 | 8.105 | .006 |
| Feed Ratio | 743.622 | 2 | 371.811 | 1.047 | .356 |
| Spindle size * Air Pressure | 3060.556 | 2 | 1530.278 | 4.309 | .017 |
| Spindle size * Feed ratio | 40842.178 | 4 | 10210.544 | 28.749 | .000 |
| Air pressure * Feed ratio | 12767.356 | 2 | 6383.678 | 17.974 | .000 |
| Spindle size * Air pressure * Feed ratio | 6175.111 | 4 | 1543.778 | 4.347 | .003 |
| Error | 25571.200 | 72 | 355.156 | | |
| Total | 5729809.000 | 90 | | | |
| Corrected Total | 105308.989 | 89 | | | |

$R^2$ = 0.757 (Adj) $R^2$ = 0.700

**Table 14: ANOVA table for Hairiness**

Dependent Variable: Hairiness

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 21.630 | 17 | 1.272 | 526.853 | .000 |
| Intercept | 1533.387 | 1 | 1533.387 | 6.349E5 | .000 |
| Spindle Size | 16.468 | 2 | 8.234 | 3.410E3 | .000 |
| Air Pressure | .113 | 1 | .113 | 46.819 | .000 |
| Feed Ratio | 3.157 | 2 | 1.578 | 653.525 | .000 |
| Spindle size * Air Pressure | .040 | 2 | .020 | 8.333 | .001 |
| Spindle size * Feed ratio | 1.610 | 4 | .403 | 166.694 | .000 |
| Air pressure * Feed ratio | .155 | 2 | .078 | 32.191 | .000 |
| Spindle size * Air pressure * Feed ratio | .086 | 4 | .022 | 8.918 | .000 |
| Error | .174 | 72 | .002 | | |
| Total | 1555.191 | 90 | | | |
| Corrected Total | 21.804 | 89 | | | |

Dependent Variable: Hairiness

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Corrected Model | 21.630 | 17 | 1.272 | 526.853 | .000 |
| Intercept | 1533.387 | 1 | 1533.387 | 6.349E5 | .000 |
| Spindle Size | 16.468 | 2 | 8.234 | 3.410E3 | .000 |
| Air Pressure | .113 | 1 | .113 | 46.819 | .000 |
| Feed Ratio | 3.157 | 2 | 1.578 | 653.525 | .000 |
| Spindle size * Air Pressure | .040 | 2 | .020 | 8.333 | .001 |
| Spindle size * Feed ratio | 1.610 | 4 | .403 | 166.694 | .000 |
| Air pressure * Feed ratio | .155 | 2 | .078 | 32.191 | .000 |
| Spindle size * Air pressure * Feed ratio | .086 | 4 | .022 | 8.918 | .000 |
| Error | .174 | 72 | .002 | | |
| Total | 1555.191 | 90 | | | |

$R^2 = 0.992$ (Adj) $R^2 = 0.990$