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Influence of ring frame process parameters on yarn structure and fabric assistance

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An attempt has been made to study the influence of ring frame parameters i.e. yarn twist multiplies, spindle speed and ring frame draft on yarn characteristics to exploit the translation of yarn structures into the fabric assistance. Understanding the relationship between yarn structure and fabric strength helps in engineering the yarn structure to improve the strength translation of yarns to fabric strength. Accordingly, study on fabric strength in weft/warp direction per yarn, weft/ warp break force inside fabric, weft/warp pull-out force and yarn failure zone length are also carried out. Yarn structure is found to affect the fabric thickness and fabric tensile behaviour. The yarn diameter has a direct effect on the yarn pull out force. The yarn structure also plays a dominant role in deciding the yarn failure zone length.

Keywords: Fabric assistance, Fabric strength, Yarn diameter, Yarn packing density, Yarn radial packing density, Yarn structure

1 Introduction

Evaluation of yarn strength is one of the critical aspects of yarn quality in spinning industry[1]. However, evaluation of yarns in terms of their likely performance in subsequent fabric manufacturing process and contribution of their strength to fabric are necessary from a fabric producer point of view[2]. It is established that the structure and mechanical properties of textile fabrics are closely related[3,4]. The tensile strength of a fabric is recognized as one of the most important quality parameters of fabric[5]. It not only depends on the strength of the constituent yarns, but also on the yarn structure as well[6,7]. Yarn structure definitely assists to bring changes in fabric strength[7].

The packing characteristics of the fibres in the yarn and, in particular, radial packing density of yarn have direct bearing on the fabric geometry[8,9]. These factors are responsible to change the characteristics of interlacement point between warp and weft and accordingly influence the frictional resistance towards the fabric extension. The degree of these changes is likely to be different for different yarns made on a particular spinning system having different structure duly influenced by the considered spinning parameters of yarn. Although yarn structure, as factor influencing the fabric assistance, has been mentioned in literature, still adequate research has not been carried out in this direction. The process parameters affecting packing factor of yarns have been systematically studied[10-12], but the reports on scientific research on interrelationship between processing parameters during yarn manufacturing and fabric assistance characteristics are scanty. Understanding the relationship between yarn structure and fabric strength helps in engineering the yarn structure to improve the strength translation of yarns into the fabric. The development of new yarn structures raises questions about the nature and quality of fabric made from these yarns. Hence, an attempt has been made in the present work to study the influence of ring frame parameters, i.e. yarn twist multiplies, spindle speed and ring frame draft on yarn characteristics to exploit the effective translation of yarn structures into the fabric assistance.

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2 Materials and Methods

Cotton fibre having following properties was used for the present study:

Property	Value
Average fineness	: 1.3 dtex
2.5% span length	: 27.7mm
Uniformity ratio	: 48%
SFI	: 11.6
Tenacity	: 20.6 cN/tex
Trash content	: 2.54%

2.1 Preparation of Sample

Yarns of 20 tex linear density was produced using rovings of three different linear densities. Total seven yarns to be used as weft were produced from considered rovings. The details of processing parameters are given Table 1. Accordingly, seven different woven fabrics were produced maintaining 100% cotton yarn of 20 tex linear density as common warp and researched yarns as weft. All the samples were produced at the fixed fabric sett of 29 ends/cm and 17 picks/cm.

2.2 Evaluation of Yarn Properties

Yarn tensile strength was measured on Instron tensile tester at a gauge length of 50 mm and testing speed of 100 mm/min due to specific requirements. Yarn diameters were measured on Leica projection microscope at 150 randomly selected points along the length of the yarn. Rothschild tensiometer-2000 was used to measure the yarn-to-yarn coefficient of friction (ASTM standard: D 3412-01). The details of yarn properties are given in Tables 2-4.

2.3 Evaluation of Fabric Properties

Fabric samples were subsequently subjected to tensile testing on Instron tensile tester using a testing speed of 100 mm/min. The specifications of fabric samples used in the strip test are given below:

- Length of the fabric strip–75 mm
- Width of the fabric strip–35 mm
- Distance between the two jaws–50 mm
- Width of the strip–25 mm (excluding ravelled portion)

The results of tensile properties of woven fabrics are shown in Tables 2-4. Single yarn pulling force from the fabric sample was measured using Instron tensile tester at a crosshead speed of 100 mm/min. During the experiment, the upper jaw gripped only the upper portion of the pulling yarn, whereas the lower jaw gripped all the yarns of the fabric sample except the lower portions of the pulling yarn. Single yarn breaking force inside the fabric sample was also measured using Instron tensile tester at a crosshead speed of 100 mm/min. During the experiment, the upper jaw gripped only the upper portion of the pulling yarn, whereas the lower jaw gripped all the yarns of the fabric sample. For calculating the ratio between fabric strip strength per thread and single yarn strength, the corresponding yarn samples were also tested using Instron tensile tester at 50 mm gauge length and 100 mm/min crosshead speed.

After tensile failure of yarns, both the broken ends were collected from the Instron tensile tester and then observed under the Leica digital microscope at ×40 magnification. The captured images are classified, depending on the disposition of fibres in the failure ends. On the basis of our observations, configuration of yarn broken ends could be classified under Sharp, Tapered and Slipped categories[13,14]. The length of yarn failure zone is defined as the average length of the reduced region of cross-section of one of the failed ends for each set of experiment[13].

The thickness of fabric was measured as per the ASTM D1777-96(2002) standard test method for

Table 1 — Yarn process parameters

Yarn code	A	B	C	D	E	F	G
TM	4	4	4	3.5	4.5	4	4
Draft	22.7	22.7	22.7	22.7	22.7	30.05	39.42
Spindle speed, rpm	10000	13000	16000	13000	13000	13000	13000

Table 2 — Effect of ring frame draft

Yarn code	B	F	G
TM	4	4	4
Draft	22.7	30.05	39.42
Spindle speed, rpm	13000	13000	13000
Weft yarn diameter, µm	209.86	199.04	190.72
Strength of weft yarn, kg	0.196	0.2255	0.2282
Weft pullout force from fabric, kg	0.1562	0.1503	0.1438
Weft break inside fabric, kg	0.2412	0.2416	0.2389
Fabric strength in weft direction, kg	19.05	20.14	19.33
Fabric strength in weft direction/thread	0.2241	0.2369	0.2274
Strength of warp yarn, kg	0.3362	0.3362	0.3362
Warp pullout from fabric, kg	0.1718	0.1691	0.1638
Warp break inside fabric, kg	0.4227	0.4134	0.4027
Fabric strength in warp direction, kg	51.5	51.03	50.09
Fabric strength in warp direction/thread	0.3552	0.3519	0.3454
Coefficient of friction	0.607	0.602	0.612
Fabric strength in weft direction per thread/strength of weft yarn	1.143	1.05	1.021
Weft pull out force from fabric/ weft break force in fabric	0.648	0.622	0.602
Weft break force in fabric/ strength of weft yarn	1.231	1.071	1.072
Fabric strength in weft direction/ strength of weft yarn	97.19	89.31	86.76
Fabric strength in warp direction per thread/strength of warp yarn	1.057	1.047	1.027
Warp pull out force from fabric/ warp break force in fabric	0.406	0.409	0.407
Warp break force in fabric/ strength of warp yarn	1.257	1.229	1.198
Fabric strength in warp direction/ strength of warp yarn	153.18	151.78	148.99
Length of failure zone for			
Single yarn break, mm	2.25	2.2	2.18
Single yarn break inside the fabric, mm	1.31	1.25	1.15
Fabric tensile test, mm	0.92	0.87	0.81

Table 3 — Effect of spindle speed

Yarn code	A	B	C
TM	4	4	4
Draft	22.7	22.7	22.7
Spindle speed, rpm	10000	13000	16000
Weft yarn diameter, µm	220	209.86	195.81
Strength of weft yarn, kg	0.2074	0.196	0.191
Weft pullout force from fabric, kg	0.1664	0.1562	0.145
Weft break force inside fabric, kg	0.258	0.2412	0.2285
Fabric strength in weft direction, kg	20.39	19.05	17.82
Fabric strength in weft direction/thread	0.2399	0.2241	0.2096
Strength of warp yarn, kg	0.3362	0.3362	0.3362
Warp pullout force from fabric, kg	0.1806	0.1718	0.1638
Warp break inside fabric, kg	0.4303	0.4227	0.4134
Fabric strength in warp direction, kg	51.71	51.5	50.65
Fabric strength in warp direction/thread	0.3566	0.3552	0.3493
Coefficient of friction	0.591	0.607	0.602
Fabric strength in weft direction per thread/strength of weft yarn	1.157	1.143	1.097
Weft pull out force from fabric/weft break force in fabric	0.645	0.648	0.635
Weft break force in fabric/ strength of weft yarn	1.244	1.231	1.196
Fabric strength in weft direction/strength of weft yarn	98.31	97.19	93.29
Fabric strength in warp direction per thread/strength of warp yarn	1.061	1.057	1.039
Warp pull out force from fabric/ warp break force in fabric	0.455	0.406	0.396
Warp break force in fabric/ strength of warp yarn	1.279	1.257	1.229
Fabric strength in warp direction/strength of warp yarn	153.81	153.18	150.65
Length of failure zone for			
Single yarn break, mm	2.31	2.25	2.12
Single yarn break inside the fabric, mm	1.41	1.31	1.20
Fabric tensile test, mm	1.10	0.92	0.85

Table 4 — Effect of twist multiplier

Yarn code	D	B	E
TM	3.5	4	4.5
Draft	22.7	22.7	22.7
Spindle speed, rpm	13000	13000	13000
Weft yarn diameter, µm	240.87	209.86	196.76
Strength of weft yarn, kg	0.1638	0.196	0.2282
Weft pullout force from fabric, kg	0.1772	0.1562	0.1396
Weft break inside fabric, kg	0.2121	0.2412	0.269
Fabric strength in weft direction, kg	17.51	19.05	21.85
Fabric strength in weft direction/thread	0.206	0.2241	0.254
Strength of warp yarn, kg	0.3362	0.3362	0.3362
Warp pullout from fabric, kg	0.1872	0.1718	0.1557
Warp break inside fabric, kg	0.4403	0.4227	0.4134
Fabric strength in warp direction, kg	51.93	51.5	50.25
Fabric strength in warp direction/thread	0.3581	0.3552	0.3466
Coefficient of friction	0.612	0.607	0.610
Fabric strength in weft direction per thread/strength of weft yarn	1.258	1.143	1.126
Weft pull out force from fabric/weft break force in fabric	0.835	0.648	0.509
Weft break force in fabric/strength of weft yarn	1.295	1.231	1.179
Fabric strength in weft direction/strength of weft yarn	106.899	97.193	95.749
Fabric strength in warp direction per thread/strength of warp yarn	1.065	1.057	1.031
Warp pull out force from fabric/warp break force in fabric	0.425	0.406	0.376
Warp break force in fabric/strength of warp yarn	1.309	1.257	1.23
Fabric strength in warp direction/strength of warp yarn	154.46	153.18	149.47
Length of failure zone for			
Single yarn break, mm	2.48	2.25	1.89
Single yarn break inside the fabric, mm	1.52	1.31	1.10
Fabric tensile test, mm	1.21	0.92	0.70

thickness using Essdiel thickness tester with an accuracy of 0.01mm. An average of 10 readings was taken for each sample.

3 Results and Discussion

3.1 Effect of Ring Frame Parameters on Yarn Properties

As per the proposed experimental plan given in Table 1, the yarn samples have been prepared on the ring frame and results are given in Tables 2-4.

3.1.1 Yarn Diameter and Fibre Compactness in Yarn

The results given in Table 2 indicate the reduction in yarn diameter with the increase in ring frame draft. The increase in draft increases drafting force per unit mass of fibre and leads to de-crimping of the fibre. This improves the fibre compactness in the yarn matrix due to the fibre straightening and hence reduces the yarn diameter. Table 3 clearly shows the reduction in yarn diameter with the increase in the spindle speed. The increase in spindle speed increases the spinning tension but the selvedge fibres of the spinning triangle possess higher tension. The increase in tension aligned the fibres towards yarn axis. This results in more fibre compactness in yarn and thus decreases the yarn diameter. Table 4 shows consistent reduction in yarn diameter with the increase in yarn twist. The lateral force acting on the fibre assembly increases with the increase in yarn twist and accordingly increases the compactness of the fibre bundle which reduces the yarn diameter. Further, it is observed from the results that maximum reduction in yarn diameter is noticed with the increase of ring frame draft followed by spindle speed and twist multiplier.

It is known that the increase in draft increases the drafting force per unit mass of fibre. The drafting force increases further due to the flattening of roving at the back-drafting roller nip. The feeding of coarsest roving provides maximum spreading of roving. Therefore, the fibre ribbon follows highest convergence angle at the nip of front rollers during drafting, accordingly the process aligns the fibres more closely due to the fibre de-crimping and straightening. Hence, the increase in draft increases the compactness of fibre ribbon (bundle) in the drafting zones. Therefore, it can be concluded that the width of the spinning triangle is governed by the range of used draft. The selvedge fibres of spinning triangle will have greater strain and core will be subjected to compression[15].

The increase in spindle speed further increases the spinning tension in yarn balloon, and the core fibres of the spinning triangle take the axial force, while the surface fibres take the force radially. The developed radial force tries to push the surface fibres towards the yarn core and orients the fibres towards yarn axis. This leads to further reduction in yarn diameter with higher fibre packing towards yarn surface in comparison to yarn spun at lower spindle speed But, subsequent twist insertion in the yarn retains the status of fibre straightening and causes fibres to be longitudinally strained. They compete to reach the position of minimum stress at yarn axis and the extent of this movement will necessarily be limited by number on physical states of the fibre competing. Therefore, the restricted movement of fibres in the spinning triangle is likely to generate slight hollowness near the yarn axis. But the increase in yarn twist increases the lateral force acting on the fibre assembly which compresses the fibre bundle and further reduces the yarn diameter. On the basis of above discussions, it is expected that core of the yarn is likely to have maximum packing density at highest value of ring frame draft but highest spindle speed is likely to generate maximum packing density towards yarn surface. Therefore, the proposed approach has created the possibilities to change the radial packing density and over all packing density of the yarn by optimising the researched variables. Hence, expected change in yarn structure can be exploited for better translation of yarn properties to optimise the tensile properties of the fabrics due to change in frictional contact area of yarns at crossover point of warp and weft in the fabric.

3.1.2 Flexural Rigidity

Table 2 shows that an increase in draft increases the yarn bending rigidity. The increase in draft increases drafting force per unit mass of fibre and de-crimps fibres, which improves the fibre parallelization in the yarn. This increases the number of fibres per unit length in the radial direction of yarn, i.e. more compactness of the fibres before twisting, which results in an increase in the yarn bending rigidity by forming a compact fibre matrix, in particular at the core of yarn.

Table 3 shows an increase in yarn bending rigidity with the increase in spindle speed. This is mainly due to the increase in spinning tension with the increase of spindle speed. But the increase in fibre tension will influence more to selvedge fibres of the spinning triangle which is responsible to make the fibres straighten and strained before twisting. Subsequently, the fibres get more compacted and results in overall increase of fibre packing in the yarn as well as towards yarn surface. This increase in yarn packing density reduces the fibre mobility during bending which results in increase in bending rigidity of the yarn.

It is evident from Table 4 that the flexural rigidity of yarn increases with the increase in yarn twist. The increase of lateral force acting on the fibre assembly due to increase in twist levels helps the fibre bundle to get compressed along its axis and increases the fibre packing per unit cross-sectional area of the yarn. The increase in fibre packing per unit cross-section leads to increase in bending rigidity of the yarn. It is observed from Table 4 that from 4.0 to 4.5 TM level, the rate of change in yarn diameter is not as high as in the case from 3.5 to 4.0 TM level. This may be due to the limitation of space available in the yarn body.

3.1.3 Yarn Strength

The results of yarn strength given in Table 2 clearly indicate that with the increase in ring frame draft, yarn strength increases. The increase of ring frame draft increases the drafting force per unit mass of fibre. The increase in drafting force de-crimps the fibres during drafting and places the fibres under more tension. The higher tension, in turn, aligned the fibre closer to each other due to fibre straightening and hence the increased packing density of yarn. The increase in packing density of yarn enhances the yarn strength accordingly. It can be observed from Table 3 that yarn strength decreases with the increase in spindle speed. The increase in spindle speed increases spinning tension in the selvedge fibre of spinning triangle. Although, increase in spindle speed increases the yarn packing density but it also increases the air drag and centrifugal force on fibres of the yarn. This is responsible for fibre slippage in the spinning triangle and thus it reduces the fibre overlap length and hence the yarn strength. It is further noticed from Table 4 that the increase in twist multiplier increases yarn strength. The increase in yarn twist increases the lateral force acting on the fibre assembly. This compresses the fibre bundle and further increases the yarn packing density which is responsible for increase in yarn strength. Understanding the relationship between yarn structure and fabric strength often helps in engineering the yarn structure to improve the strength translation of yarns to fabric strength.

3.2 Effect of Ring Frame Parameters on Fabric Properties

The characteristics of woven fabrics produced from researched yarns are discussed in this section.

3.2.1 Fabric Thickness

It is observed from Table 2 that the fabric thickness reduces with the increase in draft. The reduction in yarn diameter with the increase in ring frame draft is responsible for the reduction of fabric thickness. The effect of spindle speed on thickness of fabric is shown in Table 3. It is evident that the fabric thickness reduces with increase in the spindle speed and is due to the reduction in yarn diameter with the increase in spindle. It is evident that the fabric thickness reduces with the increase in yarn twist levels. The reduction in yarn diameter with the increase in twist is responsible to reduce the fabric thickness.

Thickness of the fabric is a function of both yarn diameter and yarn structure (i.e. radial packing density). It is obvious that the increase in yarn diameter should increase the fabric thickness. The yarn with same linear density but higher yarn diameter possesses lower fibre packing density and such yarn will get compressed at the crossover point in the fabric and thus reduces the thickness of the fabric. It is also observed from the results that the reduction in fabric thickness is found to be more with draft followed by spindle speed and yarn twist. Therefore, yarn flattening at crossover point due to structural changes in the yarn should be taken into consideration, while addressing the fabric thickness and tensile properties of fabrics.

3.2.2 Fabric Tensile Strength

Evaluation of yarns in terms of their likely performance in subsequent fabric manufacturing process and contribution of their strength to fabric are necessary from the point of view of fabric producer. The tensile strength of a fabric is recognized as one of the most important quality parameters of a fabric. The results of Table 2 show that an initial increase and then decrease of fabric strength in weft direction with the increase in ring frame draft though the strength of weft yarn increases with the increase of draft. But the results of fabric strength in warp direction show the decreasing trend with the increase of draft even though the warp yarn strength is same. It is evident from Tables 3 and 4 that fabric strength in weft direction as well as weft yarn strength decrease with the increase of spindle speed but the fabric strength in weft direction and strength of weft yarn both increase with the increase in twist multiplier. The fabric strength in warp direction first decreases and then increases with the increase of spindle speed but continuously decreases with the increase in twist multiplier.

On comparing the results of fabric strength and yarn strength, it is observed that the increase in spindle speed and twist multiplier shows the direct relationship with the fabric strength[11] and yarn strength [9], but the increase of draft shows the direct relationship with fabric strength and yarn strength at the initial increase of draft only. The results of fabric strength in warp direction show the reduction in fabric strength with the increase of draft, spindle speed and twist multiplier, while yarns of same strength are used for all the considered fabrics. However, it is interesting to note that out of 7 considered fabrics, yarn D with lowest twist multiplier shows lowest fabric strength and yarn E with the highest twist multiplier gives highest fabric strength in weft direction. But the fabric strength in warp direction is found to be lowest with yarn G made with highest draft, and the highest fabric strength is observed with yarn D having lowest twist multiplier. The result of ratio of fabric strength in weft/warp direction to strength of weft/warp yarn shows decreasing trend with the increase of considered variables.

In a fabric, the cross-section of yarn varies due to change in frictional contact area of yarns at crossover point of warp and weft, due to some sort of force acting between the yarns in the intersection region[16]. The intersecting yarn only touches the cross-yarn at the point of intersection where the curvature of yarn path is maximum and depends on the yarn diameter and flexural rigidity of yarn. This approach gives valuable information on the inter-yarn force.

Therefore, based on above observations, it can be concluded that fabric strength is not only depending on yarn strength but the factors like packing characteristics of the fibres in the yarn, particularly the radial packing density of yarn have direct bearing on the fabric geometry. These factors are responsible in changing the characteristics of interlacement point between the warp and the weft and accordingly influence the frictional resistance towards the fabric extension. Therefore, it is required to carry out comprehensive study to answer the above points and accordingly these are dealt in succeeding sections.

3.2.3 Fabric Strength in Weft and Warp Direction per Yarn

The fabric strength is influenced by the frictional forces between warp and weft, which is largely governed by the surface and internal structure of yarns. It is observed from Tables 2-4 that the trends of fabric strength in weft and warp directions per yarn and respective fabric strength in weft and warp directions are identical for all considered fabrics. It is also observed that the increase of fabric strength in weft direction per yarn with the increase of twist multiplier is more in comparison to the reduction of fabric strength in weft direction per yarn with the increase of spindle speed. However, with the increase of draft the difference in the levels of change in fabric strength, due to twist multiplier and spindle speed, initially increases and then decreases. The fabric strength in warp direction per yarn shows a decreasing trend, though having minimal difference, with the increase in draft, spindle speed and twist multiplier. This is because same warp yarn is used for all 7 fabrics. The fabrics with yarns D and E show the lowest and highest value of fabric strength in weft direction per yarn respectively, but the fabric with yarn G shows lowest and yarn D shows highest value of fabric strength in warp direction per thread among all 7 considered fabrics.

The ratio of fabric strength per yarn to single yarn strength provides more practical information to quantify the fabric assistance and this ratio is generally higher than unity. A higher ratio indicates that yarn strengths are exploited more in fabrics. The ratio of fabric strength in weft/warp direction per yarn to strength of weft/warp yarn shows the decreasing trends with the increase of ring frame draft, spindle speed and twist multiplier having higher ratio value in case of weft yarn based fabric than the corresponding warp yarn based fabric. This is mainly due to more end density than pick density in the fabric. It is further noticed that the value of said ratio in weft direction is highly influenced by twist multiplier followed by spindle speed and draft. The increase of drafts, provides lowest range of yarn diameter and accordingly highest range of overall yarn packing density as well as surface packing density. These factors decrease the area of contact between the yarns and, hence show lowest friction level which ultimately reduces the ratio of fabric strength in weft direction per yarn to the strength of weft yarn. In contrast to this, the increase of twist multiplier provides highest range of yarn diameter and accordingly lowest range of overall yarn packing density as well as more open surface structure increases the value of considered ratio. The considered ratio in warp direction also follows the similar trend. But the fabrics with yarn E show lowest ratio of fabric strength in weft/warp direction per yarn to strength of weft/warp yarn, while fabrics with D show the highest ratio value in both the directions.

3.2.4 Weft/ Warp Pullout Force from Fabric

As far as yarn pulling force is concerned, the peak load corresponds to the maximum force measured during a yarn pullout. It is noticed that when the yarn pulling force reaches the peak value of the load, the entire yarn then begins to translate within the fabric, and the pullout force gradually decreases. Basically, the peak yarn pulling force deals with the static friction between the pull-out yarn and the transverse yarn in addition to the bending deformation. Therefore, the maximum yarn pulling force will be decided by the structural changes in yarns. It is well known that yarn pullout force is governed by the yarn bending rigidity and packing density of yarn which controls the frictional contact between the yarns. The bending rigidity depends on elastic modulus and the curvature of yarn to which it bends in fabric which is decided by the yarn diameter. But the curvature to which a yarn is bend in the fabric is controlled by the yarn diameter and radial packing density of yarn. The results of Tables 2-4 clearly show the reduction of weft/warp pullout force with the increase of draft, spindle speed and twist multiplier. Yarn diameter reduces and yarn packing density increases with the increase of considered variables. Further, it is noticed that the maximum pullout forces in weft direction are observed when the yarns to be pulled have highest yarn diameter and lowest packing density. In contrast to it, minimum pullout force is observed for lowest yarn diameter and highest yarn packing density. Warp pullout force is always found to be higher than corresponding weft pullout force and the noted trend is applicable for all three considered variables. It is interesting to note that weft and warp pullout forces are found to be lowest with yarn E having highest twist multiplier and are highest with yarn D having lowest twist multiplier.

3.2.5 Weft/ Warp Break Force inside Fabric

It is evident from Tables 2-4 that, in general, weft break force inside fabric decreases with the increase of draft and spindle speed, but increases with the increase of twist multiplier. As discussed above, the yarn strength increases with the increase of draft and twist multiplier but decreases with the increase of spindle speed. It is further observed that yarn strength is lowest at the least twist multipliers but highest at the highest twist multiplier as well as highest draft. Therefore, it can be concluded that weft break force inside fabrics and the corresponding yarn strengths do not show the direct relationship and observed trend can be explained based on structural changes of yarns as discussed above. The warp break force decreases with the increase of all three considered variables. The warp break force is always found to be significantly higher than the weft break force for all 7 considered fabrics. It is further noticed that the fabrics with yarns D and E give lowest and highest value of weft break force respectively, but the fabric with yarn G shows lowest and the fabric with yarn D shows highest value of warp break force among all 7 considered fabrics.

The results of the ratio of weft/warp break force inside fabric to strength of weft/warp yarn depict reducing trend with the increase of draft, spindle speed and twist multiplier having highest value with the change of twist multiplier followed by spindle speed and draft. But the values of the ratio of weft break force inside fabric to strength of weft yarn are found to be slightly lower than the corresponding ratio of warp break force in fabric to strength of warp yarn; the observed trend is applicable to all considered variables. It is interesting to note that the fabric with yarn G gives lowest value of the ratio of weft/warp break force in fabric to strength of weft/warp yarn, and the fabric with yarn D gives highest value of ratio of weft/warp break force in fabric to strength of weft/warp yarn.

The results of the ratio of weft/warp pullout force to weft/warp break force show a decreasing trend with the increase of draft, spindle speed and twist multiplier. But the value of ratio of weft pull out force to weft break force in fabric is significantly higher than the corresponding ratio of warp pull out force to warp break force in fabric having ratio values lower than one. The ratio of weft/warp pullout force to weft/warp break force is found to be lowest with fabric E, but highest with fabric D in case of weft and with fabric A in case of warp among all considered fabrics.

3.2.6 Yarn Failure Zone Length at Different Stages of Yarn Break

The length of yarn failure zone depends on the proportion of break/slip fibre during the tensile rupture of the yarn. Higher proportion of broken fibres leads to shortening of the failure zone. In addition of yarn structure the failure zone is also influenced by spinning technologies, rate of extension and gauge length[13]. In the present study, the yarn failure zone length is carried out for the 7 considered yarns with in-built structural changes. The study of failure zone length has been carried out at the following three stages of yarn break:

(i) Yarn break during single yarn strength measurement
(ii) Single yarn break inside the fabric
(iii) Yarn breaks during fabric strength measurement

3.3 Influence of Process Parameters on Yarn Failure Zone

Tables 2-4 show the results of failure zone length measured at different stages of yarn breaks influenced by ring frame draft, spindle speed and twist multiplier. It is observed that the yarn failure zone length decreases with the increase of draft, spindle speed and twist multiplier and the trend is applicable for all the three stages of yarn breaks. It is interesting to note that the above trends of yarn failure zone length do not show direct relationship with yarn strength, but again it is the yarn structure along with yarn breaking conditions under three considered stages which are playing the dominant role to decide the yarn failure zone length.

The results given in Tables 2-4 indicate the reduction in yarn diameter with the increase in ring frame draft, spindle speed and twist multiplier and relevant explanations have been discussed in Section **3.1.1**

The higher packing density of fibres across the yarn cross-section brings the fibre closer and increases the contact points between the fibres. However, the radial packing density picture represents varying level of compactness of fibres across the yarn cross-section under axial loading and it generates different level of frictional resistance and accordingly decides proportion of fibre break and slip in the yarn [9]. Therefore, during tensile testing the fibres bear non-uniform loading and, accordingly they show combination of fibre breakages and slippages which results in different length of the failure zone of the yarns. Hence, it can be concluded that the increase of draft, spindle speed and twist multiplier increases the yarn packing density[9] and higher packing density of yarn is responsible to increase the proportion of broken fibres[9] which leads to reduction of the yarn failure zone length.

It is further noticed that the yarn failure zone length is found to be highest for yarn break during single yarn strength measurement followed by single yarn break inside the fabric and yarn breaks during fabric strength measurement. The observed trends are applicable for all three considered process variables.

In the case of yarn break during single yarn strength measurement, the individual fibre of the yarn during extension experiences different tension and the amount of tension is governed by its radial position in the yarn. The transverse force due to tension development on the fibre acts normal to fibre axis and develops frictional resistance to fibre slippage. If the tension on gripped fibre reaches the fibre breaking load and fibre enables to resist the stress furthermore then it breaks. If a balance between tension and frictional forces along the fibre length cannot be effectively built up and the fibre does not resist the tension, then the fibre starts to slip. It is an established fact [13,14] that the yarn failure behaviour of slip/break or mixed mode of two is dependent on type of fibre, yarn structure and testing conditions. But in the case of yarn break during single yarn strength measurement only yarn structure plays the dominant role to decide the yarn failure zone length because other two factors are kept constant.

But the conditions of tensile failure of yarn are quite different for single yarn break inside the fabric and yarn breaks during fabric strength measurement in comparison with the yarn break during single yarn strength measurement, hence the yarn failure zone length will be governed accordingly. The load-elongation curve of fabric possesses three distinct regions, the starting region is dominated by frictional restraint of cross-yarns, followed by de-crimping of yarns and finally yarn extension. The initial fabric modulus is governed by the frictional resistance to cross-yarn bending which includes inter-fibre friction. The fabric modulus decreases gradually as the frictional restraint is overcome. It is mainly because of the force needed to de-crimp the yarn in the direction of force decreases. After de-crimping, the force rises sharply as fibres in the yarn are strained. The fabric strength is finally influenced by the degree of binding of cross-yarns, which increases inter-fibre frictional forces and accordingly decides the tensile strength. The straightening of longitudinal yarns during tensile test develops compressive forces at the points of contact with the cross-yarns. In real fabrics, the cross-section of yarn varies considerably at interlacement points and it depends on yarn diameter and packing density of yarn, particularly the radial packing density of yarn. Further, the decrease of yarn failure zone length in case of single yarn break inside the fabric could be due to assistance provided by the second set of yarns that causes the reduction in resulting gauge length at the point of contact with the cross-yarns. But the said reasoning is likely to be more prominent in case of yarn breaks during fabric strength measurement due to high effectiveness of the multiple number of weft yarns and, hence will be responsible for further reduction in yarn failure zone length.

4 Conclusion

Yarn structure plays a significant role in defining the fabric thickness and fabric tensile properties. Apart from the yarn strength, the fabric strength also depends on fibre packing characteristics in yarn and radial packing density directly affects the fabric geometry. The yarn diameter which is indirectly influenced by the twist multiple has a direct effect on the yarn pull out force and higher yarn diameter (obtained at lower TM) shows higher pull out force. Fabric strength is also influenced by the degree of binding of cross-yarns, which increases inter-fibre frictional forces and depends on the yarn diameter and radial packing density, i.e. the yarn structure.

Yarn structure along with the yarn breaking conditions plays a dominant role in deciding the yarn failure zone length rather than the yarn strength. A higher yarn packing density, due to higher draft, spindle speed and twist multiplier, is responsible for increased proportion of broken fibres, thereby leading to reduced yarn failure zone length.

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