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Tensile Behavior of Sewing Threads under Simple-Tensile, Loop and Knot Tests

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ABSTRACT

Twenty nine sewing threads belonging to eight categories were analyzed in terms of simple-, loop- and knot-tensile properties. The structure of sewing threads and fibers constituting the threads influence the strength of the sewing threads. Tensile strengths, breaking extension and specific work of rupture in loop and knot forms are lower compared to that obtained in simple tensile test. Threads exhibit less ductility when stretched in loop and knot forms. Spun threads have higher relative- tenacity, extension and work of rupture. Heavier threads have lower relative tenacity, extension and specific work of rupture compared to the finer ones.

Keywords: Simple tensile, loop, knot, relative tenacity, specific work of rupture

1. Introduction

The study of tensile properties of sewing thread is essential to understand and predict the thread behavior during sewing and seam failure while the sewn product is in use. The Sewing Quality Index (SQI) established [1, 2] has considered the tensile and knot strengths of thread but has not included the loop strength which is considered to be an important property in determining the seam strength [3, 4], whereas in a similar study, tensile and loop strengths are considered without knot strength [5]. Thread structure affects seam strength as the friction between the sewing threads and fabric yarns influence the translation of thread strength to the seam strength. The ratio of knot and tensile strength is found to be higher for the filament thread than the spun thread [4]. Thread irregularity, ability of constituent fibers in the thread to relive their stress/or interchange their positions at the intersections of threads in the seam during application of load may also decide the strength translation of thread in loop form to the stitch strength of sewn product.

The strength of thread under loop form is expected to be twice of that obtained with the simple tensile test, as the force applied being borne by both arms of the threads (Fig. 1). At the point of intersection in 'U' shape, the bent portions of the thread become week due to the excessive stretching of fibers in the outer layer of the bent portions while the fibers in the inner layer are compressed, so the tenacity of thread in loop form is always less than that obtained from the simple tensile test. The low strength in loop form is due to the restricted relative inter-displacements of fiber cross-section layers in bending that cause higher stress concentration in a fiber cross-section at lower transversal forces [6].

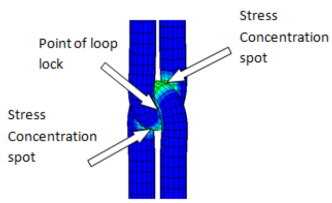


Fig. 1 Stress concentration at the point of intersection of thread loops under tensile load

The knot strength of a sewing thread is considered as a measure of brittleness of the thread. The simple tensile properties alone are insufficient for obtaining a complete understanding of the mechanical properties of fibers and their performance during processing and end-use; their brittleness also play an important role [7]. The Knot strength reflects the performance of a thread after stitching [8]. The minimum knot strength values have a good correlation with seam efficiency [9].

The sewing threads are mostly in the form of plied yarn. In a plied yarn, the majority-or all-of the single yarns composing it are distorted into helices. The twist in a yarn might be considerably altered simply by distorting the axis of the yarn into a three-dimensional structure and without the rotation of either end of the yarn [10]. The stretching of twisted thread involves tensile, bending, and torsion deformations [11] along with loss of twist on fibers. A study on cotton plied yarns had shown that the thread tenacity decreased with the increase in the diameter of threads [12].

The core spun sewing threads are made by wrapping the staple polyester or cotton fibers around a continuous filament bundle during spinning, and then plying these yarns. The core to sheath weight ratio influences the cohesion forces among the staple fibers and between the staples and core filaments as well the thread thickness. The tenacity of core spun yarn decreases when the core sheath weight ratio increases [13]. When the core spun threads go through the needle hole, the sheath fibers may be disturbed or peeled off the thread which leads to lower seam strength. A study on the nylon-cotton core spun single yarns showed that the tenacity of core-spun yam decreased with the increase in pretension of the filament [14]. The modulus of the core-spun yarn is lower than the parallel laid core filaments due to the dislocation of the core filaments from the yarn axis during spinning [15].

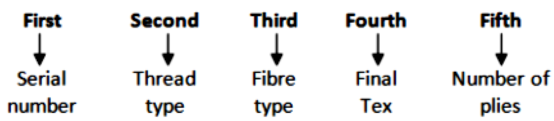
In a bonded or monocord thread, a synthetic resin or alloy coating serves as a protection or guard against individual filaments fraying out. Hence, a low amount of twist is imparted to the filaments. The bonded threads are less flexible due to bonding of filaments, and hence, the filaments don't spread on flexing/bending in loop and knot forms. The textured filament thread made from polyester is used primarily as the looper thread for cover stitches. The textured filament threads provide more cover and have high extensibility, but snags more during sewing and in use.

The above said studies are aimed at analyzing the strength properties of few types of sewing threads. However there is a lack of information regarding the causes for the difference in the loop and knot strengths compared to simple tensile strength for various thread structures. In this study, the same is analyzed with the aid of the broken end pictures of threads of eight different structures.

2. Experimental

2.1 Materials

In this study, twenty nine commercially available threads are analyzed and these threads are categorized into eight groups (Tables 1 to 4) based on the types of fibers and thread construction as: cotton, spun polyester, core-spun polyester/cotton, core-spun polyester/polyester, filament polyester lubricated (including trilobal embroidery), filament polyester textured, filament nylon lubricated and filament nylon bonded. All these threads represent the commonly used thread structures in making sewn products. Within each category, there are threads with different number of plies and tex. The threads are coded for easy categorization with five divisions divided by a slash (/) as shown below.



2.2 Methods

The tensile properties of the threads were measured under simple tensile, loop and knot tests at a gauge length 250mm and rate of traverse 300 mm/minute. The work of rupture was calculated as per the standard [4]. The specific work of rupture (*SWR*) of the thread was obtained by dividing the area under the force-extension curve by the product of thread tex and gauge length [13]. Since the strengths of threads in the loop and knot forms might also depend on the thread structure and thread diameter/tex - relative-tenacities, extensions and works of rupture were calculated in loop and knot forms. For example, the relative tenacity of a thread (*RT*) in loop form is the ratio of loop tenacity of that thread to its simple tensile tenacity. Similarly, relative extensions (*RE*) and relative work of rupture (*RWR*) were calculated.

The broken ends of threads and the fibers at the broken ends were photographed to study the macro as well as the micro mechanism of thread breakage. The thread broken ends were photographed by a NIKON Multizoom AZ100 Microscope with a digital camera with 30X to 60X magnifications. The broken ends of the fibers were photographed using SEM at a magnification of 2.5KX.

3. Results and discussion

An interesting observation made in the case of loop and knot test is that all the threads in every test got broken exactly at the loop or knot portions. This clearly indicates that the point of concentration of stress is located at the outer surface of the 'U' shaped bend of the thread where the fibers first start to break and/or slip and then the break propagates to the full cross section of the thread.

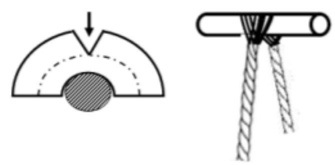


Fig. 2 Propagation of breaks in a thread: Left-loop test; Right-thread flattening over a circular rod

In tensile testing, yarn breaks at the weakest link [16]; and the contacting regions of the threads in the loop and knot are the weakest spots. The fiber rupture in a looped thread takes place only on the upper surface of bent part up to the central axis of the thread as marked by an arrow in Fig. 2 (Left). When the loops lock with each other, the threads could not flatten as they do when bent over a circular cylinder as shown in Fig. 2 (Right). In the flattened condition, the applied force would be more or less equally distributed to all the fibers. But in the case of thread loops locking with each others, the circularity of the thread might be maintained until thread breakage, so the tensile stresses concentrate more on the fibers following larger radii of the loop that start breaking first. As the break propagates further towards the central axis of the thread, the fibers start slipping than breaking because the thread loses its cohesiveness. The point of highest stress concentration in a knot is shown in Fig. 3 Top-Left.

At the knot, the 'U' shaped bending of thread takes place at least at two places which weaken the thread at these places, leading to lower strength for the thread compared to that in the loop form (Fig. 3 Top-Right). The 'U' shaped bending at two places is similar to the interlocking of two loops in loop test; but the difference is that two threads are crossing each other (Fig. 3 Bottom) and are not parallel as in the case of loop test. This arrangement could further weaken the threads because the angle of the loop bending is larger than 180°.

The tensile test results are given in Tables 1 to 4. The values of relative tenacity, extension and specific work of rupture in loop forms are larger than in knot forms; but all are below unity. The path lengths of fibers are highly unequal when the threads are in loop and knot forms. There is phase difference in the extension of the fibers; fibers following larger path length undergo more extension for a given force on the thread. When these fibers reach their breaking extension, they break and load is transferred to the remaining fibers and hence, the breaking extension of the threads in loop and knot-forms are lower compared to that in simple tensile test. The differences in path length of fibers are much longer in knot form compared to that in loop form. Hence, lower relative values are observed in the knot forms.

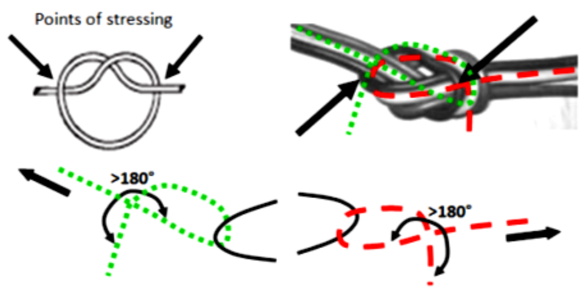


Fig. 3 Stress concentration spots in knot

Table 1. Tensile properties of cotton and spun polyester threads

Thread	codes	Twist (Single/Ply)	Test	σ	ε	SWR	RT	RE	RWR
Cotton	1/S/C/62/6	28/18	ST	21.4	8.9	0.65	-	-	-
			L	20.7	8.8	0.60	0.96	0.98	0.92
			K	17.3	8.4	0.43	0.82	0.94	0.66
Spun Polyester	2/S/P/21/2	22/14	ST	32.1	13.6	1.65	-	-	-
			L	28.1	11.7	1.38	0.88	0.86	0.84
			K	26.9	11.6	1.33	0.84	0.85	0.81
	3/S/P/24/3	21/14	ST	39.8	16.9	2.70	-	-	-
			L	34.9	15.2	2.42	0.88	0.90	0.89
			K	27.5	13.4	1.83	0.69	0.79	0.68
	4/S/P/27/3	21.5/13	ST	36.4	16.8	2.32	-	-	-
			L	32.1	15.1	2.07	0.88	0.90	0.89
			K	26.0	14.0	1.72	0.71	0.83	0.74
	5/S/P/32/3	27/17.5	ST	32.5	19.0	2.43	-	-	-
			L	30.1	18.0	2.39	0.93	0.95	0.98
			K	21.5	14.7	1.62	0.66	0.77	0.67
	6/S/P/34/3	24/15	ST	35.8	17.2	2.30	-	-	-
			L	31.2	15.2	1.99	0.87	0.88	0.86
			K	22.5	12.8	1.44	0.63	0.74	0.63
	7/S/P/39/3	21/13	ST	30.1	17.8	2.06	-	-	-
			L	27.6	16.3	2.06	0.92	0.91	0.99
			K	20.2	14.2	1.31	0.67	0.80	0.64
	8/S/P/60/2	18/11	ST	36.7	18.1	2.50	-	-	-
			L	29.3	15.5	1.83	0.80	0.86	0.73
			K	24.0	14.8	1.68	0.65	0.81	0.67
	9/S/P/70/2	16/10	ST	41.0	18.4	2.72	-	-	-
			L	31.6	15.4	1.81	0.77	0.83	0.67
			K	24.1	14.1	1.39	0.59	0.77	0.51
	10/S/P/80/3	20/12	ST	44.6	19.8	3.20	-	-	-
			L	35.6	16.3	2.40	0.80	0.82	0.75
			K	23.3	14.1	1.51	0.52	0.71	0.47
	11/S/P/95/3	10/6	ST	32.4	19.5	2.49	-	-	
			L	24.6	16.3	1.50	0.76	0.84	0.60
			K	18.5	15.4	1.24	0.57	0.79	0.50

Abbreviations: ST-Simple tensile, L-Loop, K-Knot, σ-Tenacity cN, ε-Extension %, SWR-Specific work of rupture, RT-Relative tenacity, RE-Relative extension, RWR-Relative work of rupture

3.1 Spun threads

The force-extension curves for the cotton thread 1/S/C/62/6 are shown in the Fig. 4. It can be noted that the larger part of the curve follows elastic region. The curves for both the loop and knot are similar in the elastic region and the same trend is observed for other threads. This shows that the repositioning of fibers taking place during initial stretching of loops and knots are similar. The force extension curve of knot exhibits waviness compared to the smooth curve obtained with simple tensile test. This indicates that few fibers break one after the other at the knot portion. The cotton thread has lower tenacities and extensions compared to other threads (Table 1 to 4). For a given tex of the thread (approximately, 60 tex), cotton threads have higher relative values of tenacity, breaking extension and work of rupture compared to the threads viz., spun polyester (8/SP/60/2), PC core spun (13/CR/PC/60/2) and filament threads (22/FL/P/56/2, 26/FL/53/2 and 29/FB/N/63/2) in spite of cotton fibers being the weakest and the least extensible. The cotton fibers being shorter could easily rearrange themselves in loop and knot forms and share the applied load more uniformly than the fibers/filaments in the threads which are not spun types.

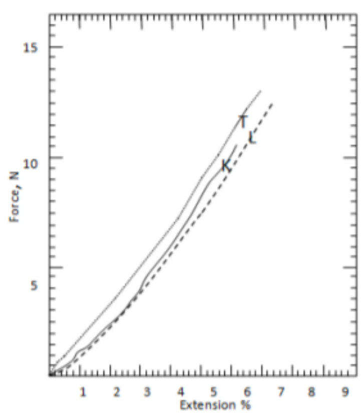
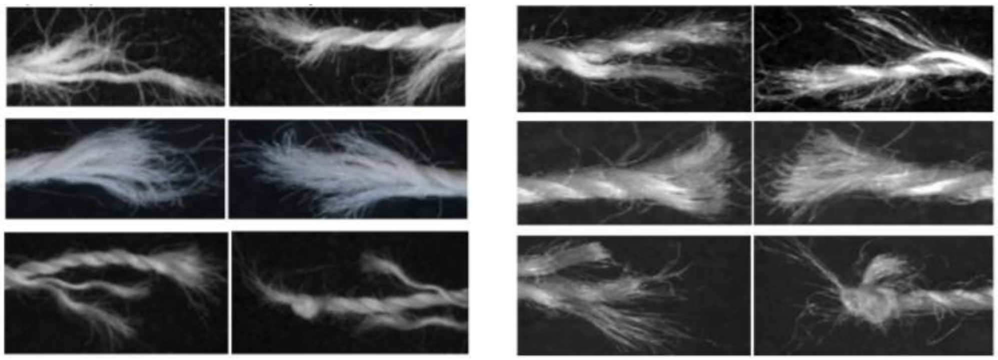


Fig. 4 Force-extension curves of 1/S/C/62/6 thread: Simple tensile (T), Loop (L) and knot (K)

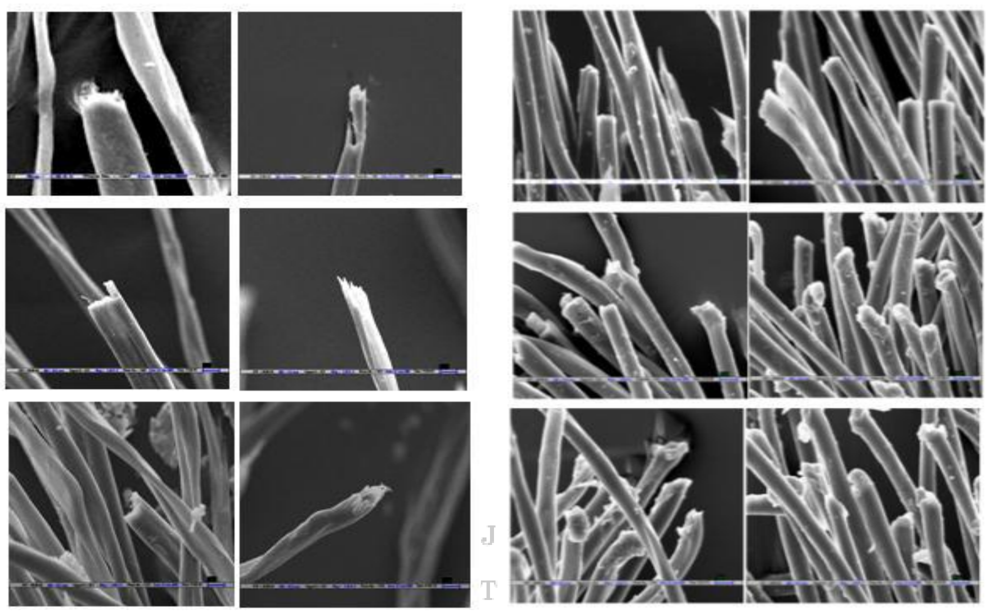
Extending this analogy, the discrete fibers in the spun threads have larger freedom of movement across the thread cross section in relieving their stresses at the regions of high stress concentration. This leads to improved sharing of applied load by the fibers and hence the spun threads have high relative values of tenacity, breaking extension, and specific work of rupture compared to the twisted filament threads and bonded filament threads of the same tex (Table 1 and 3). The spun polyester threads have higher tenacity compared to cotton thread. This can be attributed to the higher fiber strength and longer length of polyester fibers [17]. The spun threads are mostly weaker compared to the core-spun and filament threads as the later are generally made from stronger filaments.

The broken ends of cotton thread under simple tensile test are shown in Fig. 5(a)-Top Left, indicate that few fibers were slipped off. The plies of the thread had broken at different places along the thread. The proportion of broken fibers is the highest in loop form (Fig. 5(a)-Middle Left) due to high lateral pressure generated at the loop intersections that reduces fiber slippage. However, some amount of freedom is available for the highly stretched fibers to rearrange themselves to contribute to the thread extension. In the knot form, this level of freedom is not available to those fibers and they break first transferring the load suddenly to other fibers resulting in catastrophic failure (Fig. 5(a)-Bottom Left) with lowest breaking extension. Similar observations could be seen for the spun polyester thread (Fig. 5 b). All the threads exhibit more brittleness in knot form compared to that in loop form.



(a) (b)

Fig. 5 Broken ends of spun threads: (a) Cotton thread 1/S/C/62/6; and (b)-Spun polyester thread (7/S/P/39/3): Top- Simple tensile; Middle- loop; and Bottom- Knot



(a) (b)

Fig. 6 SEM image of broken fibers: (a)-Cotton thread 1/S/C/62/6; and (b)-Spun polyester thread 7/S/P/39/3): Top- Simple tensile; Middle- loop; and Bottom- Knot

In Fig. 6(a)-Top Left, a cotton fiber exhibits granular break and other axial split break (Right). The axial split break is considered to be a weaker kind of break than the granular one. Granular break is such that the breakage is across the cross section of the fiber with rough texture. A good number of fibers exhibiting axial split breaks under simple tensile test confirm that the cotton thread is the weakest. In Fig. 6(a) (Middle), a cotton fiber exhibits granular break (Left) and the other axial split break (Right). In the case of loop test, the fibers exhibit fewer axial split breaks and many granular ones due to the acute bending of fibers. As the break propagates, the thread loses its integrity and some of the fibers slip and some breaks. The images of broken fibers from the knot (Fig. 6(a), Bottom) and the loop tests (Fig. 6(a), Middle) are similar; i.e. more of granular and less of axial split.

The Fig.6 (b) - top shows that the broken fiber ends from the spun polyester thread exhibiting mostly ductile failure (Right) and few fibers (Left) have undergone axial split type break. The axial splitting thus appears to be caused by the presence of small shear stresses, in addition to the larger tensile stresses especially when the fiber helix angle is very high. The Fig. 6(b)-Middle shows that the fibers are broken by the transverse pressure (Right) which takes place on the outer bent portion of the thread in the locked loop. The ductile break (Left) indicates the fibers break at the inner portions of loops which take place after the outer layer fibers break. The fiber rupture in loop test exhibits lesser axial splits compared to that in simple tensile test. Many broken fibers from the knot exhibit breaks due to localized transverse pressure (Fig. 6(b)-Bottom) and few fibers with ductile break. It is also visible that the broken fibers are stressed in the bent condition. The mushroom heads observed on the broken fibers is an indication of generation of heat due to the localized transverse stresses.

3.2 Core spun threads

The twist levels in single ply of polyester-cotton core spun threads are higher by 30 to 50% respectively for the threads 12/CR/PC/40/2 and 13/CR/PC/60/2 compared to the spun polyester threads of similar tex (Table 1 and 2). This is to increase the friction between the core filaments and the short cotton sheath fibers so as to reduce the stripping off sheath fibers when the threads are rubbing over machine parts. The ratios of ply to single twist for these two threads are 0.6 and 0.33 respectively.

Table 2. Tensile properties of PC and PP core spun threads

Thread	Codes	Twist (Single/Ply)	Test	σ	ε	SWR	RT	RE	RWR
Polyester-Cotton Core Spun	12/CR/PC/40/2	28/17	ST	45.7	23.6	5.25	-	-	-
			L	29.2	16.8	2.84	0.64	0.71	0.54
			K	25.3	16.2	2.64	0.55	0.69	0.50
	13/CR/PC/60/2	14/9	ST	48.1	22.2	4.68	-	-	-
			L	29.9	16.5	2.59	0.62	0.75	0.55
			K	25.5	15.6	2.15	0.53	0.70	0.46
Polyester-Polyester Core Spun	14/CR/PP/16/2	28/17	ST	55.7	20.5	5.12	-	-	-
			L	38.6	16.1	3.31	0.69	0.79	0.65
			K	30.5	13.7	2.25	0.55	0.67	0.44
	15/CR/PP/21/2	25/15	ST	51.1	21.3	4.64	-	-	-
			L	34.9	17.2	2.75	0.68	0.81	0.59
			K	28.6	15.7	2.58	0.56	0.74	0.56
	16/CR/PP/24/2	20/12	ST	52.9	22.4	5.02	-	-	-
			L	35.1	16.8	2.67	0.67	0.75	0.53
			K	28.3	15.1	2.14	0.54	0.67	0.43
	17/CR/PP/30/2	20/12	ST	50.7	23.7	4.87	-	-	-
			L	35.7	18.4	3.07	0.70	0.78	0.63
			K	26.1	16.0	2.26	0.51	0.68	0.47
	18/CR/PP/180/4	10/4	ST	56.4	23.4	5.30	-	-	-
			L	38.3	18.4	2.94	0.68	0.79	0.55
			K	24.6	15.3	1.74	0.44	0.65	0.33

The P/P core threads are stronger than the P/C core threads due to longer polyester sheath fibers providing more friction among the core filaments, which adds more strength to the thread than the cotton sheath does. The relative loop tenacity values of P/P core threads are similar to the P/C core threads. This shows that the P/P core threads also suffered in the same fashion as P/C core threads in the loop form which has lead to a drastic loss of tenacity compared to that in simple tensile test. The core spun threads have lower relative tenacity, extension and specific work of rupture compared to the spun threads, because the sheath fibers are mostly slipped off during stressing the thread in loop and knot forms; thus their contribution to the thread strength is minimal during thread breaking.

A typical force-extension curve of PP core spun thread (15/CR/PP/21/2) is shown in Fig. 7. The initial region of force-extension curve obtained from simple tensile test show zigzag pattern with occasional drop of force. The same phenomenon is observed in other core spun threads (both PP and PC). This indicates that as the thread is stretched, the sheath fibers apply lateral pressure and offer resistance to stretching of the thread; then start slipping as they lose their twists. This is evidenced as short horizontal lines in the force-extension curve. The slipped-off sheath fibers which are primarily at the intersection of the plies break when their breaking extension is lower compared to that of the filaments; indicating drop in force in the force-extension curve.

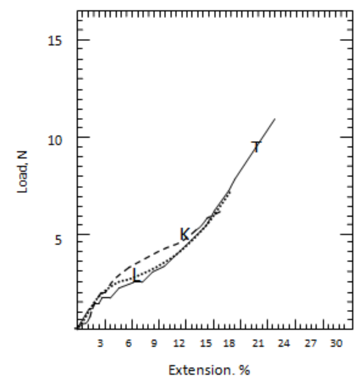
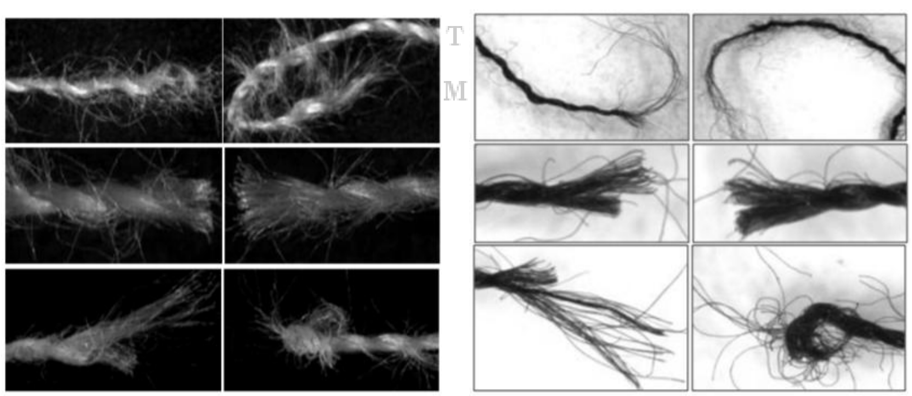


Fig. 7 Force-extension curves of PP corespun thread 15/CR/PP/21/2

The broken ends of PC core spun thread obtained from simple tensile test are shown in Fig. 8 a (Top Left). The cotton sheath (protruding perpendicular to the thread) displays more of fiber slippage and less of fiber breakage. The polyester sheath fibers exhibit less slippage and more fiber rupture in simple tensile test (Fig. 8 b Top-Right) compared to the cotton sheath fibers. This could be the reason for the observed higher tenacity of the PP core threads compared to the PC threads. In both the cases, the filament core has broken at the place where the sheath fibers are missing (slipped off) which is evident by the extended tail ends of the broken core filaments without sheath on them. The filament breakage has taken place where the support of sheath fibers is missing.



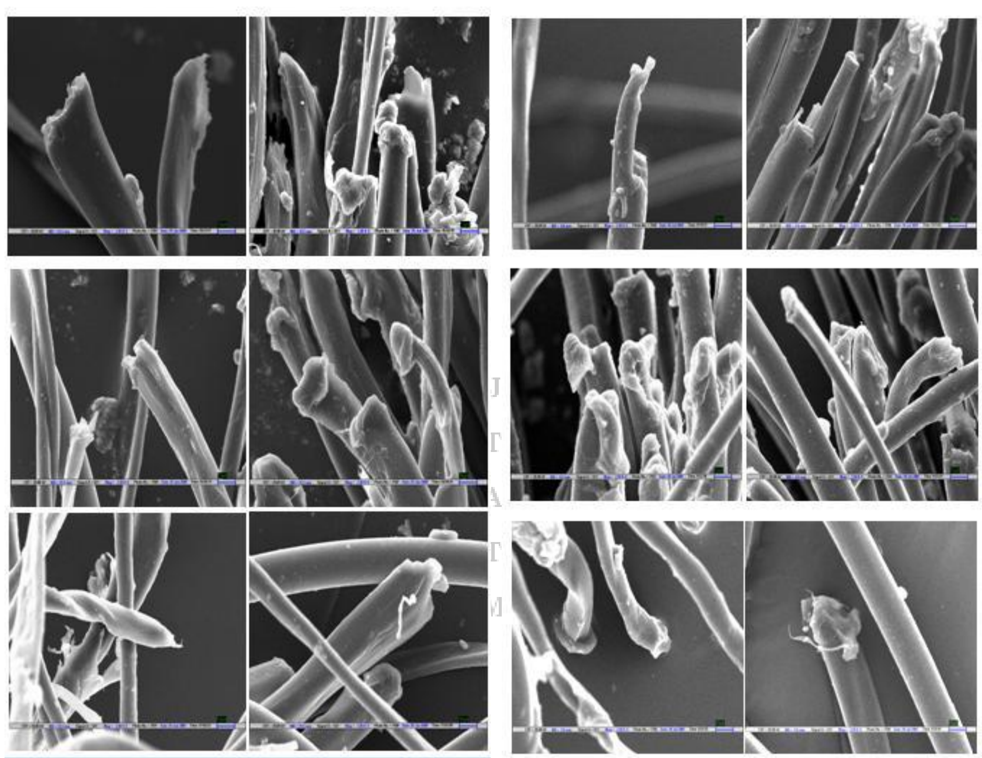
(a) **(b)**

Fig. 8 Broken ends of core spun threads: (a) Polyester/cotton core spun thread (12/CR/PC/40/2); and (b) Polyester/polyester core spun thread (16/CR/PP/24/2): Top- Simple tensile; Middle- loop; and Bottom- Knot

The broken ends of thread from the loop test shown in Fig. 8 a (Middle-Left) clearly indicates that the cotton sheath fibers are completely broken first due to their low breaking extension followed by the breakage of core filaments. The cotton fibers are inherently weak and in addition, the slipping off sheath fibers ultimately leads to lower relative loop tenacity. In the case of PP core thread, the sheath fibers are dislocated (Fig. 8 b Middle).

The broken ends of PC threads from the knot test shown in Fig. 8 a (Bottom) is similar to that exhibited by the PP thread (Fig. 8 b Bottom); one ply breaks as a sharp cut when still the knot is intact and the other ply breaks after that at different location. Despite the sharp cut on the thread, the overall tenacity of thread in knot test is low since the sharp cut damaged the fibers.

In case of fiber breakage in simple tensile test shown in Fig. 9 (Top-Right), the polyester core filaments show a pendulum breaks with mushroom head which is generally attributed to the high speed break. This may be attributed to the sudden expose of certain filaments to the tensile force after the breakage of the straight filaments that follow the shortest path. The cotton fiber shown in the Fig. 9 a (Top-Left) indicates a granular type of break across fiber which is characteristic of the bonded fibrillar elements.



(a) **(b)**

Fig. 9 **SEM images of broken fibers from core spun threads: (a) Polyester-cotton core thread 12/CR/PC/40/2; and (b) Polyester-polyester core thread 16/CR/PP/24/2: Top- Simple tensile; Middle- loop; and Bottom- Knot**

The Fig. 9 a (Middle-Right) shows the broken ends of the polyester core filaments from loop test exhibiting pendulum break showing mushroom head which is somewhat similar to the tensile one, but there is a severity seen in the case of loop. This is because a portion of the thread stressed first until break and then the whole load is transferred on the rest of the unbroken filaments, so the force is of impact nature. The broken cotton fibers shown in Fig. 9 a (Middle-Left) exhibit both granular and weaker axial split breaks, whereas in the simple tensile test, it is mostly of granular type. A broken cotton fiber from the knot test (Fig. 9 a Bottom-Left) is twisted and stretched before it breaks. This is one of the few fibers which got trapped at the point of bending in the knot while other sheath fibers got drifted away. The Fig. 9 a Bottom-Right shows the polyester core filament has undergone ductile break. This filament got stretched before breaking and it is the part of a ply that has not broken at the bent portion of the knot.

In Fig. 9 b (Top Right), broken filaments of PP thread from the simple tensile test show longitudinal striation along the filaments due to the snapback effect i.e. the release of elastic energy following the rupture [5]. The polyester sheath fibers show an axial split breakage in Figure 9 b (Top Left). The broken filaments from loop test show (Fig. 9 b Middle Left) that the filaments have undergone severe pendulum breaks with mushroom heads. In Fig. 9 b (Middle Right) the sheath fibers exhibit pendulum break. The sheath fibers that were not displaced from the point of loop inter-lock have undergone high speed pendulum breaks and got broken along with the core filaments; the ductile broken ends are of the core filaments. In Fig. 9 b (Bottom Right), the broken fiber end from the knot test shows an abruptly cut end on the core filaments which is due to the transverse force. The Fig. 9 b (Bottom Left) shows pendulum mushroom break in one of the core filaments which experienced early brittle fracture. The lone filament seen with ductile break is the one which got stretched and broken after the initial mass brittle break.

To study the configuration of sheath fibers in the core spun thread (38 tex, 2 ply), a white color polyester-cotton core spun thread was dyed with Procion Red-M8B reactive cold dye. The thread with normal ply twist of 15 TPI (Fig. 10 a) shows that the core is sparingly covered by the sheath as the proportion of sheath is only 23% of the total yarn weight, and the figure 10 (b) shows the same thread with 100% higher ply twist (30 TPI) in the same 'Z' direction. The average angle of the sheath fibers with respect to the axis of the plied thread with normal twist (fig. 10 a, α°) and high twist (fig. 10 b, β°) is 12° and 22° respectively.

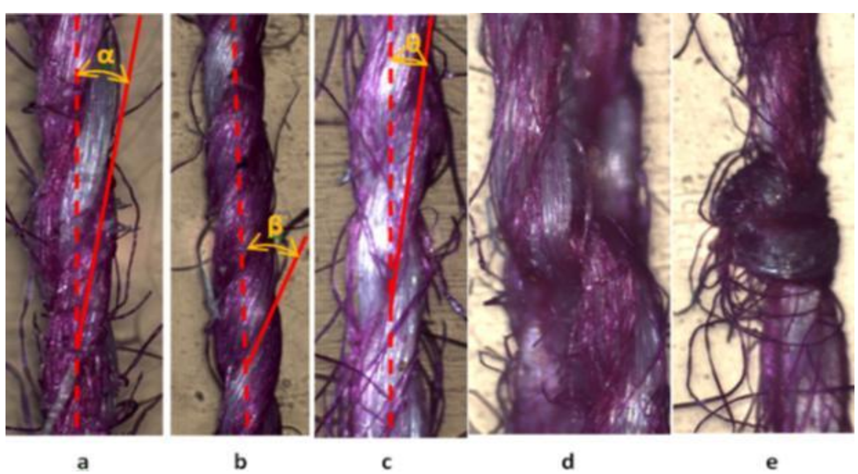


Fig. 10 Polyester-cotton core thread (White core and dyed sheath)- (a)- Normal twist (15 TPI), (b)- High twist (30 TPI), (c to e)-The normal twisted thread shown in (a) is stretched at 500 cN force: (c) simple tensile; (d) loop; (e) knot

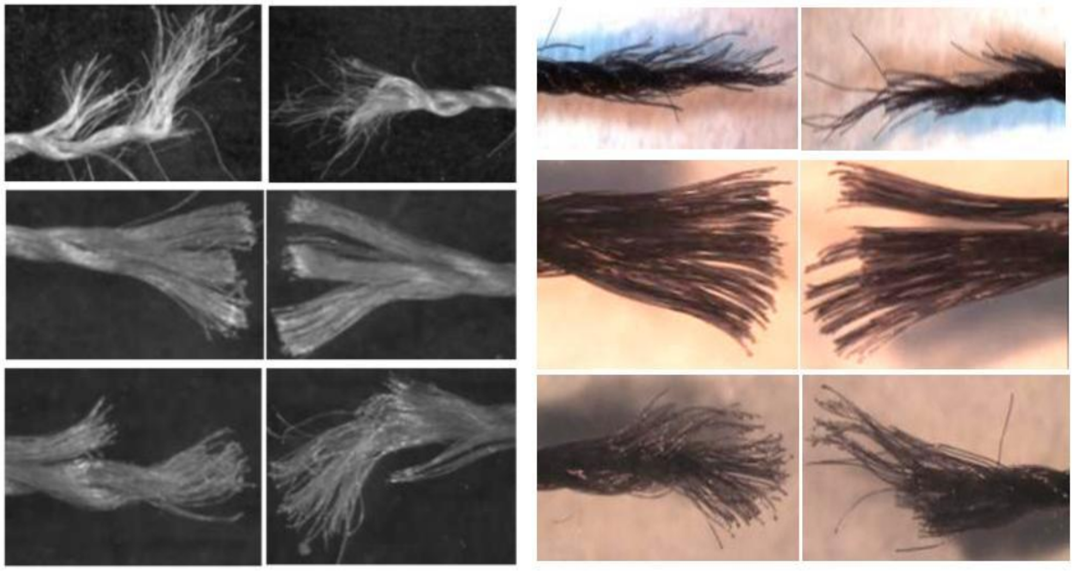
The Fig. 10 (c to d) shows the high-twisted core thread (shown in Fig 10 b) stretched at 500 cN force. The angle of sheath fibers with respect to thread axis is measured as 7° (Fig. 10 c, θ°), which shows that the sheath becomes almost parallel to the thread axis in the stretched condition and its contribution to the thread strength would be minimal. It is also evident that as the core filaments are stretched and untwisted, the sheath fibers got loosened from the surface of the core. The Fig. 10 (d and e) shows the core thread in stretched loop and knot condition respectively. In both the cases, the sheath fibers have become parallel to the thread axis and their contribution to the strength and extension might become minimal and hence, the core spun threads suffer higher losses of extension and tenacity in loop and knot forms compared to spun threads (Tables 1 and 2).

3.3 Twisted filament lubricated threads

The polyester filament threads, except the embroidery thread (19/FL/P/56/2) made from trilobal filaments have higher tenacity than the P/P core threads under simple tensile test might be due to the inherent fiber property.

Table 3. Threads test results (twisted polyester and nylon filament threads)

Thread	codes	Twist (Single/Ply)	Test	σ	ε	SWR	RT	RE	RWR
Twisted Polyester-Filament-	19/FL/P/27/2	19/13	ST	39.0	21.7	4.10	-	-	-
			L	38.4	21.1	3.76	0.98	0.97	0.92
			K	32.2	18.1	2.92	0.83	0.83	0.71
	20/FL/P/45/3	19/13	ST	66.1	18.8	5.46	-	-	-
			L	47.1	13.7	2.89	0.71	0.73	0.53
			K	32.3	10.7	1.84	0.49	0.57	0.34
	21/FL/P/50/3	14/10	ST	84.9	19.4	7.61	-	-	-
			L	52.9	15.0	3.49	0.62	0.77	0.46
			K	37.1	12.2	2.24	0.44	0.63	0.29
	22/FL/P/56/2	14/10	ST	51.6	22.2	4.80	-	-	-
			L	31.5	17.5	2.86	0.61	0.79	0.60
			K	24.4	15.0	1.88	0.47	0.67	0.39
Twisted Filament Nylon	25/FL/N/37/3	14/10	ST	62.0	22.9	5.21	-	-	-
			L	42.3	17.6	2.97	0.68	0.77	0.57
			K	33.7	16.0	2.25	0.54	0.70	0.43
	26/FL/N/53/2	14/10	ST	60.7	31.3	7.48	-	-	-
			L	44.6	24.8	4.77	0.74	0.79	0.64
			K	38.5	23.5	3.77	0.63	0.75	0.50

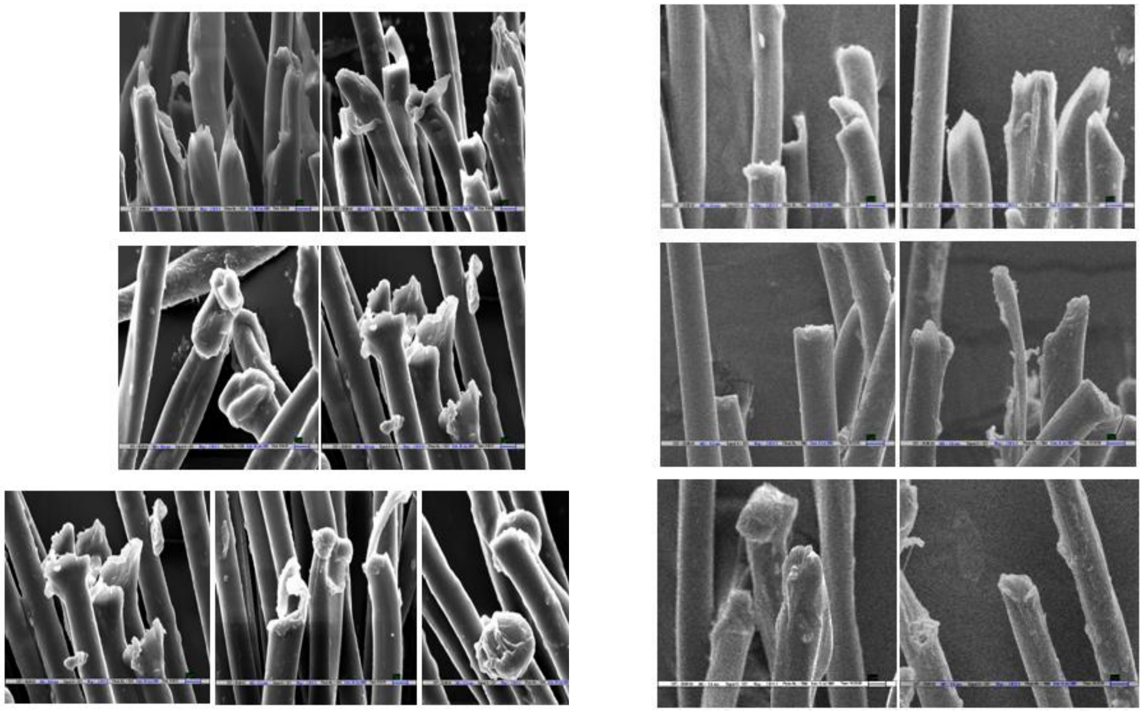


(a) (b)

Fig. 11 Broken ends of twisted filament threads: (a) polyester (20/FL/P/45/3); (b) nylon (25/FL/N/37/3); Simple tensile (top), Loop (middle), Knot (bottom)

Though the trilobal embroidery thread shows lower tenacity, it has higher relative-tenacity, extension and specific work of rupture in both loop and knot forms compared to the other lubricated ones (Tables 2 and 3). The filaments with trilobal cross section could easily spread out at the point of loop lock, the thread assumes high curvature; leading to reduction in the stress differential among the filaments in the thread. This improves both the relative tenacity and extension of the thread. Nylon threads exhibit larger relative extension and specific work of rupture compared to polyester threads due the former's high extensibility. Both the polyester and nylon threads exhibit not a sharp break in tensile test, whereas they exhibit sharp cuts in the loop and knot tests (Fig. 11).

The broken filaments of twisted polyester threads shown in Fig. 12 a (Top) indicates that all the filaments have under gone ductile breaks in simple tensile test. The fiber deformation is associated with the crack propagation, when the tensile stress reaches a certain level a crack starts to propagate into the fiber, from a surface flaw on it. Plastic yield (drawing) of material causes the crack to open into a V-notch which propagates steadily into it. The discontinuous separation at the open end of the V is linked to the continuous elongation on the other side by the long zone of plastic shear. Finally catastrophic failure occurs under the high stress on the unbroken part of the cross-section [5].



(a) (b)

Fig. 12 SEM images of broken fibers of twisted filament threads: (a) polyester thread (20/FL/P/45/3) (Top) Simple tensile- ductile breakage (both left and right), Middle Loop- Pendulum break (left), ductile break fused (right), and Bottom knot- Pendulum break (Right); Ductile break fused (Left); Cut end (Centre); (b) nylon thread (25/FL/N/37/3) (Top) Simple tensile – ductile break (left and right), (Middle) Loop – cut end (left) and angled traverse crack (right), (Bottom) Knot – Pendulum break (Left) and cut end (right)

At the time of breaking of the loop, some filaments break at a slower pace which is evident in the ductile break of fibers shown in Fig. 12 a (Middle-Right) whereas as for some filaments, which are the last ones to break, it is more of impact loading which is evident in the pendulum break fibers as shown in Fig. 12 a (Middle-Left). The broken filaments from the knot test shown in Fig. 12 a Bottom (Right) indicates that the filaments had under gone impact force which lead to the pendulum type break. The impact force is acting when the first ply got broken, suddenly the whole force start acting on the rest of the plies and in the process the filaments which are having lower helix angle mostly bear the force and break as pendulum type break. The filament break from the knot shown in Fig. 12 a Bottom (Centre) is a typical cut end break which takes place due to the transverse force when the thread bend at an acute angle. Fig. 12 a Bottom (Left) shows the ductile break of filaments which break at last. Since the thread is in compressed state inside the knot at the time of breaking, much heat is generated that results in the fused end. The simple tensile failure of nylon filaments shown in Fig. 12 b (Top) indicates mostly ductile breaks which is evident from the necking (narrowed broken tip) on a stretched filament because of the high extensibility of nylon filaments. The broken filaments (Fig. 12 b Middle Left) shows all with cut end break, which indicates that as the force applied on the loop, the breaking of filaments propagated one after the other. An angled linear broken end as shown in Fig. 12 b (Middle Right) is due to the initiation of the break may be at a crack or flaw popped up perpendicular to the fiber axis but propagated diagonally [5]. The broken filaments from the knot (Fig. 12 b Bottom Right) shows cut end which is caused by the transverse break similar to loop (12 b Middle Left). The pendulum break (Fig. 12 b Bottom Left) shows that few unbroken filaments experience an impact force.

3.4 Textured polyester filament threads

The Fig. 13 shows the force-extension curves of the textured filament polyester thread 23/FT/P/18/0.

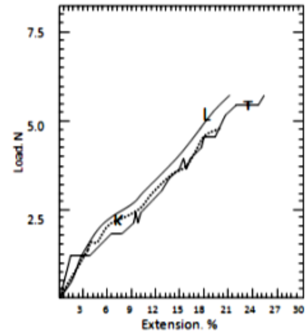
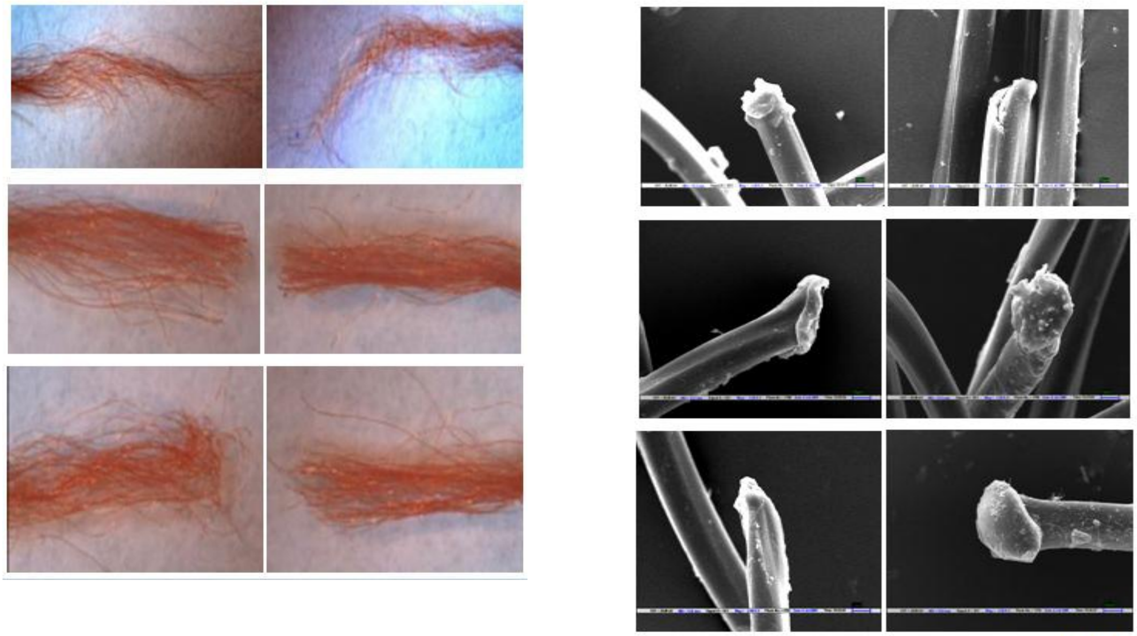


Fig. 13 Force-extension curves of textured filament polyester thread 23/FT/P/18/0

Table 4. Threads test results (textured polyester and nylon bonded filament threads)

Thread	codes	Twist (Single/Ply)	Test	σ	ε	SWR	RT	RE	RWR
Filament Polyester-Textured	23/FT/P/18/0	0	ST	34.5	22.2	4.38	-	-	-
			L	34.0	21.2	3.57	0.99	0.95	0.81
			K	28.3	19.5	2.66	0.83	0.88	0.61
	24/FT/P/35/0	0	ST	36.3	26.2	4.68	-	-	
			L	34.9	22.7	3.51	0.96	0.87	0.75
			K	28.7	18.8	3.02	0.79	0.72	0.65
Filament Nylon Bonded	27/FB/N/37/3	14/10	ST	61.2	17.1	4.48	-	-	-
			L	41.5	12.7	2.24	0.68	0.74	0.50
			K	35.4	11.6	1.86	0.58	0.68	0.41
	28/FB/N/47/2	14/10	ST	58.4	24.4	5.69	-	-	-
			L	44.3	17.4	3.30	76	0.71	0.58
			K	40.5	16.6	2.85	69	0.68	0.50
	29/FB/N/63/2	14/10	ST	50.6	21.4	4.51	-	-	-
			L	34.2	16.0	2.33	68	0.75	0.52
			K	31.9	15.5	2.17	63	0.73	0.48

The textured threads have much lower tenacity compared to the twisted filament threads because the filaments are having different degree of waviness with poor contact among themselves. The weakest filaments break first. The breakage of filaments is in stepped manner which leads to the loss of tenacity. The force extension curve exhibits kinks indicating poor load sharing of the filaments due to crimps. The relative loop tenacities of textured threads are almost unity. Due to lack of twist in the filaments, the filaments spread easily at the point of loop locking and break very similar to that of straight threads. The relative values of extension and specific work of rupture are next to the spun threads but are higher than the twisted and bonded filament threads.



(a) (b)

Fig.14 Textured filament polyester thread 24/FT/P/35/0: (a) broken ends (Top) simple tensile test; (Middle) Loop, (Bottom) Knot; (b) SEM images of broken fibers (Top) Simple tensile - high speed breakage (left and right), (Middle) Loop - Pendulum break (left and right), (Bottom) Knot – Pendulum break (Right) and angled traverse crack (left)

It is evident from the broken filaments in simple tensile test (Fig. 14a -Top) that the breakage of filaments in textured thread is not at the same place. The knot break (Fig. a 14-Bottom) exhibits abrupt break but not at the same place as in the case of loop (Fig. 14 a-Middle).The broken filaments of textured thread under simple tensile test shown in Fig. 14 b-Top indicate a high speed break, which is caused by the sudden force acting on these filaments after the break of the initially resisting filaments. The broken filaments from loop test shown in Fig. 14 b (Middle) indicate that the filaments are broken due to impact force causing the pendulum break. The cross section of the broken fiber from the looped thread (Fig. 14 b Middle-Right) shows serrations, due to flex fatigue at the acute bending portion of loop. A clear evidence of transverse force involved in knot is exhibited by a filament (Fig. 14 b Bottom-Left) broken due to the propagation of the transverse crack initiated by the acute bending of fibers in a circular bundle. The pendulum break on filament from the knotted thread (Fig. 14 b Bottom-Right) indicates that the impact force is acting on the individual filaments at the last stage after most of the filaments had already broken due to transverse forces.

3.5 Nylon filament bonded threads

The simple tensile tenacity of the bonded threads does not show higher values compared to nylon twisted filaments (Table 3 and 4) and it may be inferred that the bonding is limited only to give protection to filaments against abrasion.

(a) **(b)**

Fig. 15 Nylon filament bonded thread 28/FB/N/47/2: (a) broken ends (Top) simple tensile test; (Middle) Loop, (Bottom) Knot; (b) SEM images of broken fibers (Top) Simple tensile – ductile break (left and right); (Middle) Loop - Pendulum break (left and right); (Bottom) Knot – Pendulum break (Left) and angled traverse crack (right)

Also the resin applied on the thread adds up to its linear density (tex) and results in lower tenacity. Usually a minimum of 3 to 5% multi-polymer nylon resins (based on thread weight) must be coated on multi-cord or mono-cord threads for satisfactory results [18]. At a given cross section of a bonded thread, approximately 95% would be filaments and 5% would be resin.

When the load on the thread is increased, the resin gets removed at the interfaces in the loop and knot, and their contribution to tenacity is negligible. The bonded thread shows similar behavior in the loop and knot forms (in terms of tenacity and extension) as compared to most of the other threads. This shows that bonded threads behave in a same pattern in loop as well as in knot. The transverse break takes place generally in the case of a knot than in a loop because of its high acute bending (>180°), but in the case of bonded threads the transverse force break takes place in a loop as well because of its higher rigidity. In Fig. 15 a (Bottom) it can be noticed that the plies are breaking individually at different stages as in the case of the lubricated nylon threads.

The Fig. 15 b-middle shows that the filaments in the loop have undergone pendulum impact break, while it is ductile break in case of the lubricated nylon threads. The frictional heat due to the high compressive forces causes melting of resin and the meltdown resin are visible on the broken ends. The same is seen in the knot as well (Fig. 15 b Bottom) but it is not seen in the simple tensile break. The temperature generated goes beyond 160°C because the fusing temperature of the resin in bonded thread is about 160°C [18]. A broken filament from simple tensile test shown in

Fig. 15 b (Top Left) has the break initiated at an angled linear flaw with catastrophic failure propagating axially. The fibers show serrations on the surface as shown in Fig. 15 b (Top Right) might be the cracks formed on the resin-coat due to the filament extension.

3.6 Effect of thread tex on tensile properties

When threads are interlaced as in the loop or knot forms, the difference between the path length of fibers forming larger and smaller radii is $2\pi d$. The diameter of the thread d is related to tex, fiber density, ρ_f and packing fraction of fibers Φ_f in the thread is:

$$d = \sqrt{tex/\phi_f \rho_f} \qquad [19]$$

When the threads are stretched in bent and interlaced configurations, few fibers following larger radius of curvature are subjected to more tensile stress and they start stretching earlier before the others do (Fig. 16). The phase difference in the tensile strain makes the high stretched fibers to break much earlier than the other fibers, if the thread cross section does not allow theses fibers to move to the regions of low tensile strain.

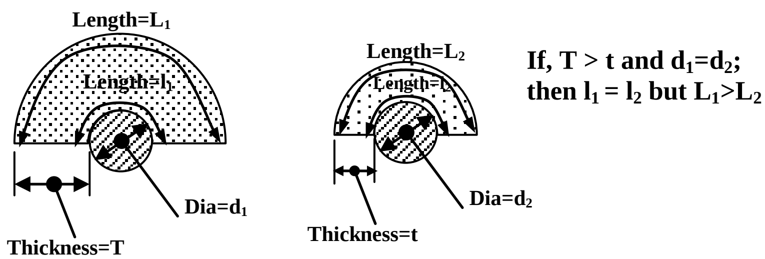
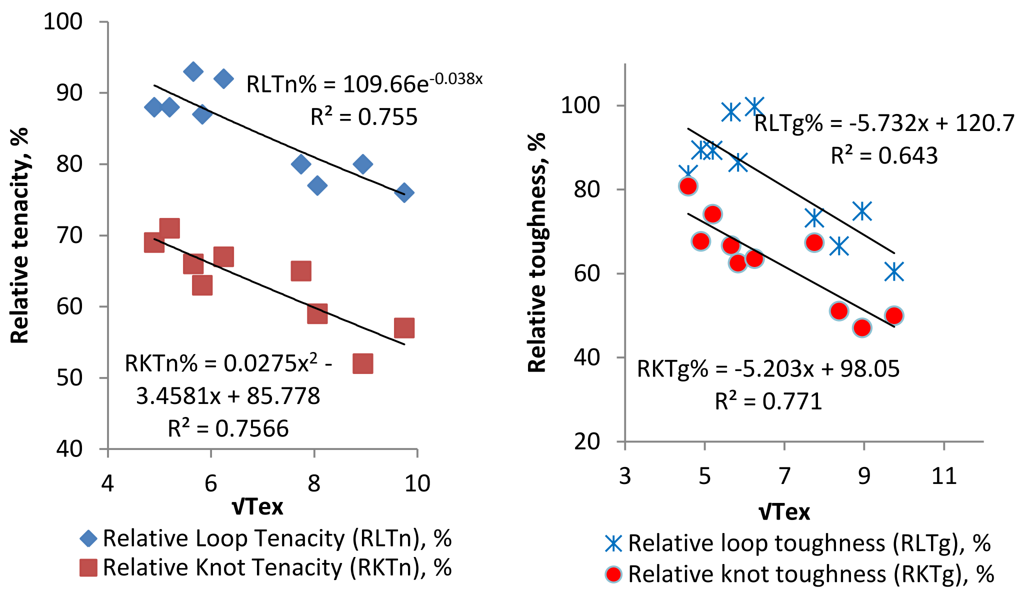


Fig. 16 Thread thickness Vs Bending Length of curvature

Consequently, the loss of tenacity, breaking extension and work of rupture would be more if the threads are having larger tex. This effect of tex on the relative tenacities and toughness of spun polyester threads are shown in Fig. 17 a and b respectively. There are other factors such as extensibility of fibers, shear strength of fibers following lower radii of curvatures that are subjected to high compressive forces. The twist levels of the thread might also play a role in influencing the relative values of tenacity, extension and work of rupture. Hence, very high correlation coefficients are not observed.



(a) **(b)**

Fig. 17 Effect of √Tex of spun polyester threads on: (a) relative Loop and Knot Tenacity %, (b) relative loop and knot toughness %

3.7 Effect of thread structure on tensile properties

Six threads of different construction but of same linear density (≈40Tex), 7/S/P/39/3, 12/CR/PC/40/2, 20/FL/P/45/3, 24/FT/P/35/0, 25/FL/N/37/3, 27/FB/N/37/3 can be compared using their test results given in the tables 1 to 4. It is evident that the spun and textured threads show the lowest simple tensile tenacity which is due to fiber slippage and the stepped failure in the spun and textured threads respectively. The textured thread shows the highest extensions. The lower simple tensile tenacity of PC core spun thread may be attributed to the low strength contribution of the sheath fibers. The bonded thread shows lowest extension which could be attributed to the resin boding the filaments. The twisted polyester filament thread shows the highest loop tenacity, which makes it to consider as an ideal high performance sewing thread. But it has poor relative loop tenacity compared to spun polyester and textured polyester threads. The polyester spun and textured threads show highest relative loop tenacity. The disconnected fiber lengths, low packing density of fibers, and helical /crimp configuration fibers are responsible for this.

4. Conclusions

The threads in a loop and knot forms always break at the thread intersections and not at the straight arms of the threads, indicating that the thread intersections are the weakest. The high differential tensile strains among the fibers/filaments across the threads in loop and knot forms reduces the tenacity and extension, thus the threads exhibit more of brittleness. The level of freedoms available for the high strained fibers/filaments in a knot is lesser compared to that in a loop. Hence, the relative values of tenacity, extension and work of rupture in a knot is always lower compared to that in a loop. The thread breakage is sharper in loop and knot forms due to the presence of high transverse forces on the fibers/filaments. In a simple tensile test, the plies break simultaneously at different locations; but in loop and knot tensile tests, the plies break sequentially, the first ply break with sharp transverse cut and the next unevenly, which is the cause for the loss of tenacity in the later two cases.

The non-circular fibers/filaments (cotton and trilobal) and highly crimped filaments could easily spread out in loop and knot compared to the circular fibers and hence, the cotton spun-, trilobal filament polyester- and textured polyester- threads have lower loss of tensile properties in loop and knot forms. The spun threads have higher relative values of tensile properties than the filament threads due to the discrete fibers in the former could rearrange easily when subjected to acute bending. In the case of twisted filament polyester threads, the lack of flexibility for the filaments to rearrange themselves at the locking spots lead to the lowest relative tenacity in loop and knot tests. The bonded nylon filament threads also suffer the same way due to the resin bonding the filaments. The textured thread shows the highest specific work of rupture due to its higher extension.

In the case of core spun threads, the cotton sheath slips off easily compared to the polyester sheath fibers. When a core spun thread is stretched close to its breaking extension, the sheath fibers are untwisted and become almost parallel to the thread axis, detached from the core which leads to minimal or nil contribution from the sheath to the thread strength. Hence, the core spun threads have lower relative loop and knot tenacities compared to the spun threads. The mechanism of breakage of core filaments in both the PP- and PC-core spun threads is similar.

Coarser threads experience greater loss of tenacities in loop and knot tests due to larger stretch differential of the filaments across the threads with the increased thread diameter.

The general fiber rupture patterns for cotton fiber are: granular and axial split in simple tensile test; and granular for the loop and knot tests. In the case of spun polyester threads, the observed fiber ruptures are: ductile for the simple tensile, pendulum for the loop and localized transverse break for the knot. Both the polyester and nylon filaments exhibit ductile failure with necking in simple tensile, pendulum in loop and transverse cut in the knot tests.

The broken nylon bonded threads exhibit fused or melted resin spots only in the loop and knot tests due to the temperature of the thread reaching beyond the melting point of the resin at the time of thread failure. All the filaments undergo impact force at the time of failure of the thread; the heat associated with it caused the formation of mushroom head on the filaments.

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