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Analysis of the Influence of Process Parameters on the Mechanical Properties of Carbon Core Friction Spun Hybrid Yarns for Composites

Abstract
Textile-reinforced composites are a leading trend in lightweight structure design. The demand for additional function integration in lightweight structures using multi-material design is growing rapidly. This article reports on the production of hybrid yarns made with the DREF-2000 friction spinning technique using carbon filament yarn (CFY) as the core component and diverse thermoplastic fibres, such as polypropylene (PP) and polyester (PET) fibres, as the sheath component. The yarns are to be used as a reinforcement and as a functional element suitable for textile reinforced thermoplastic composites. Different hybrid yarns were manufactured by varying the air suction pressure, spinning drum speed and distance between the spinning drums at a constant delivery and opening roller speed. The influence of the air suction pressure, spinning drum speed, distance between the spinning drums, sheath type and core sheath volume ratio on the properties of yarn tenacity and elongation was analysed and differentiated by a multi-factorial analysis of the individual variables (ANOVA).

Key words: *carbon filaments, friction spinning, tensile property, ANOVA.*

Introduction

Due to its superior tensile properties and low density, carbon filaments are being used extensively as reinforcements in lightweight structural design. Carbon filament possesses the ability to conduct electricity and information. Moreover, its ability to withstand the temperature and pressure required during the consolidation of thermoplastic composites has made carbon filaments a preferable candidate for use in textile based thermoplastic composites as a reinforcement fibre and as a functional component. Thermoplastic composites are comprised of at least one reinforcement material and a thermoplastic polymer as a matrix. These composites show distinct advantages as compared to thermo-set composites. Due to their high fracture toughness, easy recycling, elongation, short processing time, various forming possibilities, weld-ability, low cost and resistance to media and corrosion, they are attracting growing interest from both the academic community as well as from industry [1 - 4]. Target application areas of these composites are primarily within the aerospace, marine, defence, land transportation, lightweight construction and power generation sectors. With the development of new application areas for textile composites, the demand for additional function integration in textile composites is growing rapidly.

It is possible to integrate carbon filaments using different textile processes such as knitting, weaving or stitching them into fibre reinforced textile pre-forms for thermoplastic composites. However, for the integration of such functional components, it is crucial to protect the carbon filaments from damage during textile processing. Hence, a yarn with a carbon filament core covered with thermoplastic fibres presents a more satisfactory solution to withstand processing demands.

Ernst Fehrer developed and commercialised a friction spinning system under the name DREF in the nineteen seventies. The invention was a catalyst which served to renew the interest of research workers in core yarns. With the help of friction spinning, it is possible to manufacture hybrid yarn with a a core and sheath structure. The core component (in staple fibre/endless filament form or in a combination of both) is permanently confined to the central axis and covered by staple fibres. One of the main advantages lies in the fact that core/sheath yarns can be produced with the reinforced or functional fibre/filament in the central position, without filament breaks, with an optimum use of strength and desired level of core coverage by the sheath, thus allowing the sheath to fully protect the core during further textile processing. This method has an added advantage over the conventional spinning method, in that the roving and rewinding processes required can be eliminated, which results in reduced processing and manufacturing costs [5].

The aim of the collaborative research project – SFB 639 [4] is to integrate functional components into textile pre-forms in a single step manufacturing process. In turn, these pre-forms can then be converted into functional textile reinforced thermoplastic composites. In this paper, the discussion is confined mainly to hybrid yarns in which the core component is made of CFY, and the sheath is produced from thermoplastic fibres, such PP and PET. The function of the sheath is two-fold: Firstly it protects the core carbon filaments, and secondly it aids in the integration of the functional hybrid yarn produced with thermoplastic PP based composites.

In friction spinning, the spinning drums move in opposite directions to contact with the yarn surface, and suction air pressure is provided to hold the fibres against the surface of the spinning drums. The amount of suction air pressure influences the amount of torque on the yarn

Table 1. Characteristics of carbon filament yarns used as a core component.

Characteristics	Type of carbon filament yarn	
	Toho Tenax HTS40	Toho Tenax HTA40
Yarn fineness, tex	800	400
Number of filaments [7]	12000	6000
Breaking force, N	749	314
Tenacity, cN/tex	93.6	78.5
Elongation at break, %	0.9	0.8
Filament diameter [7], μm	7	
Electrical resistivity [7], ohm·cm	$1.6×10^{-3}$	

surface. The distance between the spinning drums is also an important factor determining the structure of the sheath. The aim of the study was to differentiate the effects of the individual factors influencing the tensile properties of carbon core hybrid yarns. A powerful tool for dealing with such problems is statistical analysis of variance (ANOVA), which enables not only an estimation of the effects of individual factors on process quality but also takes into account their interactions [6]. The hybrid yarns were manufactured with varying fineness of the carbon filament yarn, various types of sheath material, varying sheath fineness, various machine parameters, such as the spinning drum speed and suction air pressure, and various distances between the spinning drums. The relationship between the different textile physical properties of the hybrid yarns, such as tensile strength and elongation with different spinning parameters, and core-sheath ratios was also investigated.

Materials and methods

Raw materials

In the present study, *Toho Tenax HTS40* CFY of 800 tex and *Toho Tenax HTA40* CFY of 400 tex were used as the core component. Characteristics of the core components are detailed in ***Table 1***. PP sliver of 4 ktex (64.3 mm length) and PET sliver of 2.6 ktex (28 mm length) were used for the yarn sheath.

Table 2. Process variables and yarn specifications of the hybrid yarns manufactured.

Core fineness, tex	Sheath fineness, tex	Sheath material	Core sheath volume ratio	Suction pressure, hPa	Spinning drum speed, r.p.m.	Number of sliver used	Yarn specification
Distance between spinning drums: 0.25 mm							
800	600	PP	41:59	-13	1500	2	FS#01
					4500		FS#02
				-36	1500		FS#03
					4500		FS#04
				-58	1500		FS#05
					4500		FS#06
		PET	51:49	-13	1500	3	FS#07
					4500		FS#08
				-36	1500		FS#09
					4500		FS#10
				-58	1500		FS#11
					4500		FS#12
Distance between spinning drums: 0.3 mm							
800	600	PP	41:59	-13	1500	2	FS#13
					4500		FS#14
				-36	1500		FS#15
					4500		FS#16
				-58	1500		FS#17
					4500		FS#18
		PET	51:49	-13	1500	3	FS#19
					4500		FS#20
				-36	1500		FS#21
					4500		FS#22
				-58	1500		FS#23
					4500		FS#24
Distance between spinning drums: 0.25 mm							
800	100	PP	81:19	-36	1500	1	FS#25
	300		58:42			1	FS#26
400	50		81:19			1	FS#27
	140		60:40			1	FS#28
	300		41:59			1	FS#29

Design & production of friction spun conductive hybrid yarns

Hybrid yarns were manufactured on a DREF 2000 friction spinning machine (Fehrer AG, Linz/Austria), whose speed of yarn delivery and the opening roller was kept constant at 50 m/min and 4500 r.p.m, respectively, while the spinning drum speed and air suction pressure were varied. Moreover the distance between the spinning drums was varied from 0.25 mm to 0.3 mm. The yarns produced with different processing variables are listed in detail in ***Table 2***.

Tensile test

Tensile tests of the hybrid yarns manufactured were carried out according to DIN 53834 using a tensile strength testing device - Zwick type Z 100 (Zwick GmbH and Co., Germany) with special return clamps and external strain measuring. Samples of 500 mm yarn length were used. The test velocity was set at 25 mm/min, and the initial load was kept at 0.5 cN/tex. The tensile force versus deformation was recorded, and 10 measurements were taken to obtain the force average value for each type of yarn. The stress-strain behaviour was evaluated using testXpert® software. The instrument was located in a temperature and relative humidity controlled laboratory maintained at 20 ± 1 C and 65 ± 2%, respectively.

Analysis of variance (ANOVA)

The influence of four factors – the air suction pressure, spinning drum speed, distance between the spinning drums, and sheath fibre type on the tenacity and elongation at break of hybrid yarns FS#01 to FS#24 was statistically analysed using a multi-factorial ANOVA. For the study, a four-factor 3 × 2 × 2 × 2 design was used with three levels of air suction pressure, 2 levels of spinning drum speed, 2 levels of distance between the spinning drums and 2 types of sheath fibres. The average of 10 measurements of the tenacity and elongation at break was analysed using the multi-factorial ANOVA separately. Higher-order – three and four-factor – interactions were assumed to be negligible and combined into error so that F-ratios and corresponding P – values at 95% confidence limits could be calculated.

Moreover, in order to find out the effect of core fineness and the core sheath volume ratio on the tenacity and elongation at break of the hybrid yarns with PP sheath, FS#03 & FS#25 – FS#29 were statistically analysed separately using a two-factor 2 × 3 design with two levels of core fineness (800 tex and 400 tex) and three levels of the core sheath volume ratio (i.e., 41:59, 60:40 and 81:19) at a constant air suction pressure of -36 hPa, spinning drum speed of 1500 r.p.m and 0.25 mm distance between the spinning drums. In this case, ten measurement values were taken for the analysis.

Results and discussion

The tensile properties of the manufactured hybrid yarns tested are presented in detail in ***Table 3***. Typical force-elongation curves of yarns made of PP sheath spun with variable air suction pressure and spinning drum speed using a distance between the spinning drums of 0.25 mm and 0.3 mm are illustrated in ***Figure 1***.

Effect on yarn tenacity

Results of the tenacity of hybrid yarns FS#01 to FS#24 are presented graphically in ***Figure 2***. These values were also analysed using a four-factor design, as already mentioned. ***Figure 2*** shows that the hybrid yarn tenacity decreases with an increase in air suction pressure for both types of sheath. A higher air suction pressure through the friction drums leads to increased frictional forces between the fibre assembly (sleeve) and friction drum surfaces, thereby increasing the torque acting on the fibre sleeve. As a consequence, the rotational speed of the fibre sleeve increases, which results in a higher yarn twist [8, 9]. Since the chance of damaging the CFY core is higher due to higher twist insertion, the hybrid yarn's strength decreases considerably with an increase in air suction pressure. The influence of air suction pressure at a constant spinning drum speed of 4500 r.p.m on yarn tenacity is similar to that at 1500 r.p.m.

The hybrid yarn tenacity also decreases with an increase in the spinning drum speed at a constant air suction pressure, which could be due to either the damage caused in the CFY core resulting from higher twist or the increase in hooked sheath fibres at higher spinning drum speeds. As a result, sheath fibres may not wind around the core and therefore, because of their decreased length, do not

Table 3. *Tensile properties of the hybrid yarns manufactured; σ - is the standard deviation.*

Yarn specification	Hybrid yarn fineness, tex	Tenacity, cN/tex		Elongation at break, %	
		mean	σ	mean	σ
FS#01	1420	64.4	3.2	1.1	0.1
FS#02	1440	56.8	3.3	1.2	0.1
FS#03	1430	54.5	3.2	1.3	0.1
FS#04	1430	45.1	4.0	1.4	0.1
FS#05	1444	43.6	2.3	1.6	0.1
FS#06	1462	38.8	4.2	1.5	0.1
FS#07	1403	69.0	3.6	1.4	0.1
FS#08	1440	55.4	4.7	1.3	0.1
FS#09	1450	53.4	2.9	1.4	0.2
FS#10	1437	49.1	3.5	1.5	0.1
FS#11	1473	45.1	3.1	1.7	0.1
FS#12	1435	40.6	3.2	1.6	0.2
FS#13	1413	59.9	2.9	1.2	0.1
FS#14	1456	54.9	3.7	1.1	0.1
FS#15	1456	60.0	4.6	1.4	0.1
FS#16	1466	56.5	3.8	1.5	0.1
FS#17	1416	54.6	5.1	1.6	0.1
FS#18	1440	52.5	3.5	1.6	0.1
FS#19	1420	63.2	2.3	1.2	0.1
FS#20	1423	61.2	3.8	1.1	0.1
FS#21	1450	56.5	2.7	1.3	0.1
FS#22	1430	53.6	2.3	1.2	0.1
FS#23	1420	54.5	2.4	1.4	0.1
FS#24	1460	50.6	2.5	1.5	0.1
FS#25	913	58.5	4.5	1.0	0.1
FS#26	1146	66.2	3.4	1.3	0.1
FS#27	467	59.3	5.2	0.8	0.1
FS#28	550	65.6	2.4	1.1	0.1
FS#29	717	49.8	3.4	1.2	0.1

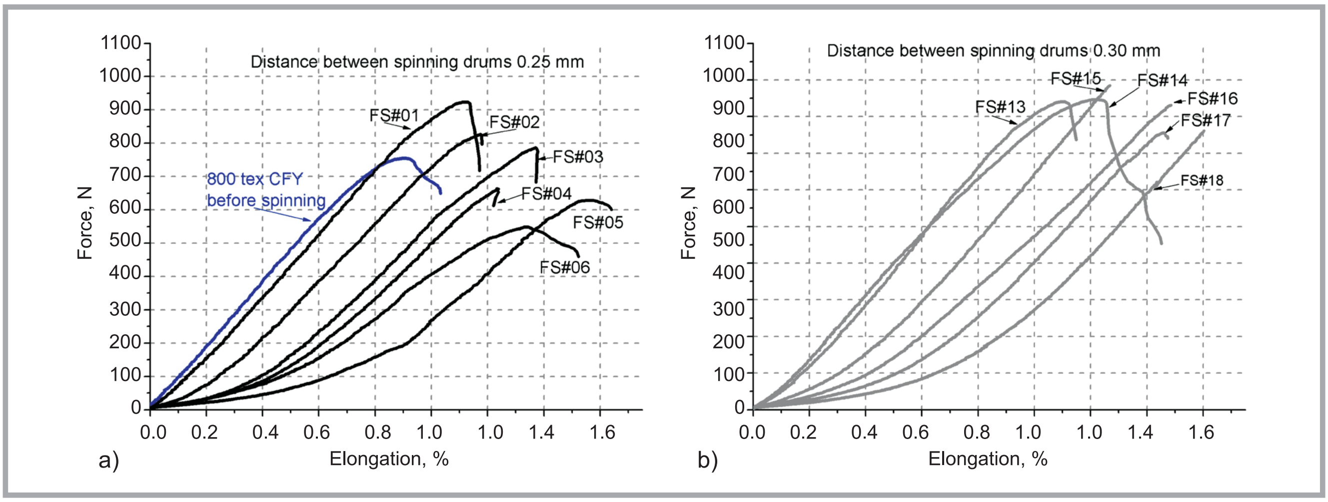

Figure 1. *Typical force-elongation curves of various hybrid yarns spun with 600 tex PP sheath and 800 tex CFY core using a spinning drum distance of a) 0.25 mm and b) 0.3 mm.*

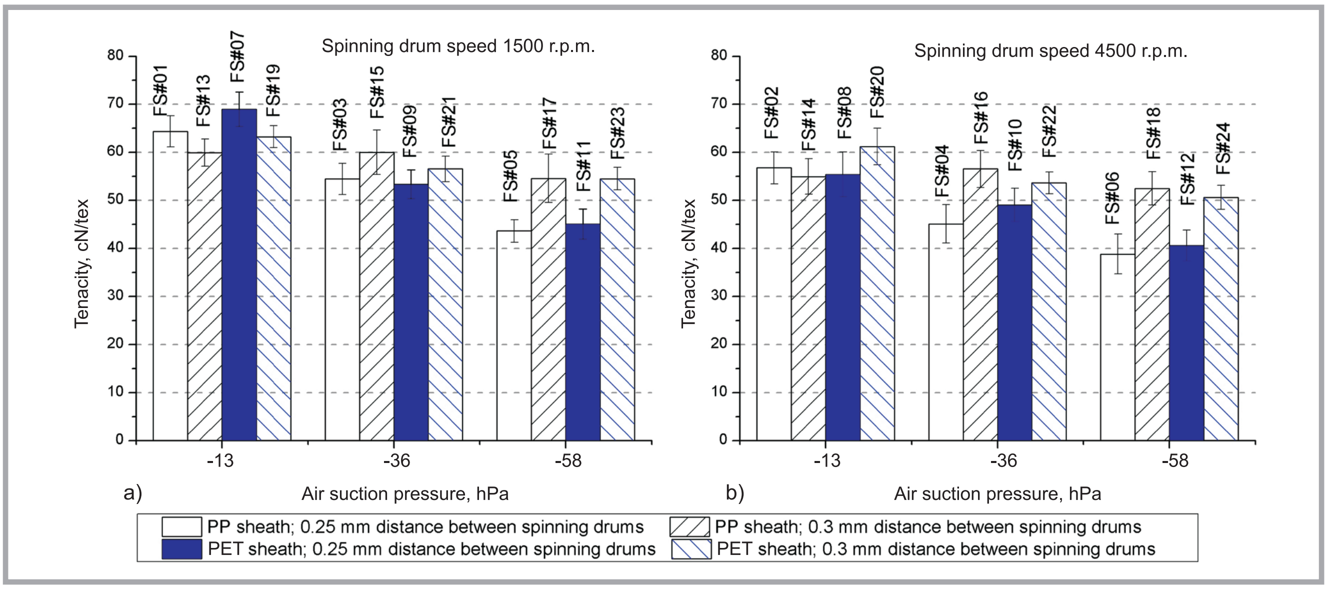

Figure 2. *Effect of air suction pressure on the tenacity of hybrid yarns of 600 tex sheath (PP and PET) and an 800 tex CFY core using a distance between spinning drums of 0.25 mm and 0.3 mm, spun at a constant spinning drum speed of a) 1500 r.p.m and b) 4500 r.p.m.*

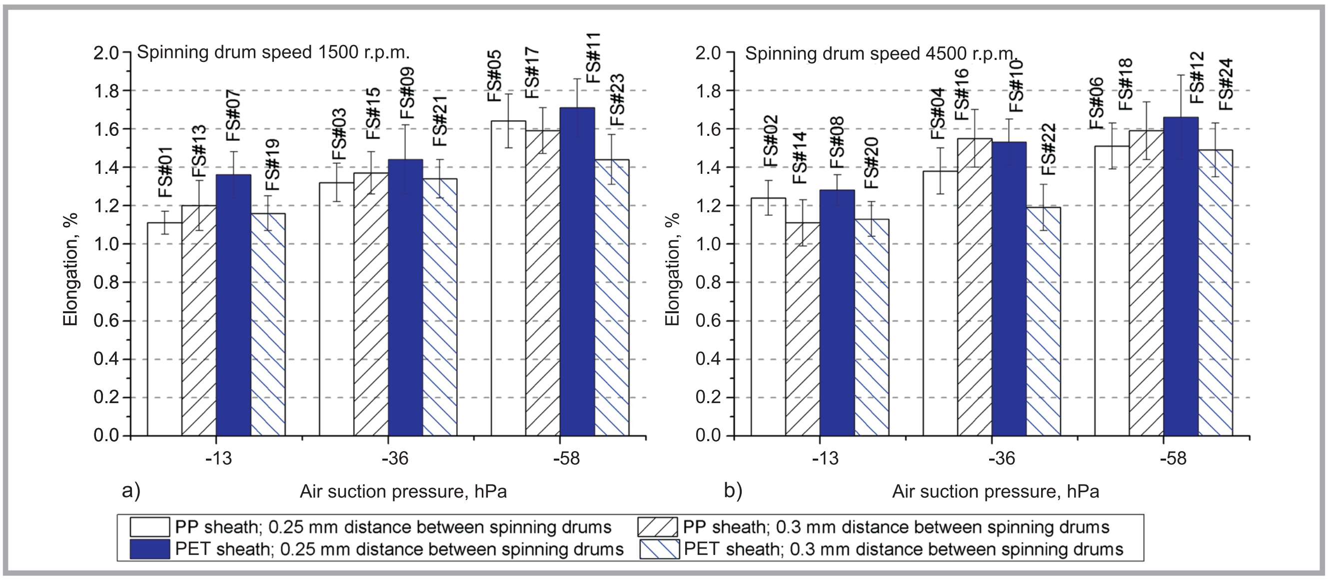

Figure 3. *Effect of air suction pressure on the elongation of hybrid yarns of 600 tex sheath (PP and PET) and an 800 tex CFY core using a distance between spinning drums of 0.25 mm and 0.3 mm, spun at a constant spinning drum speed of a) 1500 r.p.m and b) 4500 r.p.m.*

efficiently contribute to the tenacity [10]. Furthermore, hybrid yarns spun using a distance of 0.25 mm between the spinning drums have a lower tenacity as compared to that of yarns spun with a 0.3 mm distance between the spinning drums at an air suction pressure of -36 hPa and -58 hPa. This can be attributed to the higher frictional forces between the spinning drums and hybrid yarn surface. Because the sheath is loose on hybrid yarns spun at an air suction pressure of -13 hPa, it is unclear why the change in spinning drum distance at an air suction pressure of -13 hPa also affects the hybrid yarn tenacity differently. Conversely, fibre length does not seem to have any impact on the yarn tenacity.

The results from the ANOVA analysis, which evaluated the effect of the air suction pressure, spinning drum speed, distance between the spinning drums, and sheath fibre type on yarn tenacity, are collected in ***Table 4***. The higher value of the *F*-ratio of the air suction pressure, distance between the spinning drums and the spinning drum speed to the value of *F*-critical proves that the hybrid yarn tenacity is strongly dependent on the air suction pressure, spinning drum speed and the distance between the spinning drums. By comparing the *P*-values of these three factors, it can be concluded that the air suction pressure has the highest influence on the hybrid yarn tenacity, especially since the *P*-value of air suction pressure is the lowest among the other three factors.

The hybrid yarn tenacity does not change significantly with an alteration in the sheath fibre length or type as the value of the *F*-ratio is lower than that of the *F*-critical. From the comparison between the values of the *F*-ratio and *F*-critical of the two-factor interactions, it is clear that only the combination of air suction pressure - distance between spinning

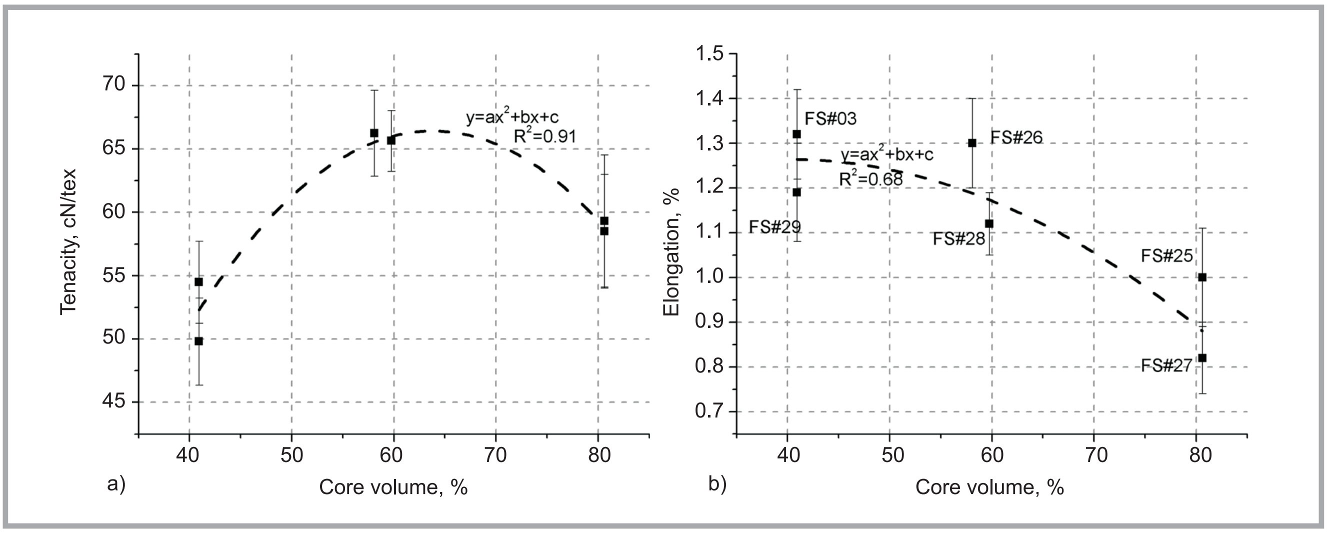

Figure 4. Influence of the core sheath volume ratio on the a) tenacity and b) elongation of the hybrid yarns.

drums has a statistically significant effect (*P*-value <0.05) on the yarn tenacity.

Effect on elongation

Figure 3 illustrates results of the elongation of hybrid yarns FS#01 to FS#24. For hybrid yarns with an 800 tex CFY core, the elongation at break of the yarns increases with an increase in the air suction pressure at a constant spinning drum speed and constant distance between the spinning drums, the reason for which may be the increase in the buckling of wrapper fibres, which may create more opportunities for hybrid yarn extension [10]. However, the effect of the spinning drum speed on elongation at a constant air suction pressure and constant distance between the spinning drums cannot be clearly identified.

In ***Figure 3*** the effect of the distance between the spinning drums on the elongation of hybrid yarns with a PP sheath cannot be clearly deduced. However, the elongation decreases for hybrid yarns spun with a PET sheath. The twist efficiency of the short PET fibres around the core at a higher distance between the spinning drums may be lower than that of the longer PP fibres. As a result, the elongation decreases with an increase in the distance between the spinning drums in the case of PET fibres used as the sheath. Similarly, from the results of ANOVA analysis of the factors effecting elongation, it is found that the value of the *F*-ratio of the air suction pressure and distance between the spinning drums (45.69 and 6.85, respectively) is higher than the respective value of the *F*-critical (which is 4.26 and 5.12), showing that the elongation of the hybrid yarn is significantly affected by the air suction pressure and distance between the spinning drums. Furthermore, the influence of the sheath type and spinning drum speed is insignificant when considering the elongation properties of the hybrid yarn.

Influence of the core sheath volume ratio

Figure 4 illustrates the influence of the core sheath volume ratio on the tenacity and elongation of yarns with a PP sheath spun at a constant air suction pressure of -36 hPa, spinning drum speed of 1500 r.p.m and distance between the spinning drums of 0.25 mm. The yarn tenacity exhibits a quadratic trend over the range of core sheath volume ratios. The maximum yarn strengths are found in the range of 55 to 65 core sheath volume ratio for both CFY core fineness specimens.

Table 5 shows the results of ANOVA, differentiating the influence of the core fineness and core sheath volume ratio on the yarn tenacity. It is clear that the

Table 4. ANOVA for the tenacity of yarns with the specification of FS#01 to FS#24.

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-ratio	F-Critical at α = 0.05	P-value
A: Suction air pressure	1277.37	2	638.69	11.618	4.26	0.00321
B: Distance between spinning drums	416.50	1	416.50	7.576	5.12	0.02238
C: Sheath type	30.06	1	30.06	0.547	5.12	0.47845
D: Spinning drum speed	424.37	1	424.37	7.719	5.12	0.02145
A – B interaction	494.39	2	247.19	4.497	4.26	0.04426
A – C interaction	155.27	2	77.64	1.412	4.26	0.29278
A – D interaction	71.79	2	35.89	0.653	4.26	0.54349
B – C interaction	35.72	1	35.72	0.649	5.12	0.44090
B – D interaction	160.89	1	160.89	2.927	5.12	0.12128
C – D interaction	54.90	1	54.90	0.999	5.12	0.34371
Residual (error)	494.73	9	54.97			
Total	3615.99	23				

Table 5. ANOVA for the tenacity of hybrid yarns with the specification of FS#03, FS#25 – FS#29.

Source of variation	Sum of squares	Degree of freedom	Mean squares	F-ratio	F-Critical at α = 0.05	P-value
A: Core fineness	34.555	1	34.555	2.595	4.00	0.113
B: Core sheath volume ratio	1889.74	2	944.869	70.957	3.15	0
A – B interaction	82.136	2	41.068	3.084	3.15	0.053
Error	719.062	54	13.316			
Total	2725.49	59				

yarn tenacity is greatly influenced by the core sheath volume ratio, while the core fineness does not affect the yarn tenacity. At a higher core sheath ratio, the coverage of the carbon core filament is inadequate due to less sheath, which results in damage to the CFY core during friction spinning; whereas at, lower core sheath ratios i.e. an increase in sheath does not contribute to an increase in yarn strength after the optimal point has been attained. Unlike the results of hybrid yarn tenacity at a variable core sheath volume ratio, the elongation is higher at lower core sheath volume ratios (cf. ***Figure 4.b***). Moreover, the elongation tends to decrease with finer hybrid yarns. Because buckled and helically wound sheath fibres cause the hybrid yarn to extend and more sheath fibres - increased extension, elongation also increases at a higher sheath ratio. The results of elongation analysed by ANOVA also show that the influence of the core sheath volume ratio and core fineness (or total yarn fineness) on hybrid yarn elongation is statistically significant.

Conclusion

With the use of multi-factorial ANOVA, the influence of the air suction pressure, spinning drum speed and distance between the spinning drums on yarn tenacity and elongation can be easily identified and quantified. The results show that the air suction pressure, spinning drum speed and distance between the spinning drums affect yarn tenacity considerably. Yarn tenacity decreases with an increase in the air suction pressure and spinning drum speed. It is assumed that carbon filament damage is most likely due to the higher air suction pressure than the higher spinning drum speed. Therefore, the influence of the change in air suction pressure on the hybrid yarn tenacity is greater than that of a varying spinning drum speed. Although the tenacity of hybrid yarns spun at a lower air suction pressure is higher, the quality of sheath spun at an air suction pressure of -13 hPa is not satisfactory for textile processing. On the other hand, yarns spun at an air suction pressure over -36 hPa are too stiff, and their tenacity is also low. Therefore, the optimum air suction pressure range for efficient production of yarns of satisfactory sheath structure with an optimum level of strength is between -13 and -36 hPa.

Due to less frictional force, the hybrid yarn tenacity increases with an increase in the spinning drum distance. The frictional forces are considered to cause less entrapped false twist in the carbon core. The distance between the spinning drums can be adjusted up to 0.35 mm. However, the quality of yarns spun at a spinning drum distance greater than 0.3 mm is not satisfactory i.e., the sheath structure is too loose. It was found that the tenacity of hybrid yarns with a CFY core can be improved by increasing the spinning drum distance up to 0.3 mm, and by spinning with an air suction pressure between -13 and -36 hPa and a spinning drum speed of 1500 r.p.m.

It was assumed that the increase in yarn stiffness with the use of sheath of a higher fibre length might influence yarn tenacity or elongation. However, fibre sheath type does seem to affect neither the yarn tenacity nor the elongation.

Though the air suction pressure and distance between the spinning drums significantly affects the elongation of the yarns, the spinning drum speed shows no effect on the elongation. Additionally, the influence of air suction pressure on the elongation is greater than that of the spinning drum distance.

The core sheath volume ratio is an important factor influencing the core coverage by surface fibres, as well as yarn tenacity and elongation. Decreasing the core sheath volume ratio improves core coverage but, at the same time, decreases yarn tenacity. A core sheath volume ratio of around 55 - 65% seems to be the optimum level to create a higher yarn tenacity. Elongation is found to be higher for yarns with a higher count and lower core sheath volume ratio.

In conclusion, we can state that a decrease in hybrid yarn tenacity at a higher air suction pressure and spinning drum speed can be attributed to damage in the CFY core. In order to quantify the level of damage in the CFY core, a more in-depth investigation is required. Lastly, it can be said that from the results of the study, a better understanding of the different factors affecting the tensile properties of hybrid yarns made of carbon filament yarn and thermoplastic fibres is obtained. A more comprehensive understanding of these influences aids enormously in the design of hybrid yarns for high-tech applications in the demanding field of thermoplastic composites.

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