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Influence of process parameters on the tensile properties of DREF-3000 friction spun hybrid yarns consisting of waste staple carbon fiber for thermoplastic composites

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Abstract
Due to their excellent strength, rigidity, and damping properties, as well as low weight, carbon fiber reinforced composites (CFRCs) are being widely used for load bearing structures. On the other hand, with an increased demand and usage of CFRCs, effective methods to re-use waste carbon fiber (CF) materials, which are recoverable either from process scraps or from end-of-life components, are attracting increased attention. In this paper, hybrid yarns consisting of waste staple CF (40 and 60 mm) and polyamide 6 staple fibers (60 mm) are manufactured on a DREF-3000 friction spinning machine with various process parameters, such as spinning drum speed, suction air pressure, and core–sheath ratio. The relationship between different textile physical properties of the hybrid yarns, such as tensile strength, elongation, and evenness with different spinning parameters, core–sheath ratio, and input CF length is revealed.

Keywords
carbon fiber, friction spinning, tensile property

Carbon fiber reinforced composites (CFRCs) are widely used for load bearing structures because of their excellent strength, rigidity, and damping properties, as well as low weight. CFRCs are comprised of at least one reinforcement material and a matrix (usually polymeric in volume applications). Depending on the type of matrix, CFRCs can often be divided into two groups, such as thermoset and thermoplastic composites. Although CFRCs are preferentially manufactured based on a thermoset matrix, thermoplastic matrix-based composites have now been developed due to some distinctive advantages over thermoset composites, such as lower density, unlimited storage, semi-products delivered ready for use, thermoformability, a faster processing cycle, no solvent emissions during the processing stage, recyclability, improved shock/ impact behavior, and environment friendliness.[1] A large range of tough thermoplastic matrix materials is also available. As a result, thermoplastic CFRCs are attracting growing interest from both the academic community and industry.[2]

On the other hand, with an increased demand and usage of CFRCs, a high volume of carbon fiber (CF) waste is produced through a number of different processes, for example during the production of fabrics/ pre-forming (cut edges) or rest yarn spool (bobbin waste). The manufacturing waste is approximately 40% of all the CFRP waste generated.[3] A major portion of such waste CF is available in the form of staple fibers ranging from 1 to 30 cm. Furthermore, a number

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of processes (e.g. pyrolysis, solvolysis, etc.) are available currently to obtain recycled CF (rCF) from end-of-life CFRCs.[3] Since waste CF or rCF products are not biodegradable, the disposal of these products assumes even greater significance. Due to European legislation, for example EU2000/53/EC, disposed automotive vehicles must be 85% recyclable.

As the energy required for producing CF is very high (about 39 MJ/kg), which leads to higher CO_2 emissions,[4] the re-use of CFs derived from the sources during manufacturing would reduce the CO_2 emissions to a large extent. Furthermore, the demand for CF is usually higher than the supply-capacity.[5] Therefore, environmental concerns, both in terms of limiting the use of finite resources and the need to manage waste disposal, have led to a focused attention on the need to find effective methods to recycle and re-use waste CF materials.

Against this back drop, extensive research works are being carried out worldwide on the development of hybrid yarns from staple CF by mixing with it thermoplastic fibers. The objective is to apply such hybrid yarns for the manufacturing of textile reinforced thermoplastic CFRCs. So far, the development of hybrid yarns from waste CF is reported using the ring spinning[6–8] and wrap spinning[9,10] processes. Apart from these spinning methods, the DREF-3000 friction spinning process offers added advantages, including the manufacturing of a core and sheath structure with the flexibility to customize the core–sheath ratio and a higher productivity.[11–13] The core component (in staple fiber/endless filament form or in the combination of both) is permanently confined to the central axis and is covered by the staple fibers. The results of investigations on the mechanical properties of friction spun hybrid yarns consisting of CF filament yarn and thermoplastic fibers have been reported.[14–16] However, the potential of DREF-3000 friction spinning for the manufacturing of hybrid yarns from waste staple CF is yet to be explored.

The aim of this study is to investigate the potential of the DREF-3000 friction spinning process for the development of hybrid yarns from waste staple CF for the application in thermoplastic composites. For this purpose, different hybrid yarns consisting of waste staple CF and polyamide 6 (PA 6) are manufactured on a DREF-3000 friction spinning machine with various machine parameters, such as spinning drum speed and suction air pressure. The relationship between different textile physical properties of the hybrid yarns, for example tensile strength and elongation, with different spinning parameters and CF content of hybrid yarn is investigated. The intended application of the hybrid yarns is the development of textile reinforced thermoplastics for automobiles.

Materials

Different hybrid yarns with a core and sheath structure are developed for the investigations. The core of the hybrid yarns consists of two components.

- Component 1: consists of staple CF and PA 6 staple fibers. CFs used for the investigations are obtained by cutting from rest spools (i.e. production rest) of a continuous carbon filament tow SIGRAFIL CT50 - 4.0/240-T140 (SGL) into 40 and 60 mm staple length and can be categorized as bobbin waste. PA 6 fibers from EMS Grilltech of 60 mm length are used for the investigations. These staple CF and PA 6 fibers are used for the development of hybrid slivers, which is then supplied as the core.

  It is to be noted that commercially available rCFs especially recovered from composites usually contain fibers of varying lengths. CF with defined lengths is used in this investigation to understand the drafting behavior during spinning. Furthermore, the measured properties of yarns and composites, which will be available from staple CFs of defined length, can be used as the reference to compare with those from rCFs.
- Component 2: a 30 tex PA 6 filament yarn (Stilon, Poland).

As the sheath of the hybrid yarn, a sliver of 4 ktex consisting of the same PA 6 staple fibers is used. PA 6 is selected due to its good adhesion properties due to available polar groups, and its growing importance in automobile industries.

Experimental details

Characterization of fiber materials

The stress–strain behavior of individual CF and PA 6 fibers is measured with a Vibromat ME (Textechno, Germany) by following the standard DIN EN ISO 5079. The test length is 20 mm. The cross-head speeds of 10 and 20 mm/min are used for the tensile test of CF and PA 6 fibers, respectively. Before measuring the stress–strain behavior, the individual fiber fineness is measured by determining the resonance frequency using the same instrument following the DIN EN ISO 1973 standard. The average value is taken from 50 single fibers tested randomly.

Furthermore, the tensile properties of PA 6 filament yarn used as the core of the hybrid yarn are tested according to ISO 3341 by means of a tensile strength testing device, Zwick type Z 2.5 (Zwick GmbH and Co., Germany), with special return clamps and external strain measuring. Samples of 250 mm yarn length are employed. The test velocity is set to 100 mm/min and the initial load is kept at 0.5 cN/tex.

The melting temperature of PA 6 staple fiber and filament yarn is studied by differential scanning calorimetry (DSC) using a Q1000 DSC instrument (TA Instruments, USA).

Development of hybrid yarns on a DREF-3000 friction spinning machine

For the development of slivers (used as component 1 in the core of the hybrid yarns) consisting of staple CF and PA 6 fibers, both fibers are mixed and carded to form a carded web. Two types of card webs are produced depending on the CF content, such as 50 and 62 volume %. The carding is done by a modified laboratory long staple carding machine at the ITM. Details about the clearance between different rollers and the specification of card clothings have been reported.[6,8]

Afterwards, drafting is carried out on the card webs using a high-performance draw frame, RSB-D40 (Rieter, Ingolstadt, Germany), modified at the ITM for the processing of waste staple CF. The fineness of the produced draw frame slivers is approximately 3 ktex. The length of different draft settings and draft for different fiber lengths that are found optimal for the processing of CF on the draw frame and flyer are detailed in Hengstermann et al.[6,8]

The hybrid yarns are manufactured at the ITM on a DREF-3000 friction spinning machine (Fehrer AG, Linz/Austria) modified for the processing of staple CF (Figure 1). The manufactured draw frame sliver is supplied to the drafting zone as the core of the hybrid yarn (component 1). Component 2 of the core, PA 6 filament yarn, is fed from the bottom of the machine. The main purpose of component 2 is to ensure the smooth production of yarns and increase the strength of the hybrid yarn. The sheath is produced from a PA 6 sliver of 4 ktex by feeding from the back of the machine into the opening rollers.

For the manufacturing of hybrid yarns of 800 tex fineness, the speed of yarn delivery and the opening roller are kept constant at 50 m/min and 4500 rpm, respectively, while the spinning drum speed, air suction pressure and core to sheath ratio are varied as detailed in Table 1.

Characterization of tensile properties of hybrid yarns

Tensile tests of the manufactured hybrid yarns are carried out according to ISO 3341 using a tensile strength testing device, Zwick type Z 2.5 (Zwick GmbH and Co., Germany), with special return clamps and external strain measuring. Samples of 250 mm yarn length are employed. The test velocity is set to 100 mm/min, and the initial load is kept at 0.5 cN/tex. The tensile force versus deformation is recorded, and 10 measurements are taken to get the average value for each type of hybrid yarn. The stress–strain behavior is evaluated using testXpert® software. The instrument is located in a temperature and relative humidity controlled

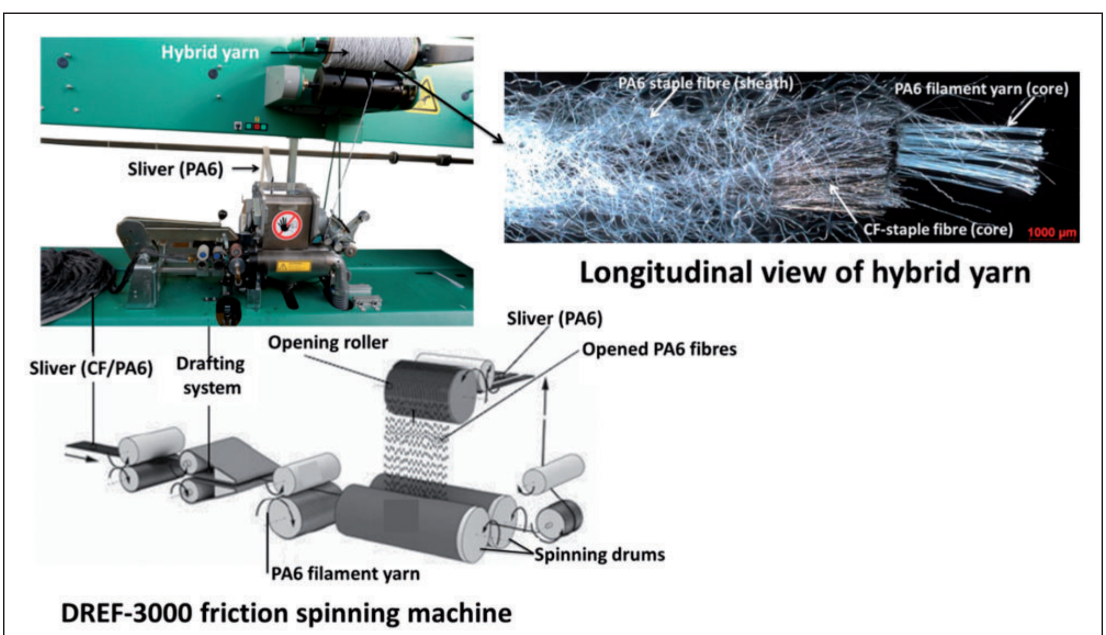

Figure 1. DREF-3000 friction spinning machine with schematic sketch (left)[17] and the developed hybrid yarn consisting of staple carbon fiber (CF) and polyamide 6 (PA 6) fibers (right).

Table 1. Process variables of the developed hybrid yarns

Input CF length (mm)	CF content of card web (volume %)	Air suction pressure (mbar)	Spinning drum speed (rpm)	Core to sheath weight ratio	CF content of hybrid yarn (volume %)	Yarn specification
40	50	–36	3000	50:50	19.1	FS#01
				70:30	28.3	FS#02
				80:20	33.4	FS#03
	62	–13	1500	80:20	41.7	FS#04
			3000			FS#05
60	62	–13	1500			FS#06
			3000			FS#07
		–36	1500			FS#08
			3000			FS#09

CF: carbon fiber.

Table 2. Properties of waste staple carbon fiber (CF) and polyamide 6 (PA 6) fibers

	Single fiber properties		Yarn properties
Characteristics	Waste staple CF	PA 6 Staple fiber	PA 6 filament yarn
Single fiber diameter (μm)	7.0 ± 2.5	18.8 ± 6.9	26.4 ± 3.0
Tensile strength (GPa)	3.9 ± 0.9	0.5 ± 0.1	0.4 ± 0.0
Modulus (GPa)	240.0 ± 85.3	1.48 ± 0.2	1.7 ± 0.0
Elongation at break (%)	1.9 ± 0.2	73.9 ± 13.4	49.2 ± 2.1
Melt temperature (°C)	–	223.8	222.6

laboratory maintained at 20 ± 2°C and 65 ± 2%, respectively. Also, prior to the tensile testing of hybrid yarns, they are conditioned for 24 hours under these conditions.

Characterization of evenness of hybrid yarns

In order to characterize the hybrid yarn evenness, the linear density of the hybrid yarns is determined based on the gravimetric method. For this purpose, the weight of the hybrid yarn of 1 m length is measured. Ten specimens are measured for each hybrid yarn variation. From the average and standard deviation of the measured values, the coefficient of variation of 1 m (CV1m) is measured according to equation (1). The lower the CV1m value is, the higher is the yarn evenness

$$CV1m = \frac{\text{Standard deviation} \cdot 100}{\text{Mean}} \quad (1)$$

Results and discussion

Properties of input materials

The results of the tensile properties of waste staple CF (single fiber) and PA 6 staple fibers (single fiber), as well as PA 6 filament yarn, are detailed in Table 2. The corresponding force–elongation properties can be seen in Figure 2. From the DSC analysis, it can be found that the melting temperature is also similar, as detailed in Table 2.

Influence of the core–sheath ratio

In Figure 3, the strength and elongation at break of hybrid yarns are illustrated in the case of hybrid yarns produced from card webs with 50 volume % CF by varying the core to sheath weight ratio in hybrid yarn (Figure 4). This reveals that the hybrid yarn strength is influenced significantly by increasing the core ratio in hybrid yarn, and it decreases with the increase of core content from 50% to 80%.

Usually the core of the friction spun hybrid yarn mainly contributes to the strength of hybrid yarn as the fibers in the core are oriented parallel in an untwisted form along the yarn axis, while the fibers of the sheath are oriented radially to the yarn axis. Therefore, it is evident in the case of conventional fibers, for example cotton, polyester, etc., that yarn strength increases to a certain level with the increase of the core–sheath ratio, and it reduces subsequently.

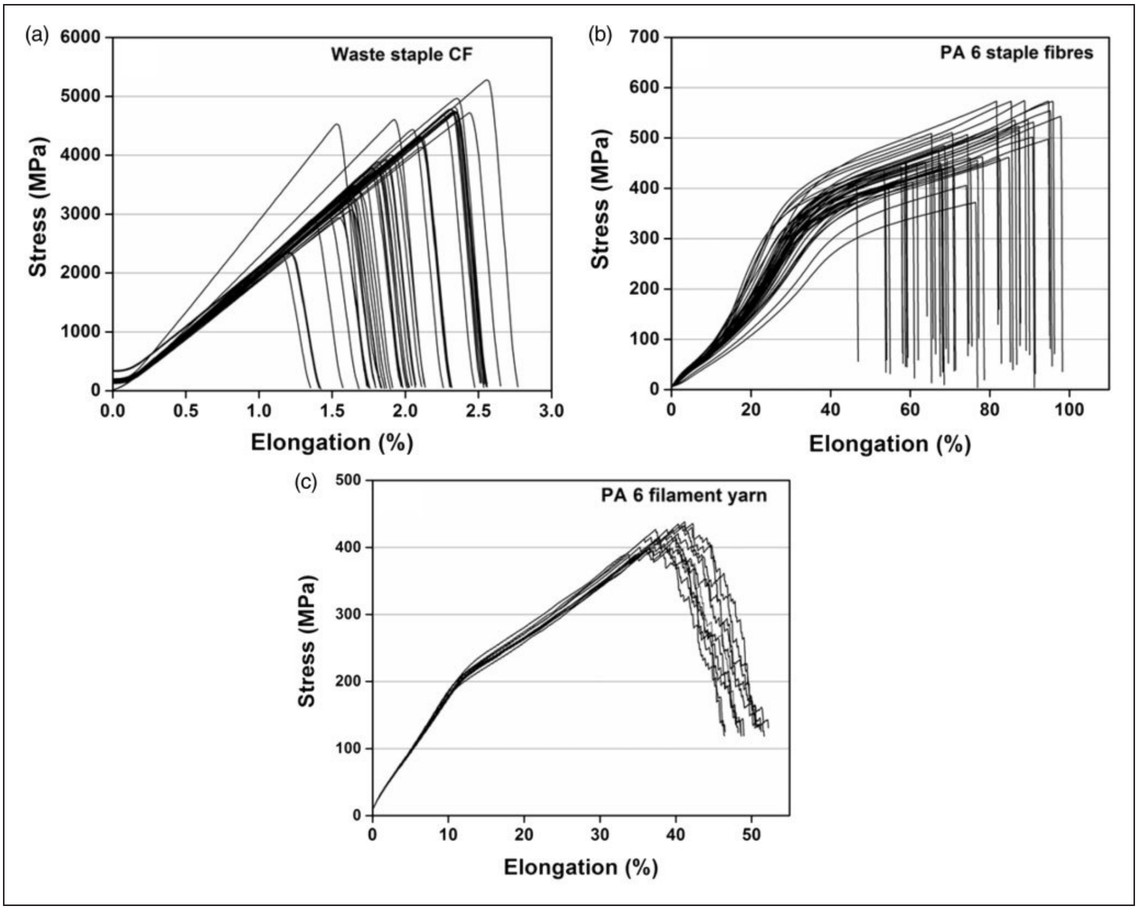

Figure 2. Stress–elongation curves of (a) carbon fiber (CF) (single fiber), (b) polyamide 6 (PA 6) staple fiber (single fiber), and (c) PA 6 filament yarn.

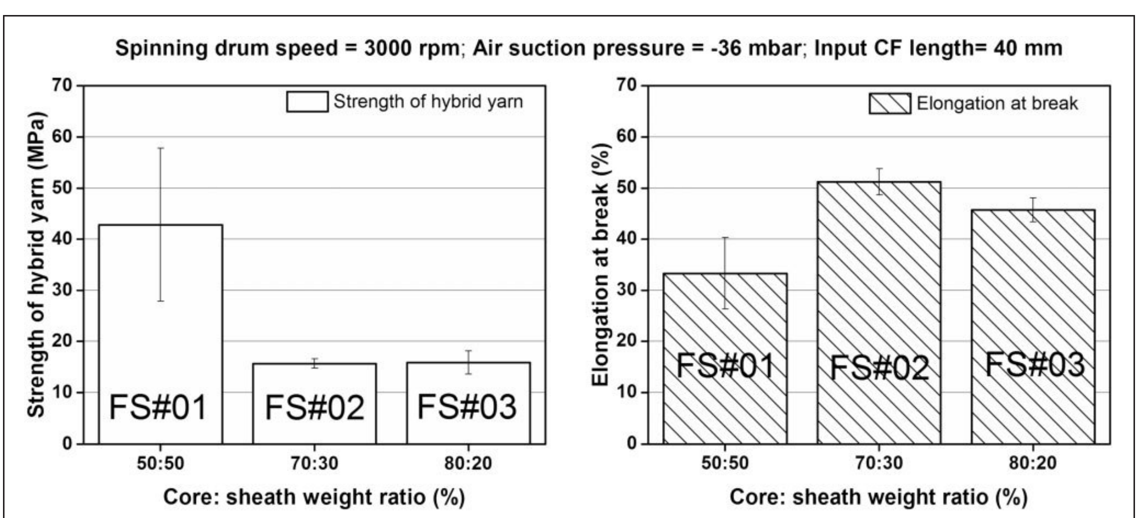

Figure 3. Strength and elongation at break of hybrid yarns depending on the core–sheath weight ratio of hybrid yarn produced from 40 mm carbon fiber (CF).

It appears that the core contributes directly to the yarn strength in the presence of sufficient wrapper fibers to maintain the yarn integrity. Exceeding the optimum core ratio probably provides too few wrapper fibers to prevent core slippage, reducing yarn strength thereafter.[18,19] The optimum core–sheath ratio is reported between 50% and 70%.

The highest strength is found in our case with hybrid yarns produced with 50% core. However, the standard deviation of the yarn strength is also found to be comparatively higher in the case of 50% core. The reason for this is that the probability for irregularity increases with the increase of sheath portion.[19] The results of the measurement of CV1m revealed the same tendency (cf. Figure 5). A tendency of higher CV1m value can be observed with the increase of sheath ratio of hybrid yarns. Since the total CF content in hybrid yarn is a decisive factor for its use in composites, hybrid yarns with lower core content are not further investigated.

The elongation at break of hybrid yarns increases with the increase of the core to sheath weight ratio of 70:30%, then it decreases gradually. The reason for lower yarn strength and higher elongation with higher amounts of CF in hybrid yarn can be attributed to lower fiber to fiber cohesion because of the smooth surface of CF. The stress–elongation curves of hybrid yarns with varying core to sheath weight ratios are illustrated in Figure 6.

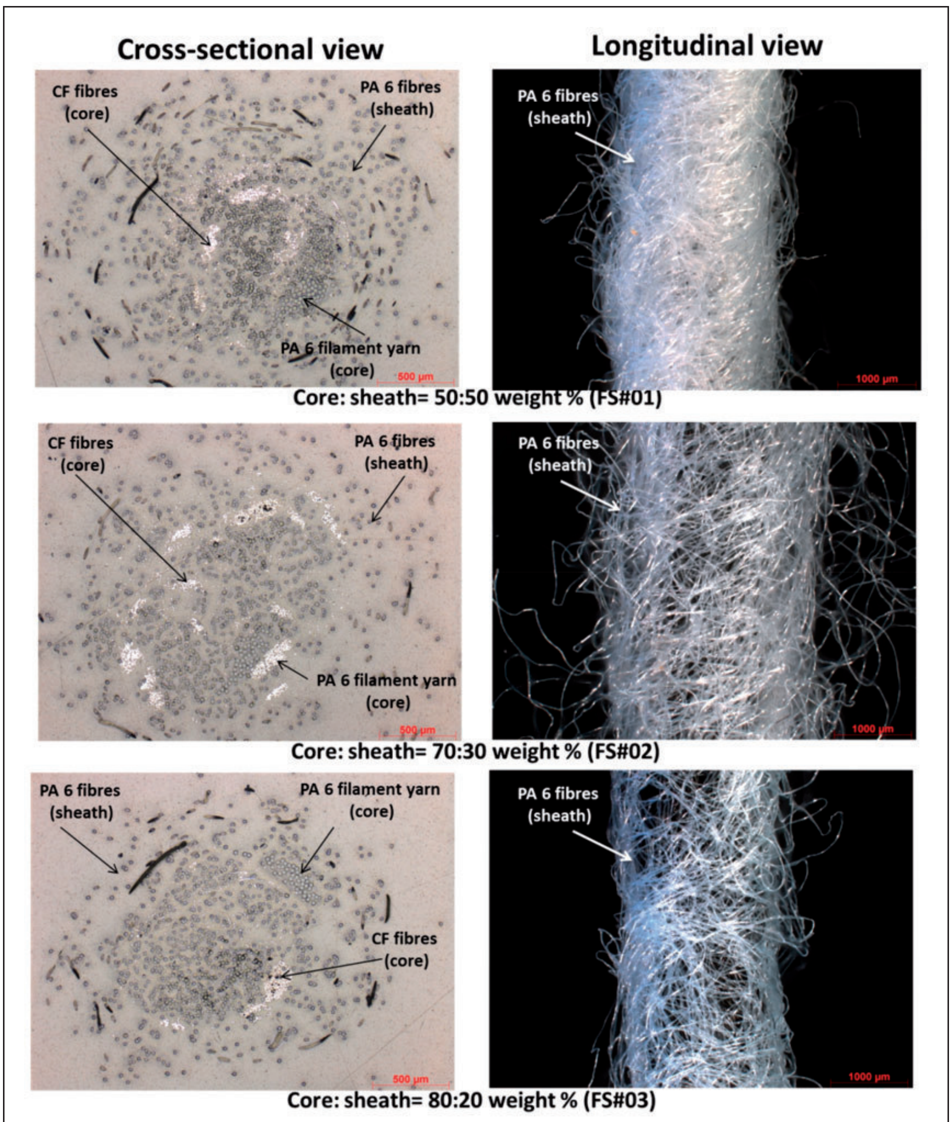

Figure 4. Cross-sectional and longitudinal view of hybrid yarns with different core–sheath weight ratios. CF: carbon fiber; PA 6: polyamide 6.

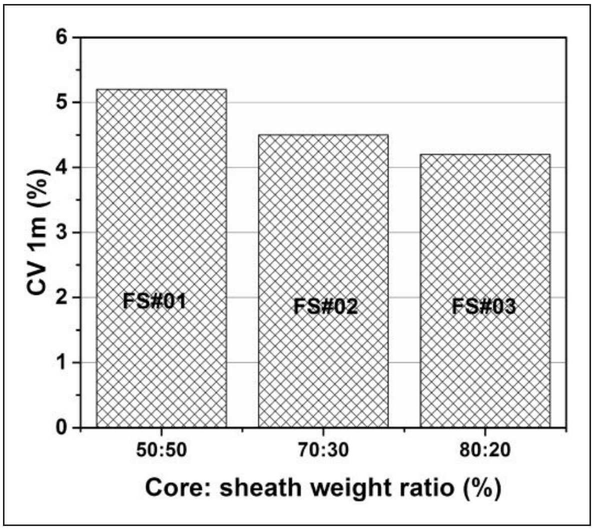

Figure 5. Influence of core–sheath ratio on the evenness of hybrid yarns.

Influence of spinning drum speed and air suction pressure

In Figure 7, the influence of the spinning drum speed and air suction pressure on the strength and elongation of hybrid yarns produced from card webs with 62 volume % CF content and a core to sheath weight ratio of 80:20 in hybrid yarn are illustrated. These hybrid yarns are produced with 60 mm waste staple CF. It is shown (Figure 7(a)) that hybrid yarn strength decreases with the increase of spinning drum speed as well as air suction pressure.

There are two reasons for the decrease in yarn strength.

- Firstly, a higher spinning drum speed and air suction pressure lead to increased frictional forces between the fiber assembly (sleeve) and the friction drum surfaces, thereby increasing the torque acting on the

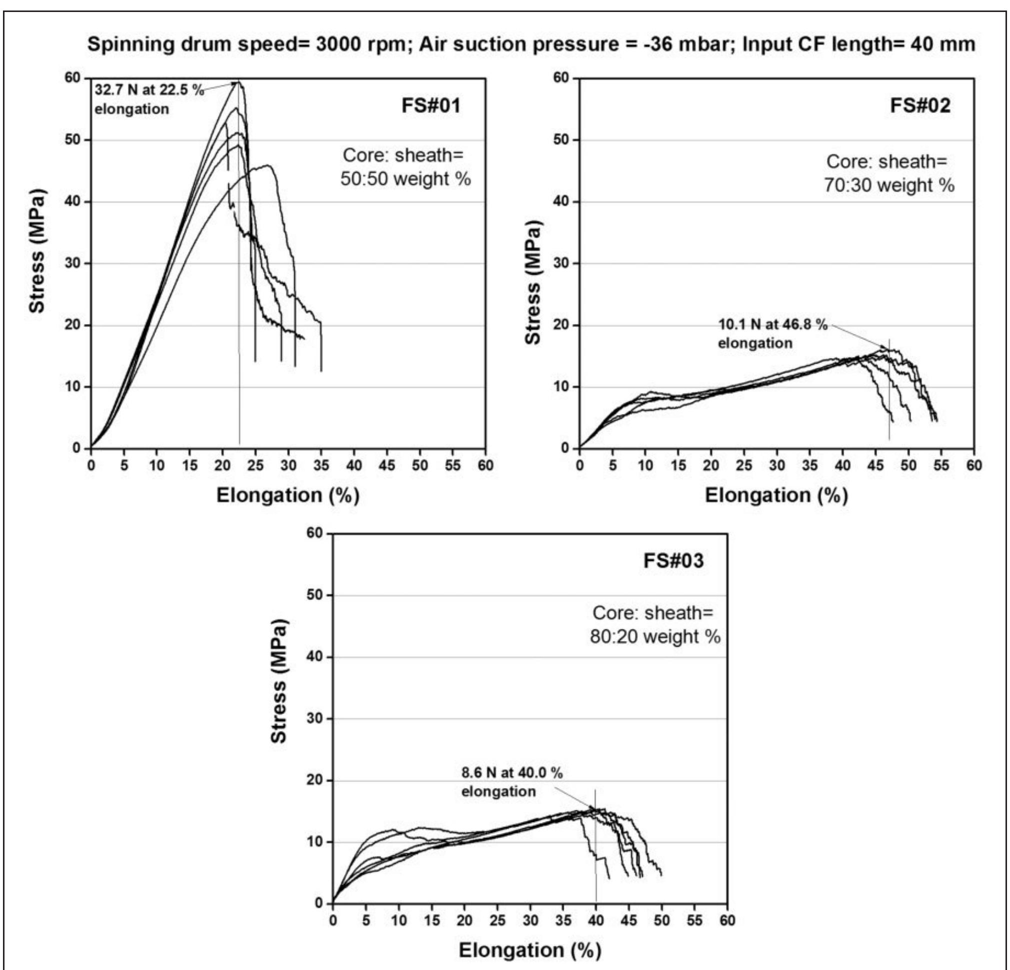

Figure 6. Stress–elongation curves of hybrid yarns depending on different core to sheath weight ratios.

fiber sleeve. As a consequence, the rotational speed of the fiber sleeve increases, which results in a higher yarn twist.[20,21] Since the chance of damaging the brittle CF in the core is higher due to higher twist insertion, the hybrid yarn strength decreases considerably with the increase of air suction pressure. A similar tendency can observed in the case of CF filament yarn in the core of DREF friction spun hybrid yarns.[14] Furthermore, the CF fibers in the core of hybrid yarns become disoriented from the yarn axis due to higher twist, which may contribute to the reduced yarn strength. This phenomenon is completely different from yarns that consist of conventional crimped fibers, for example cotton, where the yarn strength increases predominantly due to the increase in cohesion as a result of higher twist with increased spinning drum speed and air suction pressure.

- Secondly, due to the higher spinning drum speed, hooked wrapper fibers in the yarn may increase. As a result, wrapper fibers may not wind around

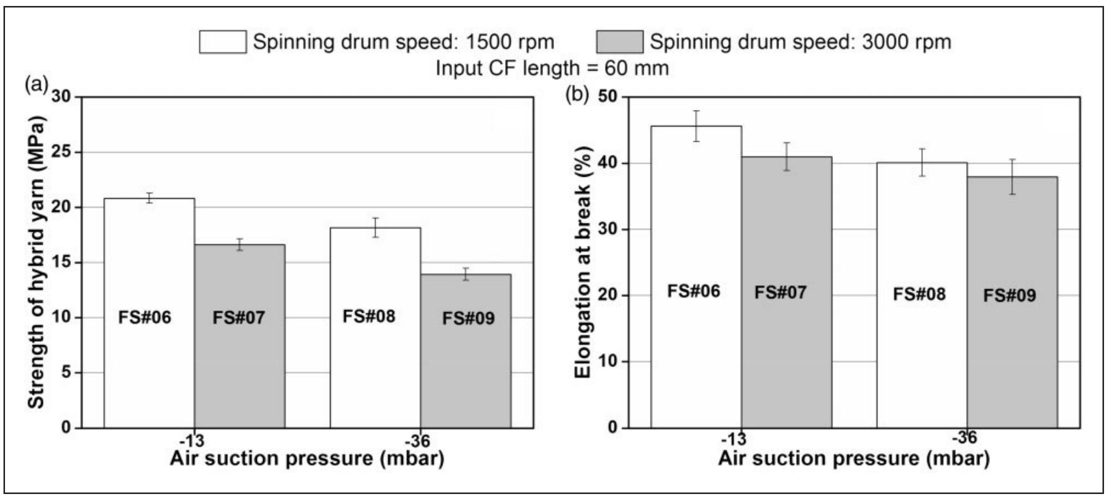

Figure 7. Influence of spinning drum speed and air suction pressure on the strength (a) and elongation (b) of hybrid yarns produced with a core to sheath weight % of 80:20 from 60 mm carbon fiber (CF).

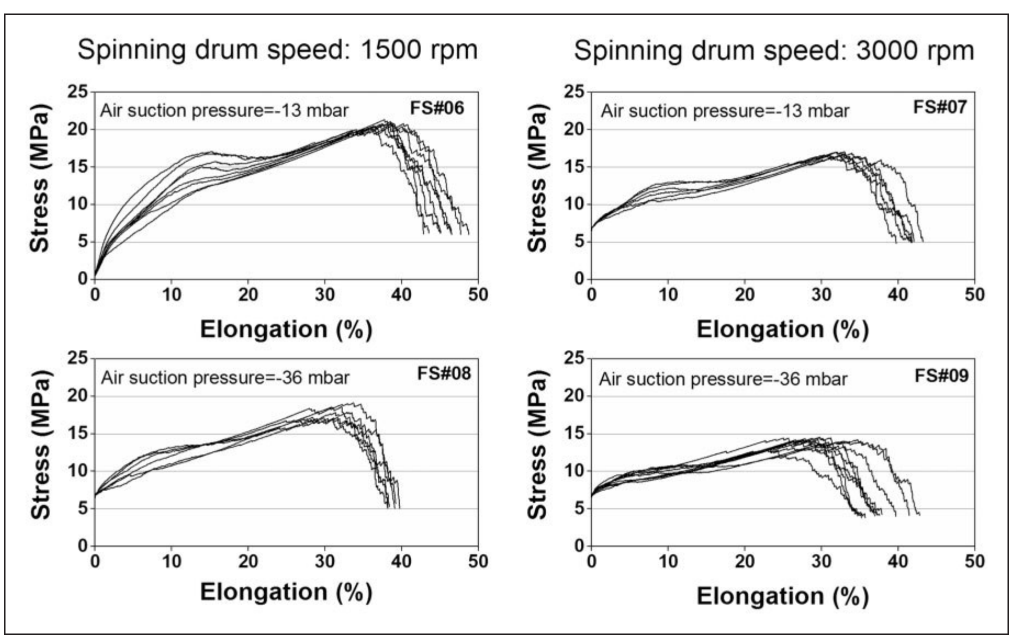

Figure 8. Force–elongation curves of hybrid yarns produced by varying spinning drum speed and air suction pressure (input carbon fiber length = 60 mm).

the core, and will not efficiently contribute to the strength due to the decreased length.[21]

From the results of hybrid yarn elongation at break presented in Figure 7(b), it can be seen that the elongation decreases with the increase of air suction pressure and spinning drum speed. At lower air suction pressure and spinning drum speed, the hybrid yarns are relatively less compact, and consequently the cohesion between fibers is lower. As a result, the hybrid yarn elongation at break is higher at low air suction pressure and spinning drum speed. The stress–elongation curves of hybrid yarns produced with varying spinning drum speed and air suction pressure are illustrated in Figure 8. From the stress–elongation curves, it can be seen that the hybrid yarns produced with higher air suction pressure and higher spinning drum speed have longer tails, that is, higher extension, compared to those produced with lower air suction pressure. Thus, due to lower fiber to fiber cohesion, the fiber slippage in the hybrid yarn during extension occurs more often at lower air suction pressure and spinning drum speed. The analysis of variance of the elongation values statistically proved that at the 95% confidence level, the mean elongation at break of hybrid yarns between FS#06 and FS#08 as well as FS#07 and FS#09 is significantly different. Hence, the influence of spinning drum speed and air suction pressure on the elongation of hybrid yarns is significant.

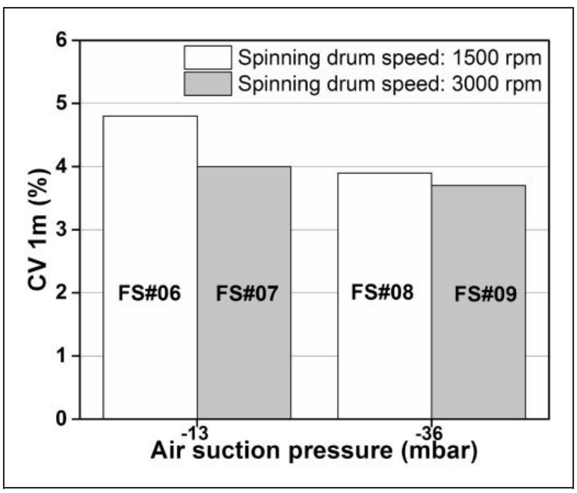

Figure 9. Effect of air suction pressure and spinning drum speed on the evenness of hybrid yarns.

The effect of spinning drum speed and air suction pressure on the evenness of hybrid yarns is illustrated in Figure 9. It shows that the CV1m value decreases with the increase in air suction pressure at a constant spinning drum speed. With the increased yarn compactness due to higher air suction pressure, the yarn evenness increases. However, the difference is lower at higher air suction pressures. The effect seems to stabilize at an air suction pressure of –36 mbar.

Influence of the input CF length in the core

In Figure 10, the hybrid yarn strength and elongation at break are illustrated in the case of hybrid yarns produced from 40 and 60 mm input CF length, where the CF content of card webs is 62 volume % and the core to sheath weight ratio in hybrid yarn is 80:20 weight %. These hybrid yarns are manufactured with varying

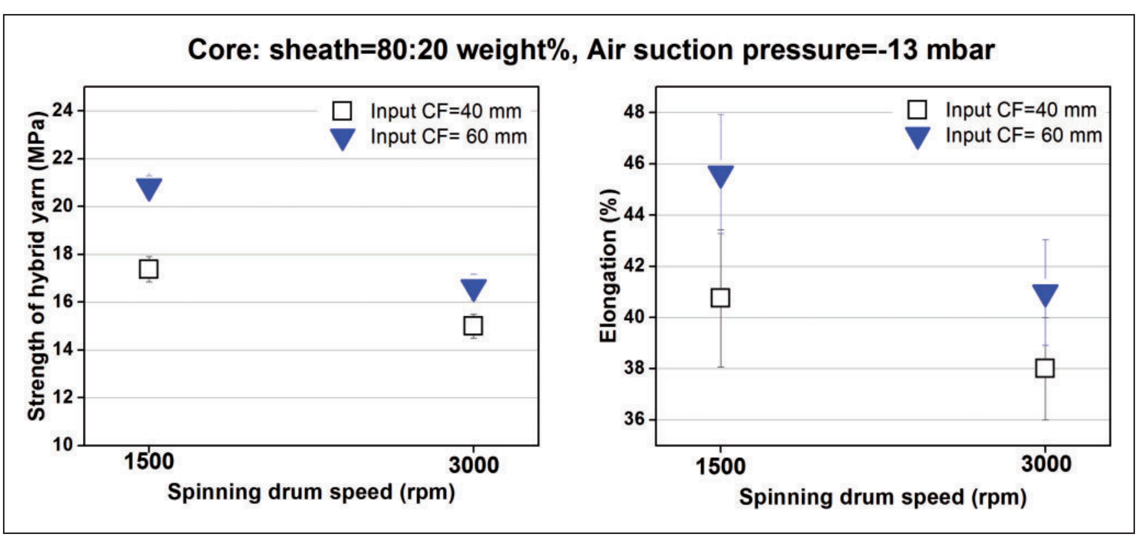

Figure 10. Influence of input carbon fiber (CF) length on the strength and elongation of hybrid yarns produced with varying spinning drum speeds at constant air suction pressure of –13 mbar.

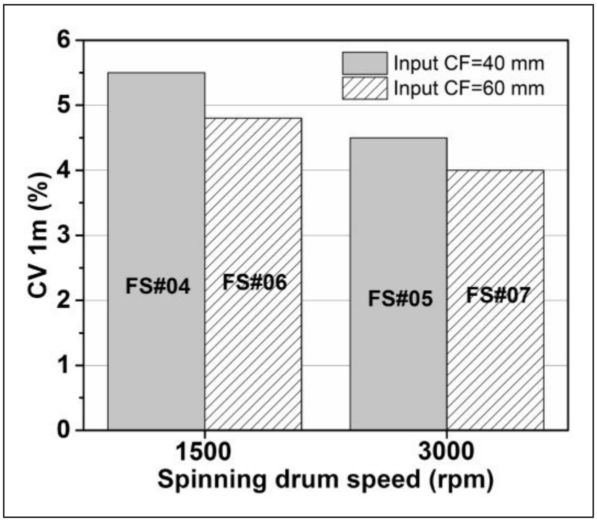

Figure 11. Effect of input carbon fiber (CF) length on yarn evenness with varying spinning drum speeds.

spinning drum speeds (1500 and 3000 rpm) at a constant air suction pressure of –36 mbar.

From Figure 10, it can be seen that strength and elongation of hybrid yarns are clearly higher in the case of 60 mm input CF length compared to 40 mm input CF length. This can be attributed to the higher fiber to fiber friction because of increased fiber length. Furthermore, the strength and elongation of the hybrid yarn is found to decrease with the increase of spinning drum speed for both input CF lengths, as already discussed in the previous section.

The effect of input CF length with varying spinning drum speeds on the evenness of hybrid yarns is illustrated in Figure 11. It shows that the evenness of hybrid yarns is improved in the case of 60 mm input CF compared to that of 40 mm CF in both spinning drum speeds. The reason may be the length (=60 mm) of PA 6 fibers used for the production of hybrid yarns. The same length of CF and PA 6 fibers results in better spinning quality.

Conclusion

The results of the investigations prove that it is possible to manufacture hybrid yarns successfully using the DREF-3000 friction spinning machine from waste staple CF and PA 6 fibers in reproducible quality. It can be revealed that the air suction pressure, spinning drum speed, core to sheath ratio, and input CF length affect the yarn strength, elongation at break, and yarn evenness considerably.

The core–sheath ratio is an important factor influencing the core coverage by surface fibers as well as yarn strength, and elongation. The highest strength is found in the case of hybrid yarns produced with 50% core. With the increase in the core, the tensile strength of hybrid yarn decreases, and elongation at break increases. The reason is lower fiber to fiber cohesion because of the smooth surface of CF resulting from the higher amount of CF in hybrid yarn.

The yarn strength decreases with the increase of air suction pressure and spinning drum speed. This can be attributed to the damage in CF caused by higher air suction pressure and higher spinning drum speed. Furthermore, the elongation at break of hybrid yarns tends to decrease with increasing air suction pressure and spinning drum speed. Because of lower fiber to fiber cohesion as a result of the less compact hybrid yarn structure, the fiber slippage in the hybrid yarn during extension occurs more often at lower air suction pressure and spinning drum speed. However, the evenness of hybrid yarns becomes better with increased spinning drum speed and air suction pressure. Therefore, a compromise must be made between hybrid yarn strength and evenness in selecting the optimum air suction pressure or spinning drum speed. In fact, both the strength and evenness of hybrid yarns are important for their further processing on different textile machines, for example for weaving, knitting, etc. Therefore, further investigations are still necessary in this regard.

Because of the higher production speed of the DREF-3000 friction spinning machine (maximum 250 m/min) compared to that of flyer (maximum 50 m/min) and wrap spinning (maximum 30 m/min), the DREF-3000 friction spinning machine can be used for the economic production of hybrid yarns from rCF. Lastly, it can be concluded that the results of this study enable a better understanding of the different factors affecting the tensile properties and evenness of hybrid yarns made of waste staple CF of defined length and PA 6 staple fibers. This will help optimize the spinning parameters in the case of processing of rCF with a wide range of fiber length distribution. However, further investigations are required for a more comprehensive understanding regarding the influences of hybrid yarn properties consisting of waste/ rCF on the properties of thermoplastic composites. Based on the obtained mechanical properties of composites, the relationship between different spinning parameters and yarn properties can be further optimized.

Declaration of conflicting interests

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