Development and Characterization of GF/PET, GF/Nylon, and GF/PP Commingled Yarns for Thermoplastic Composites

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ABSTRACT: Commingling is becoming an important method for developing thermoplastic composites, which demonstrate significant advantages over thermoset composites in several applications including aerospace, marine, sporting, and automotive industries. Although the commingling technique has a very high potential to produce towpregs with a good blending of matrix and reinforcing fibers, it has been reported that these towpregs tend to de-mingle due to nonuniform stretching during textile and other preforming processes, leading to the segregation of stiffer reinforcing fibers and matrix-forming fibers, which in turn results in poor mechanical properties. Therefore, the current research focuses on the enhancement of stability and homogeneity of commingled yarns during subsequent processing. An attempt has been made to study the effect of the commingling process variables, namely air pressure and volume fraction of matrix-forming fibers on the structure and properties of Glass/Polypropylene, Glass/Polyester, and Glass/Nylon commingled yarns. In this paper, nips are classified into different categories based on their structure. The causes of occurrence and their effect on the commingled yarn properties are identified. Other parameters including nip frequency, nip length, and degree of interlacing are also studied in relation to the process parameters. The results show that commingling process parameters as well as the type of matrix-forming fibers significantly affect the structure and properties of commingled yarns.

KEY WORDS: commingling, nozzle, thermoplastic composites, nips, air pressure.

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INTRODUCTION

THERMOPLASTIC COMPOSITES OFFER new opportunities for fast and efficient processing technology. However, along with their advantages, thermoplastic composites have also introduced new problems into processing. One of the problems encountered is the high viscosity of the thermoplastics caused by the long molecules. Because of this and the fiber interlacement, it is very difficult to inject the resin into a tightly woven textile structure and fill the pores present. This increases the void content in the composite. In order to decrease this, it is necessary to use high levels of injection pressure and heavier molds. To solve this problem, the matrix polymer needs to be mixed with high-performance fibers even before the preforming operation.

There are several techniques like hot melt, film, solution, emulsion, slurry, surface polymerization, commingling, and dry powder coating. Of these methods, powder coating and commingling have the potential for producing towpregs with considerable flexibility, which is a critical requirement for textile processing [1,2]. Studies on commingled composites with different reinforcing fibers and matrix material combinations have been reported in the literature [3,4]. Moreover, de-mingling of the commingled prepregs under tension has also been reported. This leads to improper mixing of fibers and resin in the composite [5,6].

Ye et al. [5] explained the mechanism of the separation of reinforcing fibers and polymer fibers during preforming due to the mismatch of stiffness of reinforcing and matrix filaments. Long et al. [6] also observed a similar phenomenon and explained that higher compressive and tensile forces during weaving would act on the fibers at the top and the bottom of the tow. This would cause the stiffer reinforcing fibers to migrate away from these areas and thus leave the matrix-forming fibers behind. This would result in the nonuniform distribution of fibers in the final composite part and lead to insufficient impregnation, which would affect the microstructure of composites. They also ascertained that the degree of commingling has a significant effect on the microstructure of GF/PP commingled yarn composites.

During the mingling process, the air stream impacts the yarn orthogonally, leading to the formation of an open segment at the position where the air jet is subjected to act and a compact section called nip will form on either sides of the open segment [7,8]. The structure of the nips in a mingled yarn is complex and plays an important role in the stability, since during subsequent textile processing, some of the nips may disappear when tension is applied.

The structure of nips in an intermingled yarn is of prime importance because the variations in the mingled yarn properties are mainly due to variations in the yarn structure. The structure and properties of intermingled yarns depend upon the type of the supply yarn material, the mingling process parameters, and the jet design [9–11]. The nip structure also depends upon the condition of filament separation prior to mingling. Several attempts have been made to study the effect of these parameters on mingled yarns from various fiber-forming polymers. Various researchers characterized the degree of interlacing in mingled yarns by the nip frequency regardless of the nip structure [12,13]. However, Miao and Soong [14] have categorized nips in nylon multifilament intermingled yarns, on the basis of their structure, into four classes namely, twist, braid, wrap, and entanglement and their results show that the differences in yarn properties are mainly due to a variation in the nip structure.

The stability of commingled yarns is one of the important parameters for the manufacture of preforms for thermoplastic composites because a nonuniform fiber arrangement across the cross section would deteriorate the quality of both commingled yarns and composites. Although high levels of composite properties are attained with this technique, there has been no work reported on the structure of commingled yarns. Hence, there is an obvious requirement for a detailed study on the structure of commingled yarns containing glass filaments, which have a high modulus and strength with low modulus matrix-forming filaments like polypropylene, nylon, and polyester. In the present work, an attempt has been made to study the effect of process variables namely air pressure and glass fiber volume fraction on the structure of GF/PP, GF/Nylon, and GF/PET commingled yarns. A cyclic load testing of nips have been conducted to study the stability of nips.

EXPERIMENTAL

Preparation of Samples

A laboratory model commingling equipment has been developed for the present study. Figure 1 shows the schematic of the commingling equipment. Reinforcing fibers and matrix-forming multifilament yarns from separate packages are combined and fed into a pair of feed rollers. After passing the yarn through supporting guides and an air nozzle, the commingled yarn is wound onto a package. A wide range of feed ratios, take up speeds, and air pressures could be selected to produce commingled yarns under different processing conditions. The ratio of glass and other matrix-forming filaments in commingled yarn is adjusted to get different volume fractions. Table 1 shows the properties of reinforcing and matrix-forming filaments used in the present study. Nine commingled yarn samples from GF/PET, GF/Nylon, and GF/PP with V_m 60% are developed at the following air pressures: 6, 7,

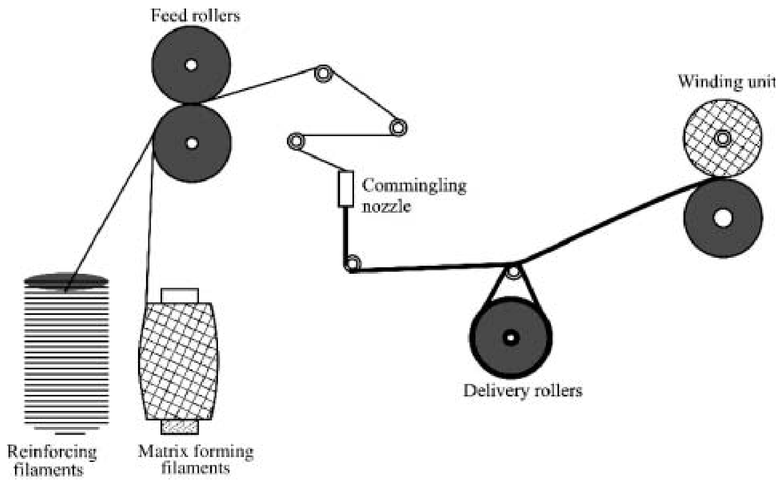


Figure 1. *Machine setup for commingling.*

Table 1. Properties of reinforcing and matrix-forming filaments.

Fiber properties	Glass roving	Polypropylene	Polyester	Nylon
Yarn fineness (tex)	600	94	140	176
Number of filaments	930	98	157	226
Denier/filament	5.8	8	8.6	7
Bulk density (g/cm^3)	2.54	0.9	1.38	1.14
Filament diameter (μ)	17	35	27	28
Diameter ratio (with glass)	1	2.05	1.58	1.64
Fiber friction (μ)				
Yarn to yarn	–	0.14	0.11	0.11
Yarn to metal	–	0.46	0.39	0.29

and 8 bar. Eleven commingled yarn samples with different volume fractions of matrix-forming filament yarns (V_m) are developed at an air pressure of 7 bar. A yarn throughput speed of 20 m/min is selected. All other process parameters are kept constant.

Commingling Nozzle Design

In the commingling process, a continuous yarn running under defined tension through an air jet can be interlaced if a perpendicular or nearly perpendicular high-pressure air stream is applied to the yarn. The air stream creates a turbulence, opens up the filaments, and the individual filaments get intertwined and mingled with each other to form compact sections called nips. The opened segments and nips alternately follow each other.

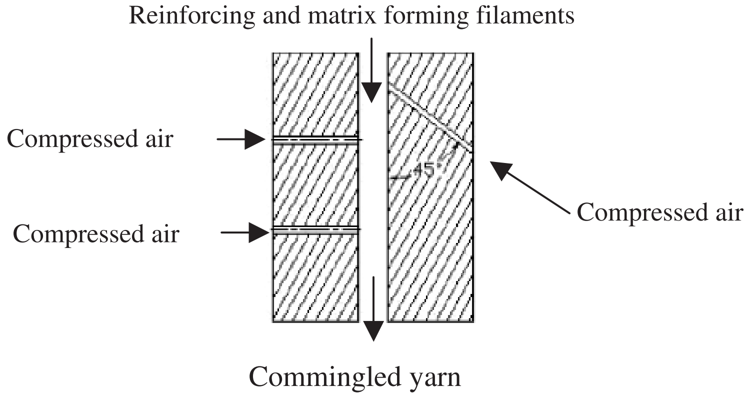


Figure 2. *Configuraton of commingling jet used.*

In air jet texturing, turbulent and asymmetric fluid forces in association with intermittent compression shock waves open up the filaments and cause longitudinal displacements of the filaments relative to each other. The texturing process gives yarns with compact core and surface loops occurring frequently at irregular intervals along its length.

However, the objective of the commingling process is the thorough blending of matrix-forming filaments and high-performance fibers by means of compressed air. Texturing jets, which have greater forwarding capacity, provide less commingling action. Therefore, it is very difficult to develop a compact commingled yarn with homogenous distribution of matrix and reinforcing fibers with forwarding jets. Neither the intermingling nozzle nor the texturing nozzle alone would provide a satisfactory commingling effect. Therefore, in the present study, an attempt has been made to develop a backward commingling jet to create mixed air vertices to facilitate the transportation of filaments for intermingling. The principle of commingling is shown in Figure 2.

Jet Design: Air Flow and Commingling

As shown in Figure 1, the yarn path in the air nozzle is provided in such a way that the required preopening of glass filaments would occur well before the yarn entry point into the air nozzle. When the preopened glass filaments and matrix-forming filaments move further, the bundles of these filaments come under the influence of the high-speed turbulent airflow and filaments vibrate rapidly between the upper and lower air vortices. Besides raw material properties, the frequency of yarn rotations inside the jet depends upon the air vortex in which the yarn is entrained. The division of vortices into two branches is mainly governed by the angle of inlet hole with respect to the yarn channel. The air entry at an oblique angle gives a nonuniform division of vortices and the perpendicular air inlet gives a uniform distribution of air vortices. The oblique air entry is responsible for the transportation of filaments, whereas the right angle air entry ensures the intermingling of transported filaments. The filament bundles are separated into small bunches to form a balloon. The small bundles of the matrix-forming filaments shift their positions and pass through the opened bunches of glass filaments. In this manner, the matrix filaments get trapped inside the opened bundles of glass filaments.

Nip Structure

The two-phase nip formation theory has been described by various authors [7,8,13]. First, the filaments are opened by the incoming jets and the airflow from different levels and directions within the yarn channel take the filaments in quick movements similar to braiding or plaiting or false twisting, leading to the formation of nips on either sides of the jets. A Leica MZ-6 optical microscope has been used to obtain the longitudinal images depicting the structure of the commingled rovings with a magnification of 6.3. A Leica DNLP optical microscope has been used to obtain a cross section of the commingled rovings with a magnification of 50.

The opened segment is produced at the position subjected to the strong action of an air jet, whereas the nips are formed on its either sides as shown in Figure 3. In this figure, colored PP is used for easy identification of the filaments. In opened sections, reinforcing and matrix-forming filaments are randomly dispersed. The opened sections are bulkier than the nips. The nips

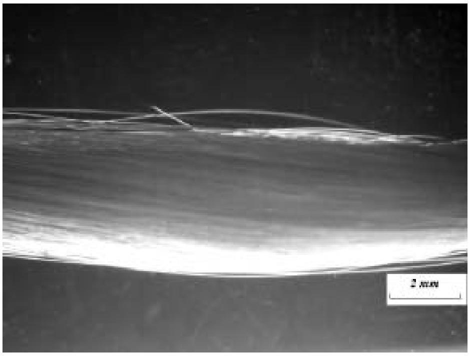


Figure 3. *Opened sections in GF-PP commingled yarn. (Light fibers: Glass, Dark fibers: PP) (Air pressure: 7 bar, Glass-Colored PP,* V_m *47%).*

in commingled yarns are compact sections, which would act as the binding points between open portions. The design of the air nozzle controls the cyclic production of nips and opening parts. Both the sections are equally important for subsequent processing of commingled yarns. The nip frequency of commingled yarns is the function of the speed of rotation of the vortex. The frequency of air vortex generated mainly depends on the air pressure and the jet design. If one of the vortices is predominant, the yarn will be retained in that vortex only and it may be twisted in one direction without any commingling effect.

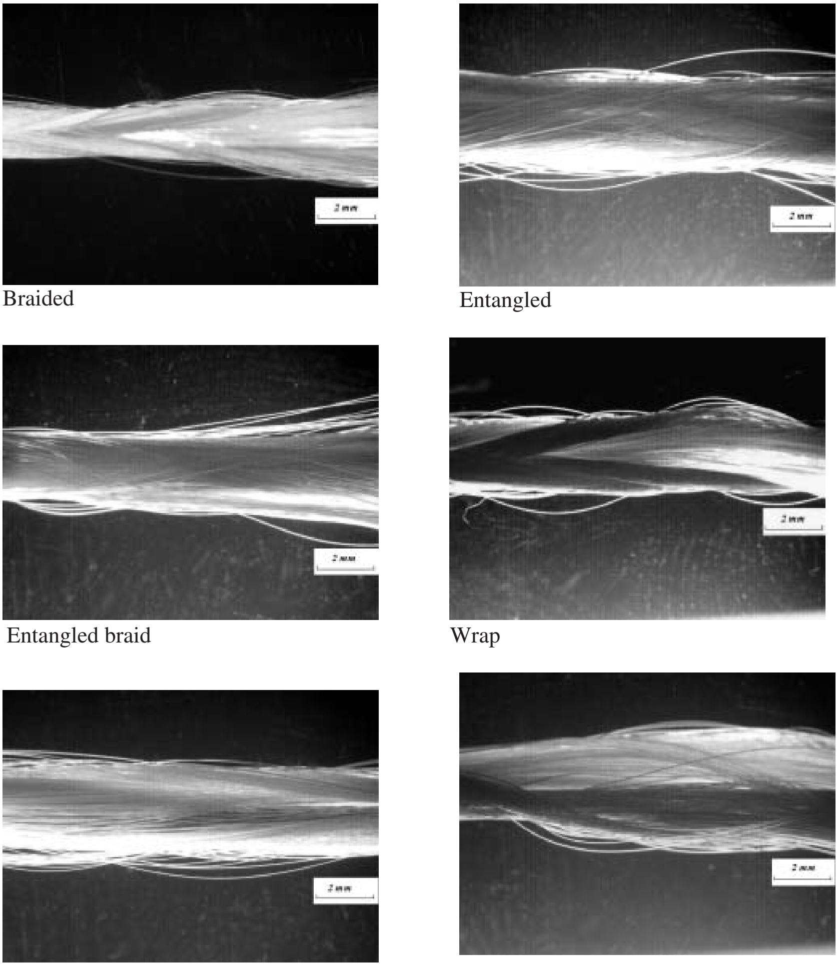
The cross sections of different types of nips are obtained by photomicrography technique. From microscopic observations, nips found in commingled yarns can be classified as braids, entanglements, entangled braids, wraps, and others (consisting of core, braided core, and side-by-side), which are shown in Figure 4. Figure 5 shows the cross-sectional view of different nip structures.

The occurrence of a particular type of nip in a jet depends on the condition of filaments when they are acted upon by the jet. Braided nips are composed of intertwined filament bundles of glass and matrix-forming fibers. It has been observed that glass filaments split into three or more groups and braid with matrix-forming filaments. Entanglement nips are formed due to the initial opening of matrix-forming fibers and glass fibers; initial opening of filaments would disorganize the filament spatial positions. A further action of the air jet would enhance the possibility of random intermingling of the small groups of opened bundles of glass and matrix-forming filaments together. Entangled braid type of nips are similar to braided nips; however, a sudden change in the direction of the strong jets acting on the filaments in small and disorganized bundles of matrix-forming filaments and glass filaments which are already built into partial braids leads to the entanglement of these filaments with each other. Wrap nips in commingled yarns are formed due to the improper opening of glass filaments and therefore, matrix-forming filaments just wrap around unopened bundles of glass filaments. This type of nip occurs when the nip formation happens at a location in the nozzle, where the air forces are weak. The other types of nips such as core and side-by-side are formed due to the insufficient opening of matrix-forming filaments.

TEST PLAN

Nip Frequency and Nip Structure

Ten specimens of 1 m length are selected from different parts of the package, for each commingled yarn sample. The nip frequency and



Braided

Entangled

Entangled braid

Wrap

Other (core)

Other (side-by-side)

Figure 4. *Different types of nips in commingled yarns. (Light fibers: Glass, Dark fibers: PP) (Air pressure: 7 bar, Glass-Colored PP,* V_m *47%).*

classification of nips are obtained by the microscopic examination of the commingled yarns. The nips have been classified into five different groups according to their structure, namely, braid, entanglement, combination of braid and entanglement, wrap, and others (consisting of core and side-by-side). As the nip frequency alone does not describe the extent of nips in commingled yarns, other parameters like the degree of interlacing and

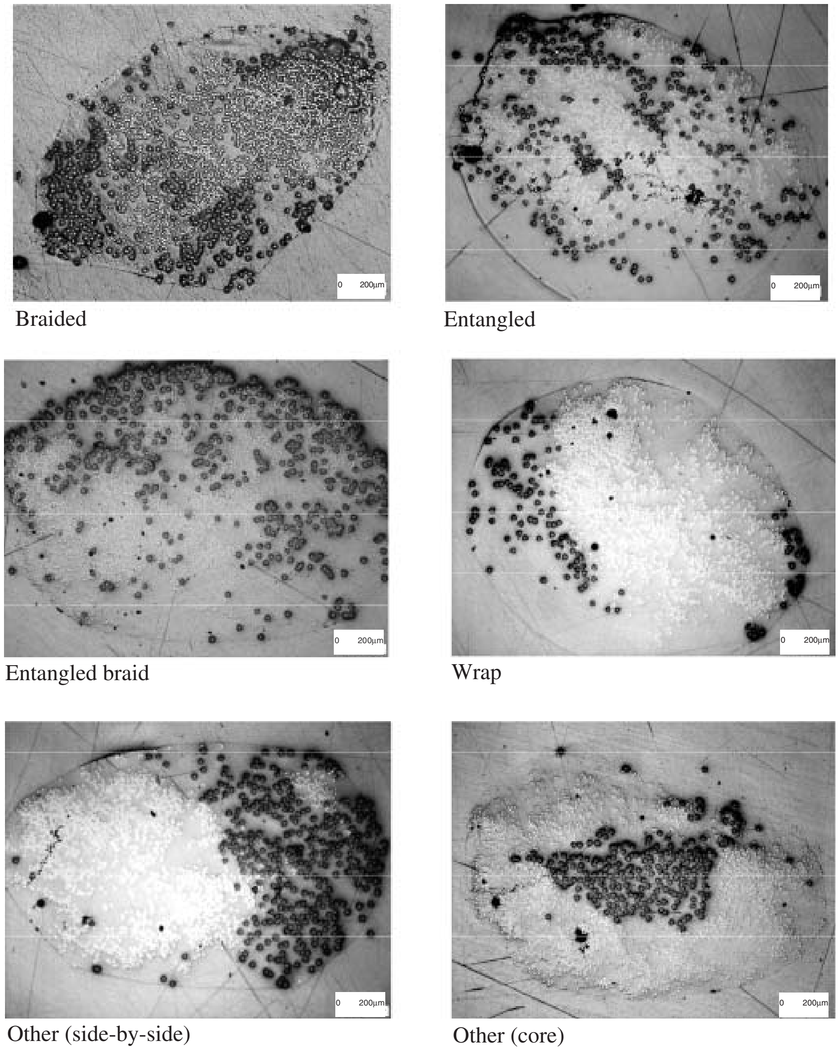


Figure 5. *Typical cross sections of nips in GF/PP commingled yarns. (Light fibers: Glass, Dark fibers: PP) (Air pressure: 7 bar, Glass-PP, V_m 47%).*

average nip length [14] in centimeters are also obtained.

$$\text{The degree of interlacing (\%)} = \frac{\text{Total length of nips in the yarn}}{\text{Length of yarn specimen}} \times 100$$

Cyclic Load Testing

Different type nips are subjected to cyclic loading to estimate the stability of the nips. Five specimens of nip from each class from GF/PET, GF/Nylon, and GF/PP commingled yarns are selected from different parts of the yarn for this study. The nips are subjected to loading between 0 and 5% strain by setting the tensile tester at strain cycling mode for ten cycles. The work done in the first and final cycles can be calculated from the stress–strain curves. These tests are carried out on LLOYD LR5K tensile tester with 50 mm gauge length and a cross-head speed of 100 mm/min. Using these data, the percent decay values are calculated as follows:

$$(\%)\ \text{Decay} = \frac{\begin{pmatrix}\text{Work done in the first}\\ \text{cycle of loading}\end{pmatrix} - \begin{pmatrix}\text{work done in the tenth}\\ \text{cycle of loading}\end{pmatrix}}{\text{Work done in the first cycle of loading}} \times 100$$

RESULTS AND DISCUSSION

Nip Frequency

Figure 6 shows the relation between the air pressure and the number of nips. It can be observed from the figure that the overall nip frequency of

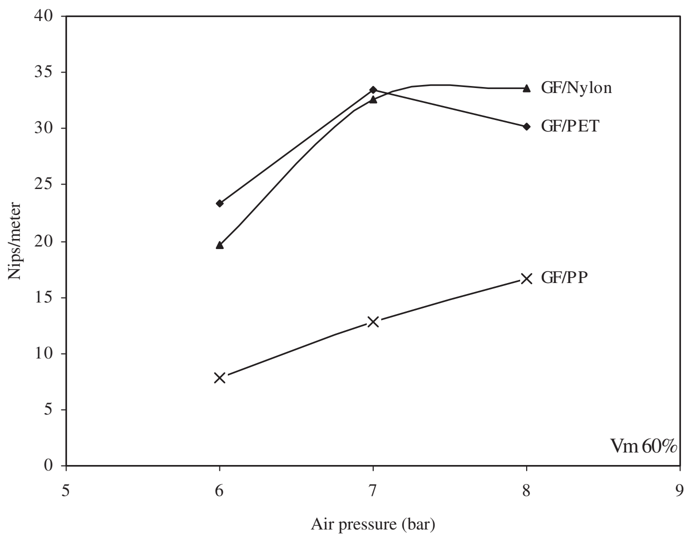


Figure 6. *Effect of air pressure on nip frequency.*

GF/PP yarn increases linearly with increase in air pressure. Nip frequencies of GF/Nylon and GF/PET also increase sharply with an increase in air pressure and the maximum nip frequency can be achieved at an air pressure of 7 bar. However, when the air pressure increases to 8 bar, the nip frequencies of GF/PET decreases slightly, whereas GF/Nylon yarns show no change. This is because Nylon and PET yarns have more number of filaments, lower diameter ratio (diameter of matrix forming fibers/diameter of glass filaments) leading to better commingling and nip formation. Anyway, the maximum nip formation happens at an air pressure of 7 bar and after that air pressure has no effect on the nip frequency. In the case of PET, the decrease in nip frequency after 7 bar pressure could be because of too high frequency of yarn rotation leading to the failure of the formation of stable nips.

With increase in air pressure, the air velocity inside the yarn channel also increases and therefore the frequency of yarn rotation inside the jet also increases. In case of PP, the nip frequency is much lower than that of Nylon and PET. This could be due to the fact that it has lower density, lower number of filaments, and highest diameter ratio in comparison to the other two filaments as can be seen from Table 1. The diameter ratio plays a critical role in commingling as shown by Beyreuther et al. [15]. Moreover, air texturing of PP have shown difficulties in terms of loop formation and development of bulk [16]. These studies clearly indicate that in the case of PP, the filament movement inside the nozzle is not quite conducive for commingling and nip formation.

Another important parameter, which affects the nip frequency, is the volume fraction of matrix-forming fibers (V_m). With an increase in volume fraction of the matrix-forming fibers component in the commingled yarns, the nip frequencies of GF/Nylon and GF/PET yarns increases and rises to the maximum when volume fractions of Nylon and PET reaches 47 and 61%, respectively, whereas GF/PP yarns show almost constant nip frequency at all volume fractions. This can be explained in terms of the number of filaments in the yarn bundle or the total linear density. In case of PP, to obtain a certain level of V_m, the number of PP filaments included is much lesser than that of Nylon and PET as the density of PP is the lowest and also the denier per filament is also 8, which is higher than that of Nylon and lower than that of PET. Any increase in V_m is attained by adding a fewer number of filaments having a higher diameter ratio. Hence nip frequency does not increase with V_m in the case of polypropylene. Moreover, the V_m is increased in all experiments by increasing the number of matrix-forming filaments, keeping the number of glass fibers constant. Hence as V_m is increased in the case of PP, the airflow inside the nozzle gets negatively disturbed as higher volumes in the nozzle get occupied by larger diameter filaments.

In the case of Nylon and Polyester, since the diameter ratios are lower, increasing V_m by increasing the number of matrix-forming filaments results in increased nip frequency. But, after a certain level, because of the disturbance of airflow in the nozzle as explained for the PP, the nip frequency starts to decrease.

Nip Structure

Table 2 shows the effect of air pressure on the proportion of different nip structures. When the air pressure is increased from 6 to 8 bar, the proportion of entanglement nips increases in all the commingled samples.

With an increase in air pressure, the speed of filament rotation also increases and therefore reinforcing and matrix-forming filaments open up into small bundles leading to the formation of more entanglement nips. It can also be observed that with a further increase in air pressure, the proportion of braided nips in GF/PET and GF/Nylon yarns significantly decrease, whereas the proportion in GF/PP yarns increase very slightly. At a lower air pressure, insufficient opening of filament bundles leads to the formation of braided nips and a further increase in air pressure would enhance opening of the filaments and this reduces the probability of formation of braided nips. The proportion of entangled braided nips in GF/PET and GF/PP yarns initially increases with air pressure, but further increase in pressure leads to a decrease in nip proportion. However, the proportion of entangled braided nips in GF/Nylon yarns continuously increases with increasing pressure. The proportion of wrap and other nip types in GF/Nylon and GF/PP yarns decrease with air pressure, whereas GF/PET yarns show an opposite trend. Table 3 shows the effect of V_m on the proportion of different nip structures. With an increase in V_m, it has been observed that there is no clear trend in the proportion of different nip structures.

Table 2. Effect of air pressure on the proportion of different nip structures.

Nip type	GF/PET Air pressure (kg/cm^2)			GF/Nylon Air pressure (kg/cm^2)			GF/PP Air pressure (kg/cm^2)		
	6	7	8	6	7	8	6	7	8
Braid	47	29	23	24	21	12	18	24	24
Entanglement	28	25	31	29	40	39	10	22	33
Entangled braid	15	40	20	20	27	39	5	27	19
Wrap	06	01	14	14	07	04	14	03	04
Others	04	05	12	13	05	06	53	24	20

Table 3. Effect of V_m on proportion of different nip structures.

Nip type	PET volume fraction (%)				Nylon volume fraction (%)			PP volume fraction (%)			
	31	47	61	67	40	57	67	31	47	58	62
Braid	20	20	29	25	13	21	29	19	22	24	25
Entanglement	41	40	25	30	31	27	17	22	28	22	18
Entangled braid	28	28	40	41	35	40	32	38	33	27	28
Wrap	03	03	01	01	06	07	04	09	03	02	04
Others	09	08	05	03	15	05	18	12	14	25	25

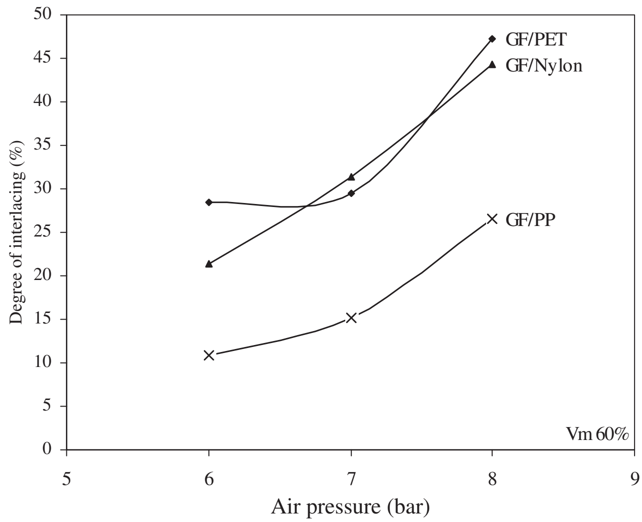


Figure 7. *Effect of air pressure on degree of interlacing.*

Degree of Interlacing

Figure 7 shows the effect of air pressure on the degree of interlacing. An increase in air pressure increases the degree of interlacing continuously. Although in case of Nylon and PET, the nip frequency increases up to 7 bar and remains constant with a further increase in air pressure to 8 bar. Figure 8 shows that with an increase in air pressure, the average nip length increases. Therefore, with an increase in air pressure, the degree of interlacing increases irrespective of the nip frequency. At higher air pressures, as velocity of filament rotation inside the nozzle increases, the momentum of the filament movement also increases. This causes the nip length to increase as the air pressure is increased. This trend has been observed for all types of nip

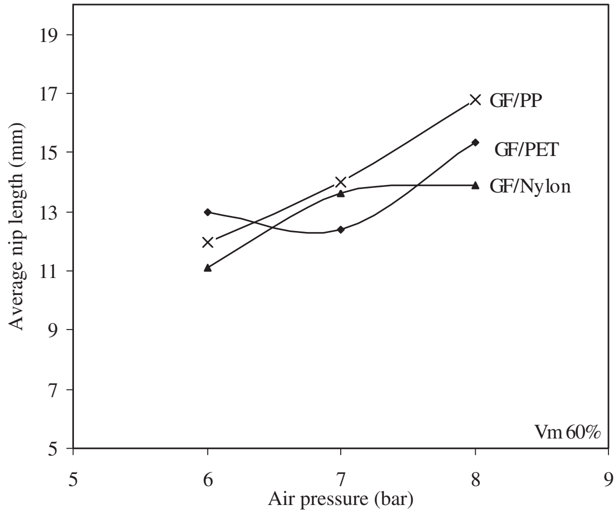


Figure 8. *Effect of air pressure on average nip length.*

structures. Although longer lengths of entangled nips, where two types of fibers are intimately mixed are preferable, increase in nip length of other types of nip structures should also result in a better resin distribution in the resultant composites. GF/PET and GF/Nylon show higher degree of interlacing than GF/PP yarns for the same reasons explained for nip frequency. The matrix-forming fiber volume fraction shows no significant effect on the degree of interlacing of GF/PP and GF/Nylon yarns.

Percent Decay

In cyclic load testing, it has been observed that after ten cycles, there is very little change in the loading and unloading curves. In the first cycle, the amount of work done is maximum and it keeps on reducing as the number of cycles increases and it stabilizes after ten cycles. In the first cycle, unstable nips and other entanglements open up. As the number of cycles increases, most of the loose entanglements and other segments are removed and the commingled structure have only more stable structures. Thus, the percent decay calculated provides the idea about nip instability.

Figure 9 shows the percent decay of different commingled yarns. Among the three types of commingled yarns studied, Glass/PP yarns show the highest decay. Although PP has marginally higher fiber to fiber friction as can be referred from Table 1, since these filaments have a higher diameter, they have lower surface area per unit mass. They also have a lesser number of filaments as compared to that of the other two types of commingled yarn.

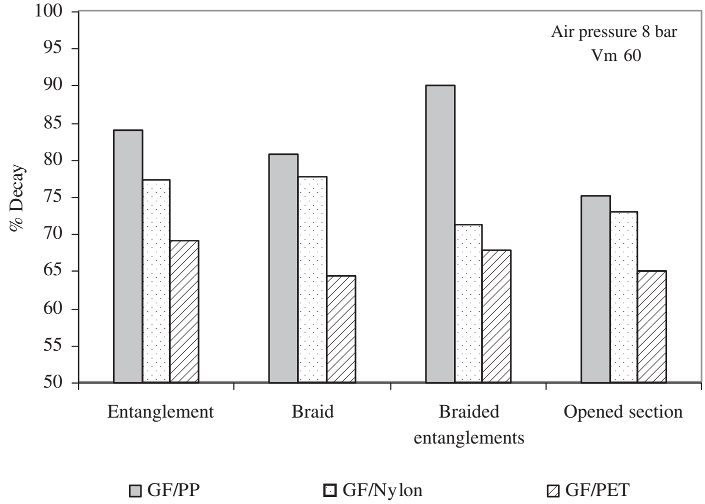


Figure 9. *Percent decay observed in commingled yarns.*

These factors lead to a poor entangling of filaments, which results in a higher decay. Among the different types of structures, opened sections have the least decay as these sections have the least amount of filament interlocking or entanglements.

The entanglement type of nip structures mostly demonstrates highest decay except in the case of PP, where the number of filaments is the least. In these types of sections, filaments entangle to a large extent. These entanglements generally open up during cyclic loading leading to a higher decay. Decay of braids and braided entanglement type of nips mostly lie in-between opened sections and entanglement nip structures. This is due to the fact that braids hold group of filaments tightly which open up to a lesser extent during cyclic loading.

The commingled yarns with low percent decay values will maintain the high degree of mixing obtained in the process of commingling through out the textile preforming operations where they will be subjected to cyclic loading. This will lead to a preform, where the reinforcing filaments and the matrix filaments are intimately mixed. The composites produced with this preform are expected to provide higher mechanical properties with least void content because of good fiber matrix distribution.

CONCLUSIONS

The structures of Glass/PP, Glass/Nylon, and Glass/PET commingled yarns have been characterized. The nip structures are classified into entanglement, braids, entanglement braids, and others. The influence of air pressure and volume fraction of matrix-forming fibers on the nip frequency, degree of interlacing, and types of nips formed are studied. It has been found that Glass/PP yarns have lower nip frequency and degree of interlacement and both of these properties generally increases with an increase in air pressure. It has also been observed that entanglement type of nip structures preferentially form at higher air pressures, whereas braid type nips form at lower air pressures.

Studies on percent decay indicate that Glass/PP yarns have lower stability, whereas the opened sections have higher stability. The present work shows that density of the matrix-forming fibers, the cross section of matrix-forming filaments, the number of filaments in yarn bundle, filament fineness, and diameter ratio of reinforcing and matrix-forming filaments influence the nip frequency, degree of interlacing, and percent decay of commingled yarns significantly. Further investigation of these commingled yarn structures in terms of aggregation and distribution of constituent filaments in the cross sections using different indices is in progress. The relationship between these indices and the final properties of the composite will be established.

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