Commingled CF/PEEK Hybrid Yarns for Use in Textile Reinforced High Performance Rotors

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SUMMARY: Owing to a higher melt viscosity compared to the thermoset plastics the impregnation of the textile reinforcement structure with a thermoplastic matrix is significantly difficult. Commingled hybrid yarns produced on the basis of air-jet texturing technique have the potential for a homogeneous distribution of reinforcement and matrix filaments over the yarn cross section. The so achieved very short flow paths during manufacturing of the composite part make a fast and complete impregnation of the reinforcement filaments possible. In this study, first investigations are performed to optimize the process and to develop the hybrid yarn further. Mechanical properties of yarns and unidirectional composites made of these are examined to evaluate selected hybrid yarns produced under different process conditions. Composites produced from the commingled hybrid yarns show a more even impregnated state as those from a compared material (Side-by-Side structure). The mechanical property reaches the level of composites from other hybrid yarns with regard to fiber-matrix-adhesion. This lecture introduces the first results obtained using the air-jet texturing process and provides an outlook for further work-steps.

KEYWORDS: commingled yarn, pre-impregnation, CF/PEEK, mechanical properties

INTRODUCTION

Complex material requirements in high-tech applications demand increasingly the use of hybrid materials with load adapted properties, since conventional isotropic material frequently do not fill the demanded specification of the applications optimally. Continuous fiber reinforced plastics are especially suited for this since their properties can be designed according to demand [1, 2].

The presented results were obtained within the scope of a research collaboration group about textile reinforcements for high performance rotors at the Dresden University of Technology. Known textile reinforcement structures cannot or only insufficiently meet the requirements in critical areas (blade mounting sections, load initiation, notches, and perforations) of industry rotors, e.g. centrifuges or sorters, resulting from their complex shape. Therefore the highest degree of freedom possible for the design of the reinforcing structure is planned to be achieved by utilizing the current potential of textile technology for the production of load adapted preforms with optimal fiber arrangement according to outer loads.

The project “Hybrid Yarn Development” is focussed on commingled CF/PEEK hybrid yarns particularly for the production of failure tolerant high performance rotors for high temperature applications

Continuous fiber reinforced composites with a thermoplastic matrix gains market importance on the basis of numerous advantages regarding manufacturing and application. Compared to thermoset matrix composites they are characterized by higher toughness, failure tolerant material behavior, and the ability of being reshaped and repaired subsequent to manufacturing as well as the unlimited storage time of the prepregs. Owing to a higher melt viscosity compared to the thermoset plastics the impregnation of the textile reinforcement structure with the thermoplastic matrix is significantly difficult. This can result in insufficient composite properties. It is extreme for the application of PEEK as a matrix material for example. In order to solve this problem prior to consolidation, hybrid yarns can be used for production of the preforms.

HYBRID YARN

hybrid yarns consist of reinforcing filaments or fibers and the matrix component integrated into the yarn structure in form of powder, staple fibers, filaments, or split-films. Thus manufacturing of the composite part from such textile preforms for example directly in a hot press is possible without any separated impregnation process [3, 4]. Figure 1 shows some types of hybrid yarn produced by different technologies. Both components are, however, mostly distributed not homogeneously over the yarn cross section. The so achievable fiber impregnation is often insufficient because under pressure the melted matrix cannot penetrate completely the reinforcement fiber bundles [5].

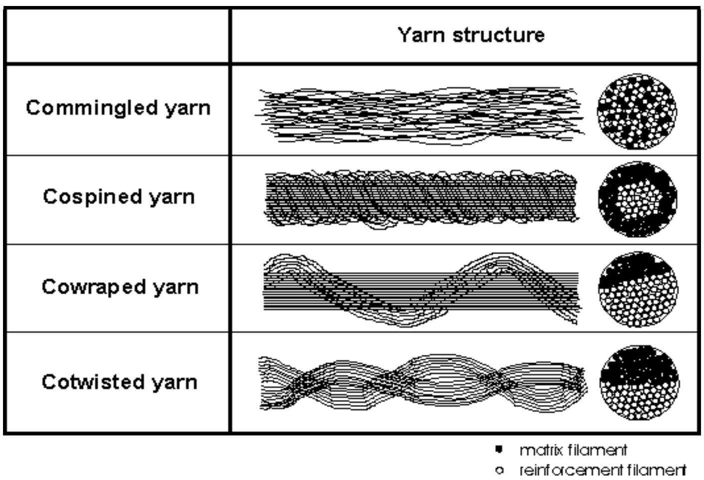


Figure 1. Various hybrid yarn structures

Commingled hybrid yarns in contrast have the potential for a homogeneous distribution of reinforcement and matrix filaments over the yarn cross section. The so achieved very short flow paths during manufacturing of the composite part allow a fast and complete impregnation of the reinforcement filaments. Additionally the desired ratio of fiber to matrix can be achieved by variation of the number of yarns during hybrid yarn production. A further advantage is the comparatively good processibility of the commingled hybrid yarns by almost all known textile-manufacturing technologies. In combination with a development of suited textile structures significantly improved mechanical properties of the composite parts and a rationalized production process compared to conventional manufacture technologies for the production of thermoplastic composites can be obtained [6, 7].

This lecture introduces the first results achieved using the air-jet texturing process and provides outlook for further works.

MANUFACTURING PROCESS

Air-Jet Texturing Machine

At the ITB a modified air-jet texturing machine (Type RMT-D, Stähle) is used for producing the commingled hybrid yarn. Opening of the reinforcement and matrix filaments takes places essentially aerodynamically in an air-jet nozzle. The machine allows the usage of different types of the air-jet nozzle and is equipped with a device for yarn wetting. It is also equipped with heating rollers for shrinking or fixing the filament yarns prior to texturing. The commingling process is schematically shown in figure 2.

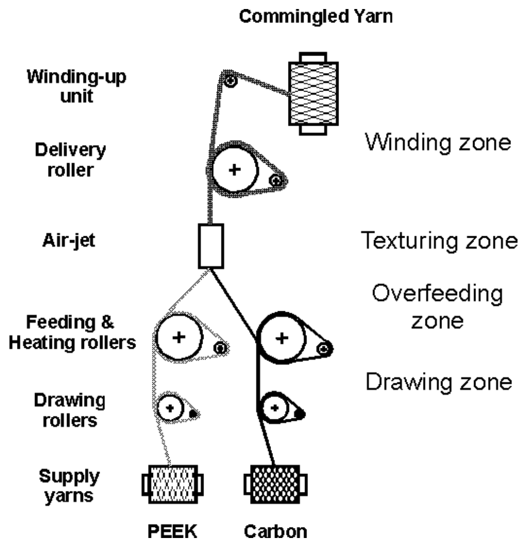


Figure 2. Commingling process on the basis of a air-jet texturing machine

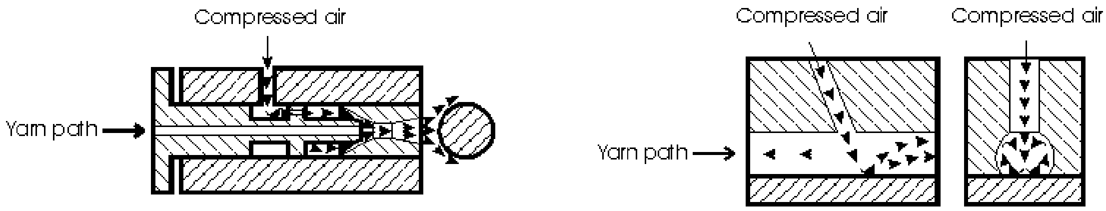
The Properties and appearance of hybrid yarns produced by means of the air-jet texturing technique are significantly influenced by process parameters e.g. over feeding ratio of both filament yarns at the nozzle, take-up speed, air pressure, nozzle setting, type of the nozzle, yarn wetting, and pre-heating temperature. Goal of the developments is the minimization of filament damage and a homogeneous distribution of both components over the yarn cross section. This is especially intended to achieve gentle opening of the filament yarns and mixing of reinforcement and matrix filaments at low air pressure.

Air-Jet Nozzles

According to this point of view different types of air-jet nozzle as following were selected for the investigation:

- Texturing nozzle (Du Pont Type XV, Venturi 100, Needle 86D)
- Intermingling nozzle (Temco LD 32.04, 32.05, 32.06)

These nozzles are designed initially for a modification of classical man-made fibers and work after different principles represented in figure 3. During air-jet texturing the airflow, directed mainly parallel to the yarn path, results in shifting of single filaments longitudinally to the yarn path together with the formation of filament loops. In contrast to this the airflow during intermingling acts quasi perpendicular to the filament bundles. It opens filament bundles, and then builds mingling sections.



(a) air-jet texturing nozzle (b) intermingling nozzle

Figure 3. Principle of different air-jet nozzles

MATERIAL AND PRESS MOULDING

Material

Because of its high temperature and good chemical resistance PEEK in combination with carbon fibers is suited as base material for parts under high thermal and mechanical stresses. The investigations presented refer to CF/PEEK hybrid yarns with a yarn count of 600 tex and a fiber volume fraction of 60 %. Table 1 specifies the base materials.

Table 1: Base Material

Type of material	Count [tex]	Number of filament	Filament diameter [µm]	Density [g/cm^3]
Toray T300J	198,0	3000	6,9	1,78
Hoechst PEEK M	49,5	72	26,0	1,30

First, the dependence of hybrid yarn structure on the ratio of overfeeding of carbon and PEEK filament yarns was investigated with focus on the optical yarn appearance (closeness of structure, hairiness and component distribution over the yarn cross section). Overfeeding of carbon filament yarn of 3% and that of PEEK filament yarn of 7.5 % was found to be optimal. The take-up speed was set to 50 m/min. Using these settings the air pressure was varied between 0.4 and 0.6 MPa during the further investigations.

Consolidation of CF/PEEK Composites

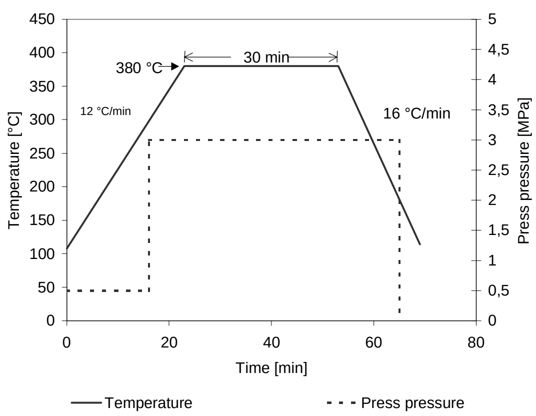


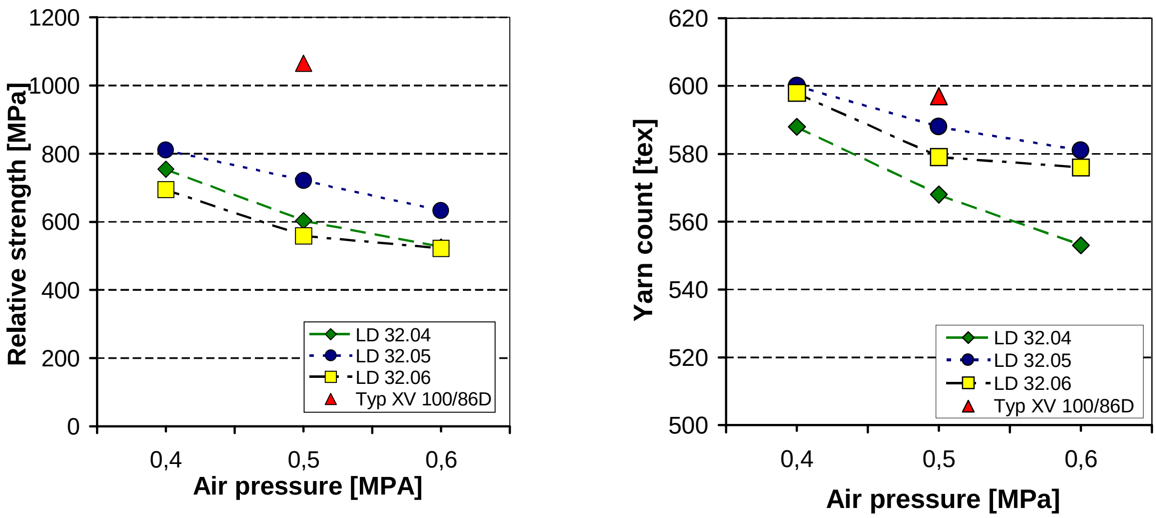
Figure 4. Processing cycle for consolidation of CF/PEEK composites

The manufactured hybrid yarns were examined visually to evaluate the outer appearance and the yarn cross-section as well as experimentally in view of their stress-strain behavior. Selected hybrid yarn variants were unidirectional wound onto a special frame and dried for 4 hours at 150°C. Consolidation of the unidirectional plates (130 x 100 x 2 mm^3) was done in a hot press. The processing cycle is illustrated in figure 4.

CHARACTERISATION OF HYBRID YARNS

The yarns produced by air-jet texturing show a significantly more stretched arrangement of reinforcement filaments compared to air-jet intermingled yarns. On the other hand the later show a more homogeneous component distribution over the yarn cross-section, mingling sections, and a higher hairiness. Although the reinforcement and matrix filaments are well connected to each other by the air-jet texturing and by the intermingling process respectively, examinations of yarn cross sections show that entire mixing of the filaments is not achieved with the current settings. Sticking of the carbon filaments to each other resulting from the applied size and the extremely different stress-strain behavior of carbon and PEEK filaments are assumed to be the reasons for this. Therefore there is still a significant necessity for improvement of component mixing.

The relative tensile strength (referred to the carbon filament fraction) and the yarn count of the produced hybrid yarns are taken into account for evaluation of the occurring property degradation of the carbon fibers. Figure 5 shows the dependence of the relative tensile strength and the yarn count on the nozzle type and the air pressure applied.



(a) (b)

Figure 5. Dependence of the relative tensile strength (a) and the yarn count (b) on the nozzle type and the air pressure

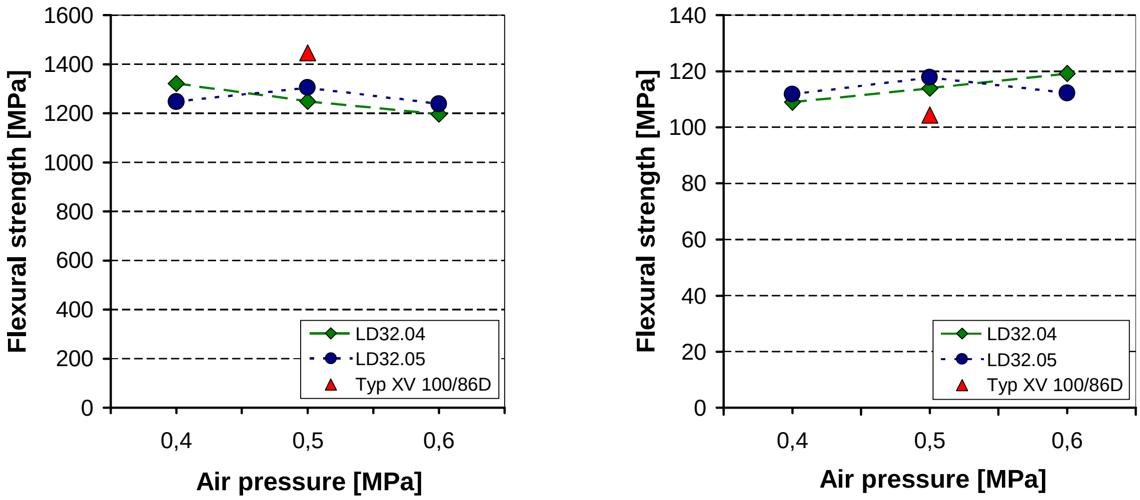
It showes for all types of nozzle that with decreasing air pressure the damage of carbon filaments decrease and following from that strength and yarn count of the hybrid yarns increase. This proves that the decrease of the relative strength connected to current level of process development is caused by breakage of reinforcement filaments with a loss of fiber. Thus the necessity of significantly reduced air pressure for the commingling process mentioned above is confirmed.

Besides, it can be seen that by having all process parameters constant the use of the texturing nozzle leads to a lower filament damage compared to that occurring with the intermingling nozzle. However, disadvantage of the gentle treatment of the carbon fibers by the texturing nozzle is an unfavorable component distribution over the yarn cross section. This is explained by the different work principles of the air texturing and air intermingling nozzle. Because of the high sensitivity of carbon filaments to mechanical stresses perpendicular to their longitudinal direction the use of intermingling nozzles leads to a higher filament damage.

PROPERTIES OF COMPOSITES

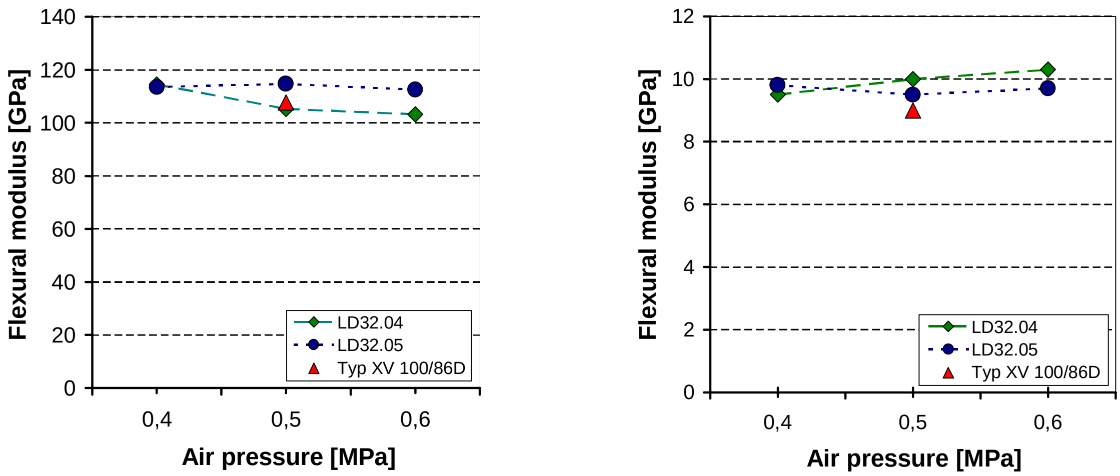
4-Point Bending Test

A Four-point bending test has been carried out to determine the mechanical properties. For this specimens in 0° (120 x 10 x 2 mm^3) and 90° (90 x 10 x 2 mm^3) direction were prepared from the unidirectional composites made of the different hybrid yarns.



(a) (b)

Figure 6. Dependence of flexural strength of the composites in 0° (a) and 90° (b) on the nozzle type and the air pressure



(a) (b)

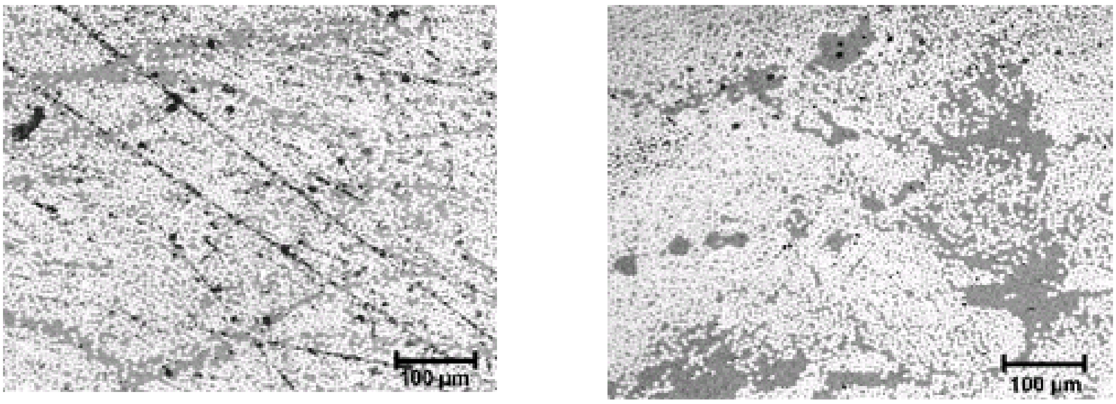
Figure 7. Dependence of flexural modulus of the composites in 0° (a) and 90° (b) on the nozzle type and the air pressure

The results (see figure 6 and 7) for both directions show that the dependence of bending strength and modulus of the composites on the type of used air nozzle and air pressure is much smaller than that of the yarn strength. The mechanical properties of the composites made of intermingled yarns are almost at the same level. This is explained since the filament damage of the hybrid yarn is of a much smaller influence owing to the uniform embedding in matrix material. Damage and break of filaments are overcome through a distribution of applied load by effects of matrix and boundary surface. It results in a considerably little influence of the damaged positions on global-mechanical “in-plane” behavior of composite materials.

As expected the bending strength of the unidirectional composites of air-jet textured hybrid yarns in 0° direction is higher than that of the composites of intermingled hybrid yarns. But a lowered fiber-matrix adhesion deriving from the flexural strength values in 90° direction caused by insufficient mixing of the components is assumed in case of air-jet texturing.

Comparison to Side-by-Side Structure

To allow a comparison unidirectional composites were consolidated under the same conditions from wound yarns whereas the carbon and PEEK filaments are not mixed but wound next to each other (side-by-side structure: SBS). Tensile test of these structures led to a tensile strength of 8.2 MPa for the SBS composites. Opposite to this a tensile strength of 86.5 MPa in direction perpendicular to the longitudinal filament axis was determined for the unidirectional composites made of the air-jet textured hybrid yarns. Furthermore, in order to characterize the quality of fiber impregnation microscopic examinations of the composite cross-section were carried out. Figure 8 shows as an example the homogeneous fiber-matrix distribution in a composite of commingled hybrid yarns compared to that of an SBS-composite which clearly shows matrix rich areas. Both results prove that the commingling process leads to a significantly improved fiber impregnation compared to the SBS variant.



(a) (b)

Figure 8. Microscopic photos of cross section from unidirectional composite made of CF/PEEK

(a) Commingled hybrid yarn (b) Side-By-Side structure

Comparison to another Hybrid Structure

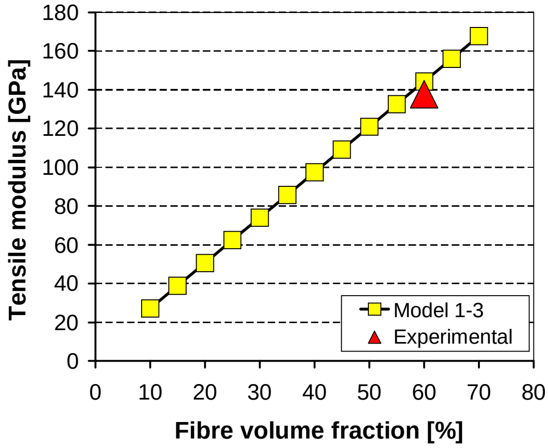
In table 2 are shown additional mechanical property values of the examined unidirectional composites made of the CF/PEEK hybrid yarn compared to such from literature. The results of tensile test in 90° to the fiber axis show that the fiber-matrix adhesion achieved within the first stage of investigations already widely complies with the expectations. The lower tensile strength in filament direction compared to that of the other preforms is caused by the at this time very high damage of carbon filaments during process at high air pressure.

Table 2. Comparison of the mechanical properties resulted from the tensile strength tests of unidirectional composite materials made of various hybrid yarns

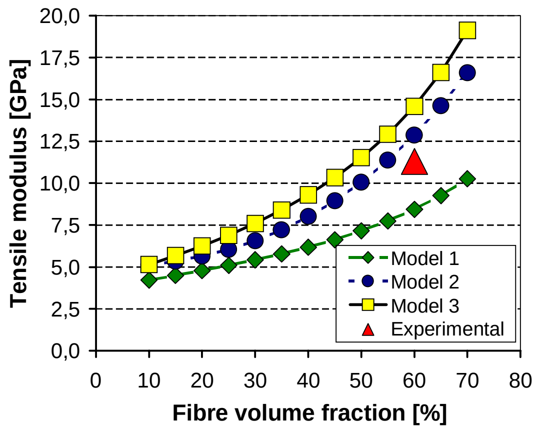
Type of material	Fiber volume fraction [%]	Tensile strength [MPa]		E-Modulus [GPa]	
Direction of loading		0°	90°	0°	90°
T300J/PEEK M – Commingled hybrid yarn, ITB	60	1388	87	138	11
AS4/PEEK-Hybrid yarn, BASF	55	1507	89	125	9
Powder impregnated hybrid yarn, BASF		-	63	-	10

Simulation of Elastic Property

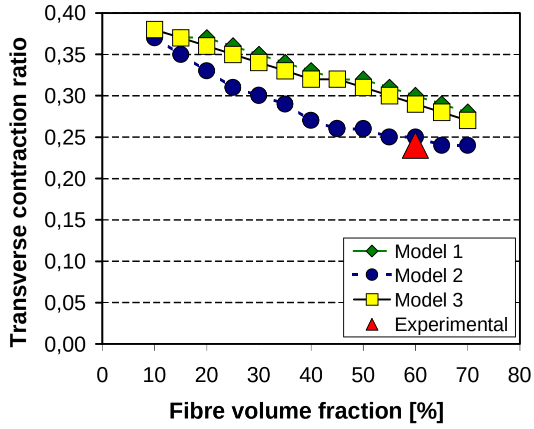
Parallel to the mechanical test, the elastic property of CF/PEEK composite was investigated at the `Institut für Leichtbau und Kunststofftechnik´ at the Dresden University of Technology on the basis of known micro-mechanical models. For the calculation three different models (model 1 after Abolinsh, model 2 after Hill, model 3 after Hashin) were used. Figure 9 shows the result of simulation for fiber volume fraction from 10 to 70 % [9].



(a) Tensile modulus in 0° direction to reinforcement fiber



(b) Tensile modulus in 90° direction to reinforcement fiber



(c) Transverse contraction ratio

Figure 9. Comparison the results of the simulation to the experimental value

For the tensile modulus in 0° to the fiber direction all three models have yielded almost same values. The calculation of the tensile modulus in 90° to the fiber direction and of the ratio of transverse contraction has yielded a little different results according to used model. The experimentally determined values agree with the results of the Models well. This also confirms that the mechanical properties of composite made of the commingled hybrid yarn are in the expected level.

CONCLUSIONS AND OUTLOOK

The results of investigation show that, at the present stage of development of the commingling process on basis of conventional air texturing technique, the necessary filament yarn opening and filament mixing leads to a certain damage of reinforcement filaments.

But it also becomes clear that the commingled hybrid yarns produced by air texturing technology provide homogeneous and complete fiber impregnation even though the texturing machine and process have been modified only slightly and that they already reach the level of known composite materials in view of fiber-matrix adhesion

Further optimization of the commingling process is carried out with the aim of achieving a homogeneous distribution of reinforcement and matrix filaments over the yarn cross section with low damage to the brittle reinforcement filaments.

Since the air texturing technique was not developed for this purpose a technical-technological process optimization is necessary which is carried out for selected material combinations and yarn counts within the scope of further investigations under the following priorities:

- Modification of the yarn guiding areas for a defined yarn feeding,
- Application of additional devices for pre-opening of the filament yarns prior to air-jet texturing or intermingling,
- Partial fixation of the yarn structure or size application for maintaining the distribution of reinforcement and matrix filaments over the cross section and to prevent carbon fiber damage by further processing.

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