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Polypropylene/glass fibre 3D-textile reinforced composites for automotive applications

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ABSTRACT

Textile-reinforced thermoplastic composites offer huge application potentials for a rapid manufacturing of components with versatile possibilities of integrating functions. However, an application of these new materials requires the knowledge of the directional dependent material properties. In this study, results are presented concerning selected relevant load cases for industrial applications. For the new group of multi-layered flat bed weft-knitted glass fibre/polypropylene composites (MKF-GF/PP), tensile tests under different temperatures and test velocities have been carried out as well as Charpy impact tests, open hole tension tests and dynamic-mechanical analysis. The mechanical properties of MKF-GF/PP and unidirectional GF/PP composites with tailored fibre surface and interphase, respectively, have been compared to those of woven GF/PP composites and GF/PP composites made of non-crimp fabrics (NCF) as a benchmark.

1. Introduction

In structural applications, textile composites are usually used as reinforcement because of the possibility to tailor the load bearing capacity through the fibre architecture. As a result of their growing potential for lightweight applications, textile-reinforced thermoplastic composites are getting of greater interest for the industry. Thermoplastic composites show a number of advantages compared to classical composites based on thermoset matrices, among which the possibility for a low-cost, rapid production has to be mentioned first [1–5]. Traditionally, textile thermoplastic composites are processed by stacking alternating layers of textile fabrics and polymer sheets in a hot-press. After heating above the polymer melting point, the press is closed to obtain the required product shape. In a subsequent cooling step, the product solidification takes place followed by demoulding. Clear advantages can be made when so-called hybrid fabrics made of commingled yarns are used. Such yarns consist of reinforcing filaments (e.g. glass, carbon) and thermoplastic filaments (e.g. polypropylene, polyetheretherketon). The thermoplastic filaments melt during the pressing process and form the matrix so that no additional polymer needs to be added. The main advantage of commingled yarns is that the thermoplastic yarns are uniformly distributed in the reinforcement yarns to reduce the flow length of the thermoplastic after melting [6,7]. In general, composites made of commingled yarns feature improved basic properties (strength, stiffness, toughness, impact resistance, environmental resistance) compared to traditional thermoplastic composites [6–10].

To be targeted at providing a cost-effective solution to the automotive industry with possible function integration, research focuses on the material combination of glass fibres and polypropylene (GF/PP) [1–12]. Commingled woven GF/PP fabrics are commercially available, and offer distinct advantages over powder impregnated fabrics (notably lower cost and better impregnation by the thermoplastic material). However, industrial demands on high-tech applications increasingly require the use of fabrics with adjustable mechanical properties. Traditional woven fabrics fulfill this requirement profile usually only on a small scale. In this context, the development of novel textiles in combination with adapted manufacturing technologies provide promising alternatives [11,13–15]. Multi-layered flat bed weft-knitted fabrics (MKFs) and non-crimp fabrics (NCFs) with hybrid yarns should be mentioned as typical examples of this new material group.

At present time, the material behaviour of the novel textile GF/PP composites (MKF-GF/PP and NCF-GF/PP) is insufficiently investigated. Most of the existing studies are limited to quasi-static loading conditions. Hence, this research focuses on the behaviour of this new material under practical conditions in automotive engineering which is a crucial topic if hybrid GF/PP textile composites

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are to be used for structural parts. The aim of this work is therefore to provide more experimental data, and in particular to assess the behaviour of this material under typical loading conditions that are relevant for automotive applications (Table 1). Since novel multi-layered flat bed weft-knitted GF/PP composites are always compared to commercially available materials of the same class, hybrid textile composites with woven fabrics and composites made of NCFs have also been tested, to provide a benchmark against which to compare the properties of MKF-composites.

2. Tailored thermoplastic composite materials made of commingled yarns

2.1. GF/PP commingled yarns

Hybrid yarns consist of reinforcing filaments or fibres and a matrix component integrated into the yarn structure in form of powder, staple fibres, filaments or split-films. The advantage of textile preforms made of hybrid yarns lies in the manufacturing of composite parts without any separated impregnation process. The achievable fibre impregnation is often insufficient because molten matrix cannot completely penetrate the reinforcement fibre bundles under pressure [7,16–18]. The highest potential for a homogeneous distribution of reinforcement and matrix filaments over the yarn cross section can be found in commingled hybrid yarns. There, the achieved very short flow paths allow a fast and complete impregnation of the reinforcement filaments during the manufacturing of the composite. Additionally, the desired fibre volume fraction can be realised by variation of the yarn count during the hybrid yarn production. With the commingling technique, it is also possible to create multi-reinforced hybrid yarns with fitted properties consisting of two reinforcing components and one matrix component [19]. The comparatively good processibility of the commingled hybrid yarns by almost all known textile-manufacturing technologies is a further advantage of this technology. The use of commingled hybrid yarns leads to tailored textile structures, improved mechanical properties of the composite and a rationalised production process compared to conventional thermoplastic composite manufacturing technologies [7,17,18].

For this study, commingled hybrid yarns have been produced at P-D Glasseiden GmbH Oschatz on a modified air-jet texturing machine developed on the basis of the experience of the ITM. The opening of the reinforcement and matrix filaments takes places mainly using aerodynamics in an air-jet nozzle. The machine allows the use of different types of air-jet nozzles (texturing or intermingling) which have a yarn tension controlled take-up unit and is equipped with a device for yarn wetting. The commingling process is schematically shown in Fig. 1.

The properties and the appearance of hybrid yarns produced by the air-jet texturing technique are significantly influenced by process parameters like 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.

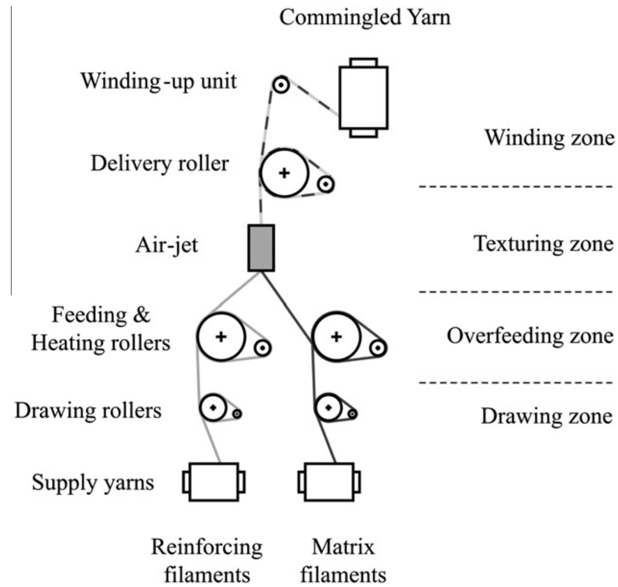

Fig. 1. Schematic of a commingling process based on an air-jet texturing machine [17].

Table 1
Relevant automotive data and related experimental tests.

Test	Automotive issue	Suitable experimental test
Standard tests	Basic properties	Standard quasi-static tests
Advanced applied tests	Thermomechanical properties	Tensile tests at different temperatures
	Structural impact and crash design	High-speed tensile tests Charpy impact tests
	Design of load transmission areas	Pin-loaded hole tests
	Comfortable car acoustics	Dynamic-mechanical analysis (DMA)

2.2. Multi-layered flat bed weft-knitted glass fibre–polypropylene composites

Multi-layered flat bed weft-knitted fabrics (MKF) are uniquely produced by the ITM [14]. Such MKFs are available with biaxial (up to 11 layers) and with multi-axial (up to five layers) in-plane reinforcement. The reinforcing warp and weft yarns are fixed in line to each other with one or two stitching yarn systems (Fig. 2). MKFs combine the advantages of stitched structures and reinforcing yarns with almost no ondulation. They feature high stiffness and strength values as well as a very good draping behaviour and excellent crash properties. Especially due to their excellent drape properties, the MKFs are ideally suited for the use in composite components with complex geometry. A previous study [3] has shown the capability of MKFs to be manufactured to automotive components without loss of quality in critical draping zones (cf. Fig. 3). Other materials of the same class fail to shape the contours of such structures.

The investigated MKF-GF/PP composites were manufactured using hybrid yarns from P-D Glasseiden GmbH Oschatz and consist of four [0/90]-MKF layers (notation : $[0/90//90/0]_2$) with the areal density of 1058 g/m^2. Table 2 shows the textile parameters for the used MKF. The theoretical glass fibre content of 47.6 vol.% was controlled by an experimental determination where 47.3 vol.% was measured as the average value.

2.3. Benchmark materials

As a benchmark, a $[0/90//90/0]_2$ glass-fibre-reinforced polypropylene composite made of non-crimp fabrics was investigated. The NCFs are a novel development by P-D Glasseiden GmbH Oschatz and are available with biaxial and multi-axial reinforcement. The NCF (type KNH G 1040.1) consists of the same commingled yarn than the MKF for the warp and the weft thread and got an areal density of 1028 g/m^2. The z-thread is made of PES so that a laminate almost without z-reinforcement arises after consolidation. Additionally, a glass-fibre-reinforced polypropylene composite

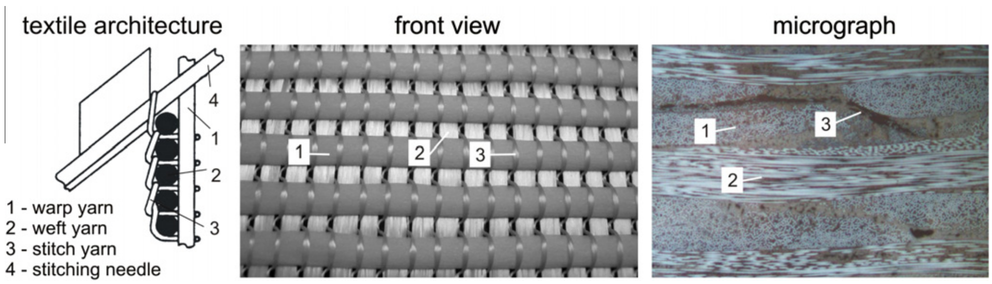

Fig. 2. Textile architecture of multi-layered flat bed weft knitted fabrics (MKFs).

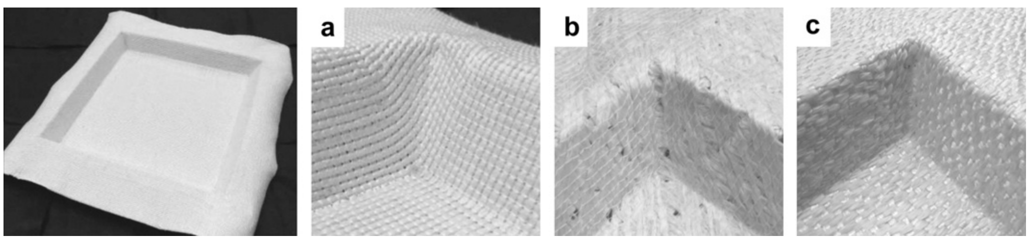

Fig. 3. Textile preforming for a composite component with complex geometry: made of GF/PP-MKF (a), of GF/PP-NCF (b) and of woven GF/PP (c).

Table 2
Textile parameters of the used MKF.

Yarn	Material	No. of fibres	Yarn count nom. lin. density (*tex*)	Yarn content in MKF (wt.%)	GF content in MKF (vol.%)	Mass ratio warp:weft
Weft	PD-HG 1	1	1655	41.4	20.2	1:1
Warp	PD-HG 1	1	1655	42.6	21.0	
Stitch	PD-HG 2	1	168	16.0	6.4	–

with woven reinforcement was used. The woven fabric PD GWT 840 KK1/3 has an areal density of 899 g/m^2. Four woven layers were stacked in the same orientation and manufactured to plates so that a $[(0/90)]_4$ lay-up arises. Both benchmark materials showed a slightly higher glass fibre volume content: 48.6 vol.% for the NCF-GF/PP composite and 51.0 vol.% for the woven GF/PP composite.

2.4. Specimen manufacturing

It has been shown that all types of fabrics used in this study can be manufactured to composites in less than a minute by means of using a fast-stroke press, see e.g. [1–3]. Due to financial questions and because the optimisation of the manufacturing time is not the focus of this study, the composites were fabricated using autoclave technology. Fig. 4 summarises the manufacturing parameters temperature, pressure and vacuum. Although the properties of GF/PP composites manufactured by autoclave technology and press technology are not always exactly the same, it has been shown that there are just few variations.

All three materials have been tested in three different directions: 0°, 45° and 90° so that effective lay-ups of $[0/90//90/0]_2$, $[45/-45//-45/45]_2$ and $[90/0//0/90]_2$ arise. Fig. 5 summarises the geometry of the specimens and gives additional information about the used test devices and the test standards taken as a basis for the

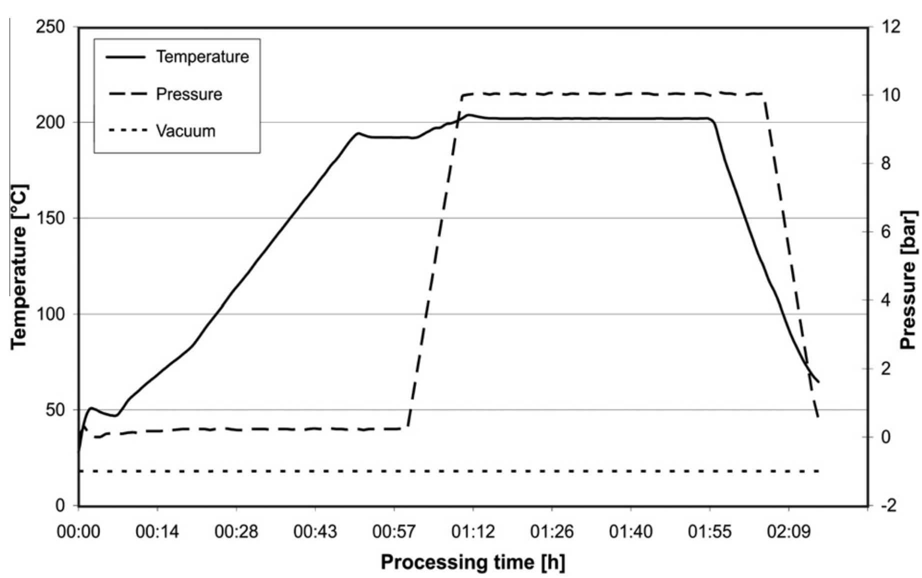

Fig. 4. Autoclave manufacturing parameters.

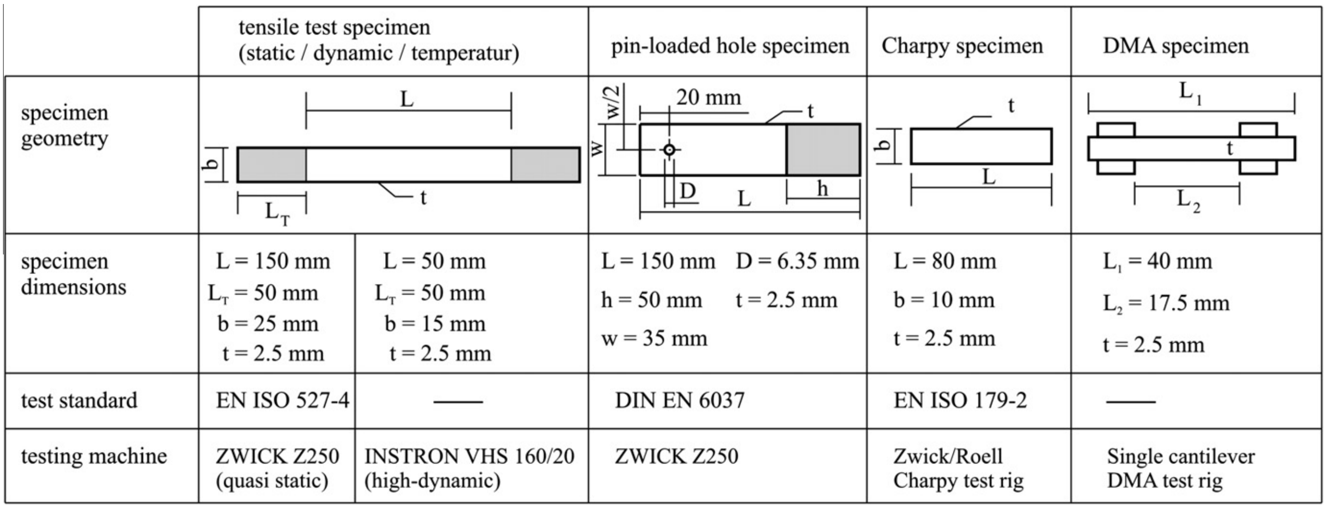

Fig. 5. Specimens geometry, test standards and test devices.

Table 3
Basic properties of the tested textile composites.

Composite	Engineering constants				Tensile strengths	
	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12} (–)	$R_1^{(+)}$ (MPa)	$R_2^{(+)}$ (MPa)
MKF-GF/PP	14.1	15.4	1.65	0.26	254	323
NCF-GF/PP	17.9	16.8	1.66	0.20	307	281
woven GF/PP	14.2	14.7	1.79	0.09	299	280

performed experiments. The quality assurance undertaken on the specimens by ultrasonics has proven that all specimens appeared to be of a homogeneous good quality without larger initial voids, although a few initial voids are inevitable. Previous studies have shown that these inhomogeneities can be included in engineering design by suitable phenomenological models [20].

3. Experimental results and discussion

3.1. Tensile tests

In a first step, all materials have been experimentally investigated under quasi-static loading conditions. There, the loading is applied strain-controlled with a velocity of 2 mm/min at 50% relative humidity and different temperatures. Because of its relevance for automotive applications, the focus was set to room temperature and a temperature of 80 °C. The applied loads have been measured directly by the test machine whereas the strains have been recorded with adapted long-range strain twist extensometers. Table 3 summarises the basic properties (engineering constants, tensile strengths) for the three materials at room temperature. Additionally, Fig. 6 (left) shows the measured stress–strain curves for 23 °C and 80 °C in different loading directions. The extracted temperature dependent values are also shown in Table 4.

To evaluate the strain rate depending material properties, high speed tensile tests were performed using a servo-hydraulic test device where velocities up to 20 m/s can be realised. The influence of the strain rate on the engineering constants and the failure behaviour was quantified in a velocity range from 0.1 mm/s up to 10 m/s. Fig. 6 (right) compares the measured stress–strain curves from quasi-static loading and the test velocity of 1 m/s. The strain rate dependent Youngs modulus and the associated tensile strength are additionally shown in Table 4.

As expected, the NCF-GF/PP composites show the highest stiffness values because no ondulation of the reinforcing fibres occur compared to the woven GF/PP. Because the Young‘s modulus strongly depends on the glass fibre content in loading direction, the MKF-GF/PP composites show slightly lower values. There, 6.4% of the glass fibre content is arranged in *z*-direction (Table 2). Even if the degree of anisotropy in the MKF-GF/PP composites is slightly higher, the tensile strength values of all three materials are in the same range. This conclusion is also valid for increased temperatures and increased test velocities. It has been shown that the material properties of all materials are clearly strain rate dependent. Both, the engineering constants and the tensile strength, increase by 50% with increased test velocity. That means, this factor has to be considered within the engineering design of GF/PP structures that are loaded in crash or impact.

3.2. Charpy impact tests

To evaluate the energy absorption capability of the new materials, numerous Charpy impact tests have been performed under different temperatures. The Charpy test device used in this study is a dynamic three point bending experiment of an un-notched beam [21]. The experimental setup consists of the specimen, the anvils where the specimen is freely supported and a pendulum with a defined mass attached to a rotating arm pinned at the machine body. The pendulum falls following a circular trajectory and hits the test specimen at the middle span length transferring kinetic energy to it. According to EN-ISO 179-1 which has been used as a guideline within this investigation, the pendulum hammer had a speed at impact of around 3.6 m/s and a stored energy of 15 J. Due to their small contribution to the energy balance, possible energy losses due to bearing friction and air resistance have been neglected. The specimens for the Charpy tests under 80 °C have been heated up to 85 °C in a malleablising furnace. The cooling time from 85 °C to 80 °C was determined in preliminary tests. By that procedure, the specimens could be tested at the accurate temperature.

The energy absorption capability of the tested composites is usually evaluated using force–displacement curves [10,21]. There, the absorbed energy during the impact event is represented by the area beneath the curve. Fig. 7 shows the characteristic force–displacement curves for the three tested materials. It becomes obvious that the energy absorption capability of the MKF-GF/PP specimens is significantly higher than in the benchmark

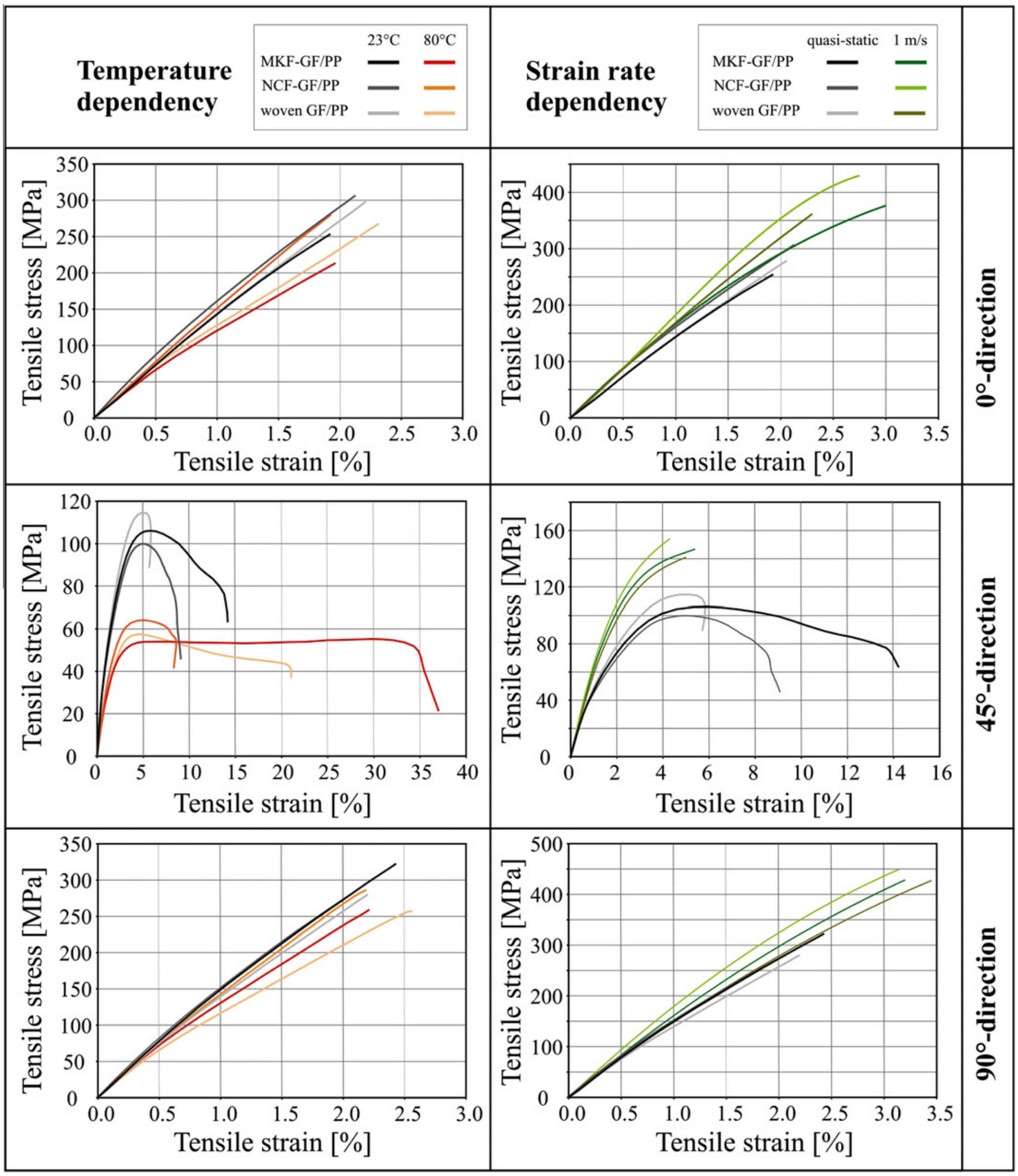

Fig. 6. Stress–strain curves of the tested composites for different temperatures and different strain rates.

materials. Compared to the NCF-GF/PP specimens and the woven GF/PP specimens, the increase in energy absorption is 18% and 35%, respectively. It has been shown that the higher energy absorption in the MKF-GF/PP is not due to large deformations of the specimens but because of the energy absorption capability of the textile preform itself. Obviously, the stitching yarn system can be identified as the big advantage of the MKF-GF/PP composite with respect to the load transfer mechanisms during crash loading.

Table 4
Youngs modulus and tensile strength of the tested textile composites at different temperatures and velocities.

Direction		MKF-GF/PP		NCF-GF/PP		Woven GF/PP	
		E_1 (GPa)	$R_1^{(+)}$ (MPa)	E_1 (GPa)	$R_1^{(+)}$ (MPa)	E_1 (GPa)	$R_1^{(+)}$ (MPa)
0°	23 °C	14.1	254	17.9	307	14.2	299
	80 °C	12.7	214	15.2	280	13.8	268
	1 m/s	16.1	376	19.0	430	17.7	362
45°	23 °C	5.54	106	5.99	100	5.48	115
	80 °C	3.22	55	3.68	64	2.88	58
	1 m/s	7.47	147	7.71	154	7.23	141
90°	23 °C	15.4	323	16.8	281	14.7	280
	80 °C	14.5	260	15.3	287	13.3	257
	1 m/s	15.7	428	19.6	450	15.2	427

The same trend has been observed for higher test temperatures, too. Under 80 °C test temperature, the energy absorption of the MKF-GF/PP is 30% higher compared to the NCF-GF/PP and 67% higher than in the woven GF/PP. In this case, the energy absorption capability of the MKF-GF/PP even increases to 16% compared to room temperature whereas the values of the benchmark materials remain nearly constant. The better capability of absorbing energy during crash and impact loading of the MKF-GF/PP composites makes the material attractive for automotive components which are mainly loaded by crash or impact. The values also illustrate their good suitability especially under increased temperatures.

3.3. Pin-loaded hole tensile tests

Due to the fact that load transmission areas and joining elements are often considered to be a weakness of textile-reinforced materials, the characterisation of the strongly anisotropic properties in the area of such load transmission zones is of particular importance. In such regions, the influence of the textile preform itself is usually higher compared to undisturbed areas. Especially for the textile composites used in this study where the representative volume elements of the preform are relatively large compared to conventional composites, an assured material characterisation is extremely important for industrial applications.

The stress concentration behaviour of pin-loaded holes occurs as a sub-problem of the technically relevant problems dealing with bolt joints, rivets, screws or other fasteners. In order to evaluate that sub-problem in load transmission zones, pin-loaded hole tensile tests have been performed according to DIN EN 6037. The holes have been drilled into the specimens according to Fig. 5 by using a secured one-sided drilling process that has been developed especially for composites. Afterwards, the holes are fettled and calibrated.

A tensile load is applied via the parallel pin. The standard DIN EN 6037 defines the so-called yield bearing strength at 2% permanent hole deformation and the ultimate bearing strength at total failure as characteristic values for the load transmission zone. With F_y as the measured force, D as pin diameter and t as laminate thickness, the yield bearing strength at 2% permanent hole deformation p_y is determined by

$$p_y = \frac{F_y}{D \times t}. \quad (1)$$

Analogously, the ultimate bearing strength at total failure p_u is determined with the measured force F_u at total failure:

$$p_u = \frac{F_u}{D \times t}. \quad (2)$$

The experimental evaluation shows that all three materials (MKF-GF/PP, NCF-GF/PP and woven GF/PP) have comparable pin-loaded hole properties. Table 5 summarises both measured values p_y and p_u in order to show that trend. It was found that the scatter of the data of the MKF-GF/PP composite was slightly smaller compared to the two benchmark materials, see Fig. 8. Both conclusions have also been verified at increased temperature (80 °C). In order to further enhance the load transmission behaviour, a simple material replacement is therefore not useful. Instead of that, the use of a novel textile-adapted notching technology for bolted joints is recommended which is described in [22]. Because none of the three materials shows a significantly better load transmission behaviour

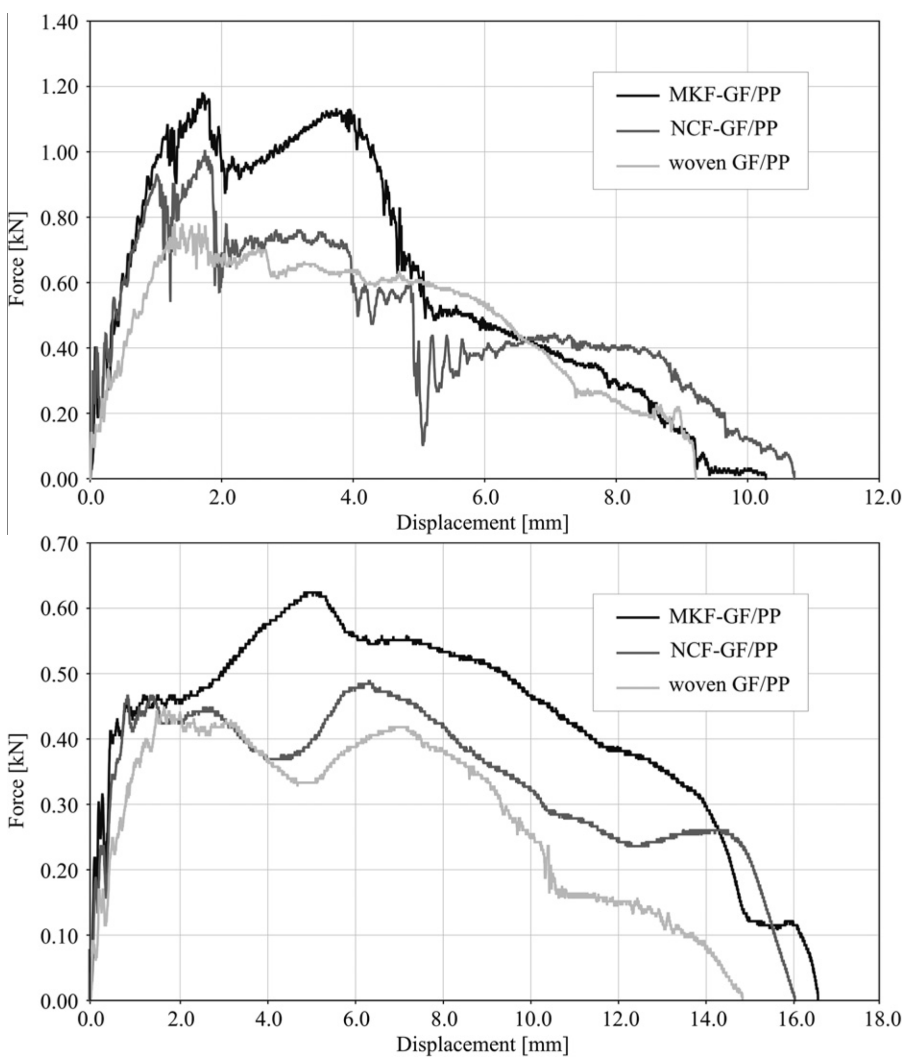

Fig. 7. Force–displacement curves of Charpy tests performed at ambient temperature (top) and at 80 °C (bottom).

Table 5
Measured strength in the pin-loaded hole tensile tests.

Composite	Yield bearing strength at 2% perm. hole deformation (MPa)			Ultimate bearing strength (MPa)		
	0°-test	45°-test	90°-test	0°-test	45°-test	90°-test
MKF-GF/PP	121	131	135	374	344	380
NCF-GF/PP	117	132	119	382	347	403
woven GF/PP	126	129	128	388	336	406

during the performed pin-loaded hole test, it could be concluded that all tested materials are similarly suited for the use in load transmission areas and joining elements.

3.4. Dynamic-mechanical analysis

By using dynamic-mechanical analysis (DMA), the viscoelastic properties and damping features of composites can be determined. Particularly with regard to a pleasant atmosphere in automobiles, an adjustable vibroacoustic property profile of the material can be important. In this context, materials with good damping properties are of notably higher interest for the industry. The DMA tests have been performed using a single cantilever beam configuration. The specimens have been heated with 3 K/min starting from −40 °C up to 140 °C. During that process, the free edge of the specimen is loaded with a frequency of 1 Hz and an amplitude of 20 μm in order to obtain the damping properties depending on the temperature.

By determining the damping value tanδ from the ratio of loss modulus and storage modulus, the general damping properties of composites can be significantly evaluated with the DMA. Table 6 summarises the observed damping values for all tested materials both for room temperature and 80 °C test temperature. It can be shown that the damping properties of the MKF-GF/PP specimens are notably higher in the axes of reinforcement (11% higher than in the NCF-GF/PP specimens and 21% higher than in the woven GF/PP specimens). In contrast to that, the damping values in off-axis directions (here: 45°) are slightly lower compared to the benchmark materials (2% lower than in NCF-GF/PP and 6% lower than in woven GF/PP). It will be shown within further investigations if this difference has significant influences on automotive structures, especially if other materials are also considered.

4. Tailored interphases for enhanced composite properties

Independent of the textile architecture of continuously reinforced composites, their mechanical performance is affected by the fibre/matrix interface and the interphase properties as well. A strong fibre/matrix bond can be regarded as a necessary prerequisite for textile composites when aiming at high mechanical performance. Within this study, different fibre surface modifications have been applied to commingled GF/PP yarns in order to investigate the effect of the surface modification on the composite properties.

4.1. Experimental

The online commingled GF/PP yarns were spun at the Leibniz-Institut für Polymerforschung Dresden as described elsewhere [33]. The sizings were composed of an aminopropyl-triethoxysilane and different commercially available PP film formers based on maleic anhydride grafted PP (MAH-PP). The sizing content of the as-spun GF was in the range of 0.5–1 wt.% as determined by loss on ignition, whereas the GF weight fraction of the composites was found to be 75 ± 1.5% (DIN EN-ISO 1172), being equal to approximately 50 vol.%. As spinning finish for the PP-filaments a commercial finish, Fasavin HT11 (Zschimmer & Schwarz) was used.

After filament winding of the hybrid yarns, unidirectional composites were compression moulded in computer controlled long term cycle (heating, consolidation and cooling in the mould) at 225 °C for 45 min. In detail, heating from ambient temperature to 225 °C took 23 min at a pressure of 0.5 MPa, followed increasing the pressure to 3 MPa for 2 min, before cooling down to 40 °C within 20 min. During the cooling pressure was kept constant at 3 MPa.

The transverse tensile strength of the unidirectional GF/PP composites was measured according to specification DIN EN-ISO 527-5 with a velocity of 1 mm/min^{-1} for at least 10 specimens for each test series.

4.2. Effect of surface modification on composite properties

By varying the surface modification of the commingled yarns, the interphase properties of the GF/PP composites can be affected to a great extent. The interphase is a three-dimensional region between fibre and matrix, mainly formed by the interdiffusion of the

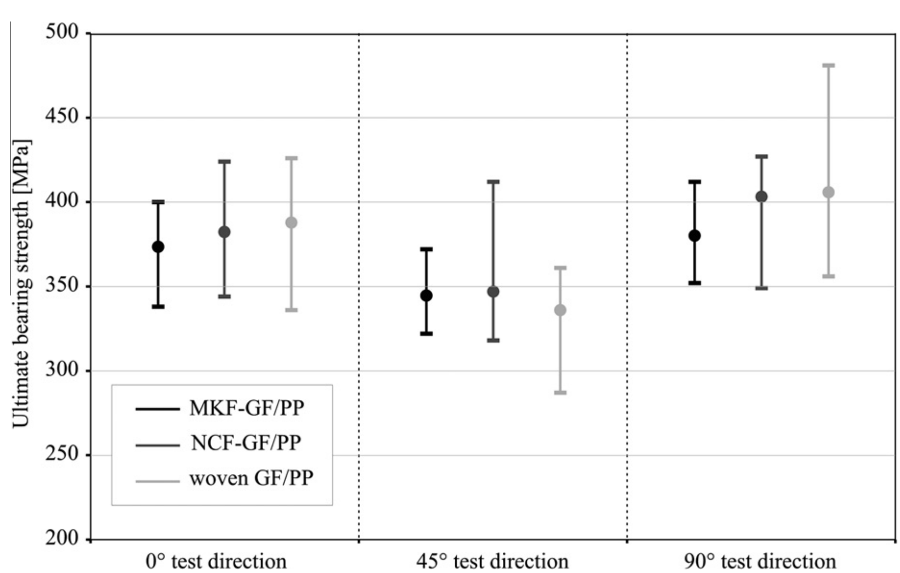

Fig. 8. Mean values and scatter of the ultimate bearing strength.

Table 6
Damping values tanδ (–) of the tested materials.

Composite	At ambient temperature			At 80 °C		
	0°-test	45°-test	90°-test	0°-test	45°-test	90°-test
MKF-GF/PP	0.03183	0.03056	0.03031	0.05257	0.05772	0.05011
NCF-GF/PP	0.03034	0.03151	0.02490	0.05063	0.06219	0.04437
Woven GF/PP	0.02861	0.03267	0.03008	0.04863	0.05862	0.04901

sizing and the matrix in the course of composite consolidation. The local properties, such as thermal, mechanical, chemical, and morphological characteristics are different to the ones of the surrounding bulk matrix. Nowadays, the existence of an transition region between fibre and matrix is widely accepted and new characterisation methods revealed locally different properties within a region of a few tens to a few hundreds of nanometers [23–27]. Sizing chemistry and interdiffusion play a great part in the development of such interphases and when the sizing layer becomes the "weak point" of the system, failure occurs within it [26,28–30].

In order to realise a mechanically strong fibre/matrix interphase in GF reinforced PP composites, different strategies have been pursued resulting in distinct levels of fibre/matrix bond strength. Besides numerous micromechanical approaches, transverse tensile tests on unidirectional composites provide one possibility for assessing the interface properties on the macro-mechanical level. Fig. 9 shows the transverse tensile strength of continuously reinforced, unidirectional GF/PP composites with a GF volume fraction of 50%. Irrespective of the applied sizing system it becomes evident that the modification of PP with maleic anhydride grafted PP (MAH-PP) is crucial for the transverse tensile strength, due the non-polar nature of PP [29,31]. Even in combination with the GF treated with sizing MAH-PP1, only values of around 5 MPa are obtained for the unmodified PP, although for a MAH-PP modified matrix this sizing results in the highest transverse strength of 22.2 MPa. Furthermore, Fig. 9 shows the influence of film former variation on the transverse tensile strength and demonstrates the need for careful tailoring of the sizing formulation.

Another issue which is of relevance when dealing with commingled yarns is the surface modification of the polymeric filaments. Melt-spun polymeric filaments like PP are commonly manufactured by applying an additional spin-finish onto the filaments serving as a lubricant and processing aid. Although this is essential for the process itself it has a detrimental effect on the transverse tensile strength of the composites as those systems are not designed for enhancing fibre/matrix bond strength. Moreover, the application of different film former systems in combination with a MAH-modified matrix and without any spin-finish on the PP-filaments was evaluated with regard to the transverse tensile strength of the composites. All film formers used are based on MAH-PP enhanced compatibility, however, distinct mechanical properties are obtained depending on the characteristics of each system, ranging from 7 to 22.2 MPa. Hence, the careful choice of the sizing constituents as well as an understanding of interphase formation of the given system [32] are necessary for strong fibre/matrix bonding.

A further possibility to enhance interface strength is the incorporation of nanofillers into the GF sizing, thus modifying the interphase properties [33,34]. Additionally, the incorporation of electrically conductive nanoparticles, e.g. carbon nanotubes, allows functionalising composites interphases by realising interphase sensors suitable for health monitoring of composites and early defect warning [34–37].

5. Conclusion

Textile-reinforced thermoplastic composites made of hybrid fabrics have been developed as an alternative to textile composites with thermoset matrices for the application in the automotive industry. The possibility for a rapid and cost-effective manufacturing and partially higher mechanical properties are amongst the advantages that these materials offer compared with conventional composites. However, at present time, the mechanical behaviour of this new material class is almost unstudied. Hence, the aim of this study was to contribute in this area providing experimental data concerning typical load cases that are relevant for automotive applications.

In this context, a novel 3D-textile reinforced composite, a so-called multi-layered flat bed weft-knitted glass fibre/polypropylene composite, was compared with two benchmark materials (a woven GF/PP composite and a NCF-GF/PP composite). By performing different experimental test, it has been shown that the advantages of this new material become apparent if out-of-plane loading

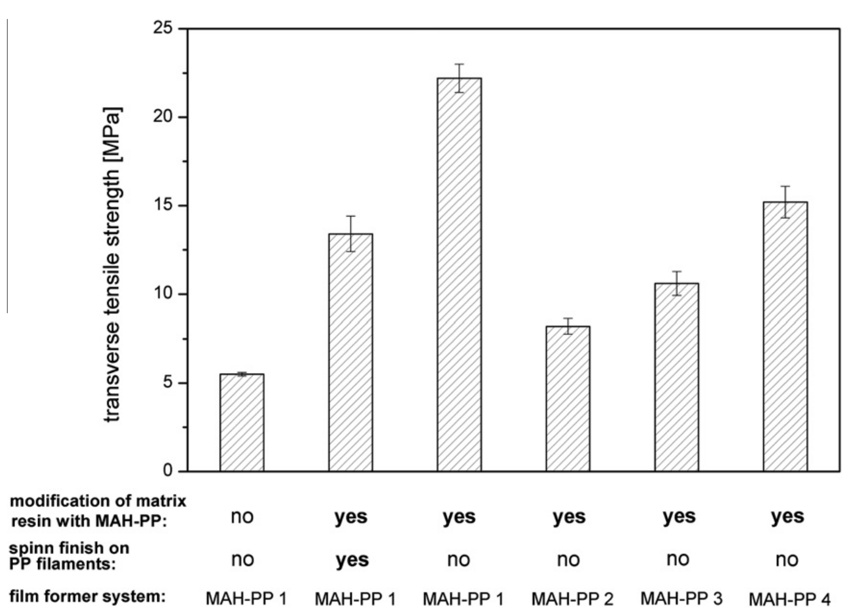

Fig. 9. Effect of differently modified GF/PP commingled yarns on the transverse tensile strength of unidirectional composites made thereof (GF content is 50 vol.%).

is involved or three-dimensional stress states occur. Especially the energy absorption capability of the MKF-GF/PP composites is significantly higher than of other materials because the textile architecture of the 3D stitching yarn systems provide an additional load carrying capability in *z*-direction. Together with their excellent drape behaviour, that makes the MKF-GF/PP composites most interesting for crash and impact applications in automotive parts with complex geometry. Although the fibre volume content of the MKF-GF/PP composite was slightly lower than in the benchmark materials, the in-plane properties are comparable in almost all cases. It has been exemparily shown that the in-plane properties of such 3D-textile reinforced composites can be further enhanced if the fibre/matrix interphase is strengthened.

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