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Stitched glass/PP composite. Part I: Tensile and impact properties

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ABSTRACT

Stitching has proven to be an effective way to increase the through-the-thickness mechanical properties of fibre-reinforced polymer composites. However, there are rare investigations which concentrate on the stitching effect on fibre-reinforced thermoplastic polymer composite, particularly under different temperature environments. Here, we investigate the tensile and impact behaviours of stitched glass/polypropylene woven composites. The effect of various sewing threads, stitch row orientations, and spacing are evaluated. Our data indicate that the stitching in through-the-thickness direction considerably increases the impact damage tolerance especially at low temperature. In addition, glass sewing threads does not deteriorate the tensile performance of the stitched composite. The study of ductile ratio (D.R.) shows that suitable sewing thread can reduce the sensitivity of ductile behaviour of composite to the variation of temperature. A strong correlation of energy absorption with respect to sewing thread fracture work in relation to its fibre volume fraction was found.

1. Introduction

Advanced fibre-reinforced composites have been widely used for structural components and engineering applications. Laminate composites usually exhibit low out-of-plane strength and low damage resistance, which leads to internal failures, such as delamination. Additionally a low damage tolerance leads to inferior mechanical properties for comparably small damages. Therefore, composite parts are restricted to load or strain levels far below their potential during service. To enhance the damage resistance and tolerance as well as damage characterization of composites, several techniques are developed and reviewed [1,2]. These techniques have been the subject of much interest and extensive research, namely tough matrix materials [3], hybrid fibre composites [4,5], interleaving strips [6], modification of fibre/matrix interface [7–10] as well as 3D-weaving and braiding [11]. The practical advantages of these techniques in terms of improvement of interlaminar fracture toughness, reduction of damage area, enhanced energy absorption capability and improved residual compression-after-impact (CAI) strength are widely recognized. However, these approaches have some limitations such as high material and fabrication cost for developing a new matrix material and modifying the fibre/matrix interface and low in-plane strengths for 3D-woven and 3D-braided composites [12–14]. Recently, stitching the reinforcement in through-the-thickness direction based on sewing technique is emerging as a new method because of its low costs, quick process and simple operation. Besides its ability in strengthening laminate in the thickness direction, stitching exhibits benefits such as ensuring geometric accuracy with over-edge stitching [15], holding preform plies in its own position to avoid slipping, joining 2D preform pieces to form 3D structures and assembling small parts together to complete larger structures [16].

Because of the complexity of composite structures special sewing techniques have been lately developed. Single-side stitching techniques like tufting, single thread blind stitch, two-needles-two-threads and two-needles-one-thread sewing techniques are capable to complete the stitching from only one side [17], so that they are suitable for complex structures. Robot- and CNC-control techniques ensure near-net shape and reproducibility. Many efforts have been made to investigate the stitching effect on in-plane and out-of-plane mechanical properties of fibre-reinforced thermosetting polymer composite, particularly the impact properties of stitched composites. Improved damage tolerance and significantly reduced delamination area but decreased tensile strength for stitched composites compared with unstitched ones are extensively reported [7,8,18–20]. It is explained that the stitching serves to suppress the delamination and to carry the load. In this way, stitches which are located vertically to crack propagation direction prevent crack opening effectively. The so-called bridging effect caused by debonding from matrix and crack of sewing thread largely increases the toughness of composite. The balance of fibre fracture and fibre debonding from matrix is proved to be influenced by fibre strength, modulus, and interfacial strength [21]. Besides, stitching improves Mode I interlaminar fracture toughness and reduces the influence of in-plane fibre orientation [22].

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In contrast, a few studies proved that the stitching does not induce any significant improvement in damage resistance [23,24]. Jang studied Charpy impact behaviour of stitched composite made of Kevlar fabric and epoxy resin [25]. Although stitched composites are superior in delamination resistance, the unstitched samples absorbed more energy than stitched ones. So far, sewing approach is mainly limited to the application of fibre-reinforced thermosetting plastic composite such as carbon/epoxy and glass/polyester. Recently there is a growing interest in the use of thermoplastic resins as matrix materials instead of thermosetting matrix. Besides the advantages like low-cost manufacturing and possibility of recycle raw material, thermoplastic composites have advantages with respect to good damage tolerance and impact toughness [26]. However, it has not been reported up to now how the stitching influences the mechanical properties of fibre-reinforced thermoplastic composites, particularly under different temperature conditions. Except of Kevlar yarn, other kinds of sewing thread materials have also been rarely investigated.

The purpose of this study is to investigate the effect of the stitching on tensile strength and impact behaviour of a fibre-reinforced thermoplastic composite made of glass filaments and polypropylene (PP) filaments. The effects of different sewing threads, stitch row orientations, and stitch row spacings as well as temperature effect on the impact properties were detected. Impact properties were studied using an instrumented Charpy impact approach. A new PBO (polyphenylenbenzobisoxasol) thread was chosen as sewing thread to find out whether this high strength thread will increase the impact toughness.

2. Experimental

2.1. Materials

Twintex® – fabric (Saint-Gobain Vetrotex) made of E-Glass filaments and polypropylene filaments (PP) was used in this study. This twill weave fabric consists of the same number of warp yarns and weft yarns per unit area. The area weight of Twintex® – fabric is 745 g/m^2. The glass fibre volume fraction is 35% and the PP volume fraction 65%. A size of 274 mm $\times$ 274 mm was cut from Twintex® – fabric. Four plies for tensile testing were stacked in the same orientation and then stitched using an industrial plain stitch sewing machine (Altin Textima). The same procedure was done on six plies for impact testing. Applied sewing threads for both tests are given in Table 1. Lock stitch with 4 mm stitch length was chosen for tests. The stitches were in straight rows and spaced evenly apart along the length or across the width of the preform. Then these staples were processed in a mould which was pressed at 200 °C and with a pressure of 0.4 MPa for 4 min in a programmable press with built-in water cooling system. Specimens without stitches were also processed and tested in the same procedure for comparison with the stitched specimen results. For tensile testing, the laminates of four ply plates were cut into rectangular specimens with a width of 25 mm and a length of 250 mm (Fig. 1a and b). For impact testing, the un-notched specimens were cut from laminates of six ply plates at a dimension of 3 mm $\times$ 8 mm $\times$ 85 mm. The detail dimensions, stitch rows, and stitch row orientations of specimens are given in Fig. 1c and the specifications of stitching as well as temperatures for mechanical testings are shown in Table 1.

2.2. Characterization

2.2.1. Tensile test

The tensile tests of the specimens in accordance with DIN EN ISO 527-4 were performed in a tension machine (Zwick/Roell) driven at gauge length of 150 mm with a crosshead speed of 2 mm/min. Each system was evaluated by at least nine single tests. Error bars in all figures of this paper represent standard deviations.

Table 1
Sewing threads listing and specifications of stitching for specimens of both tensile and Charpy impact testing.

	Symbols
Materials of sewing threads	
Without stitching	ON
Glass fibre, 132 tex, tensile force 62 N, loop force 47 N	GF 132
Glass fibre, 208 tex, tensile force 104 N, loop force 82 N	GF 208
Glass fibre, 282 tex, tensile force 130 N, loop force 108 N	GF 282
Glass and PP-filaments, 646.7 tex, fibre volume fraction: GF 82.5%, PP 17.5%	GF/PP
Glass and PP-filaments, 132 tex, fibre volume fraction: GF 24.4%, PP 75.6%	mGF/PP
Polyphenylenbenzobisoxasol, Zylon®	PBO
Polyester as needle thread, cabon fibre yarn as bobbin thread	PES-OF, CF-UF
Twist of polyester yarn with thin carbon yarn	PES/CF
Polyester sewing yarn, 107 tex	PES
Polyetheretherketon, 72 tex	PEEK
Stitch specification	
Stitch length	4 mm
Stitch row orientation	0°, 90°
Stitch row spacing	
Tensile	8 mm, 4 mm
Charpy impact	3 mm, 1.5 mm
Temperature	
Tensile	20 °C
Charpy impact	20 °C, 0 °C, −20 °C

2.2.2. Charpy impact test

The Charpy impact tests were carried out using an instrumented impact pendulum (Zwick/Roell) in accordance with DIN EN ISO 179. The principle is shown in Fig. 1d. The machine was equipped with load cells used for measuring the impact force. The impact energy was calculated by integrating the area under the load–displacement curve and by dividing this number by the cross sectional area of the specimen. Specifically, absorbed impact energy, W_B, and impact toughness, a_{cU}, are calculated according to

$$W_B = E_a - E_b \tag{1}$$

$$a_{cU} = \frac{W_B}{b \cdot h} \tag{2}$$

where E_a and E_b are potential energy before and after impact. W_B, b and h are absorbed impact energy, width and thickness of specimen, respectively. All specimens were tested at the same impact energy of 15 J. Three groups of specimens, at least seven for each group, were kept at temperature conditions for 2 h, were tested at temperatures of −20 °C, 0 °C and 20 °C, respectively.

Fig. 1d also shows a typical force–deflection curve derived from an impact test on a stitched composite. The peak force (F_m) is the maximum force that the specimen can sustain on fracture, which indicates the beginning of significant damage. The associated energy absorbed up to this point is symbolized by E_m and it represents the energy to initiate crack. After F_m, the dropping off in force indicates crack propagation. E_p represents the energy absorption in this phase. The total energy absorption E_t is

$$E_t = E_m + E_p \tag{3}$$

which is the area under the entire force–deflection curve.

To represent the ability of material plastic deformation during fracture propagation process, ductile ratio (D.R.) which is the percentage of energy absorption E_p divided by total energy absorption E_t is defined as [27]

$$D.R. = \frac{E_p}{E_t} \tag{4}$$

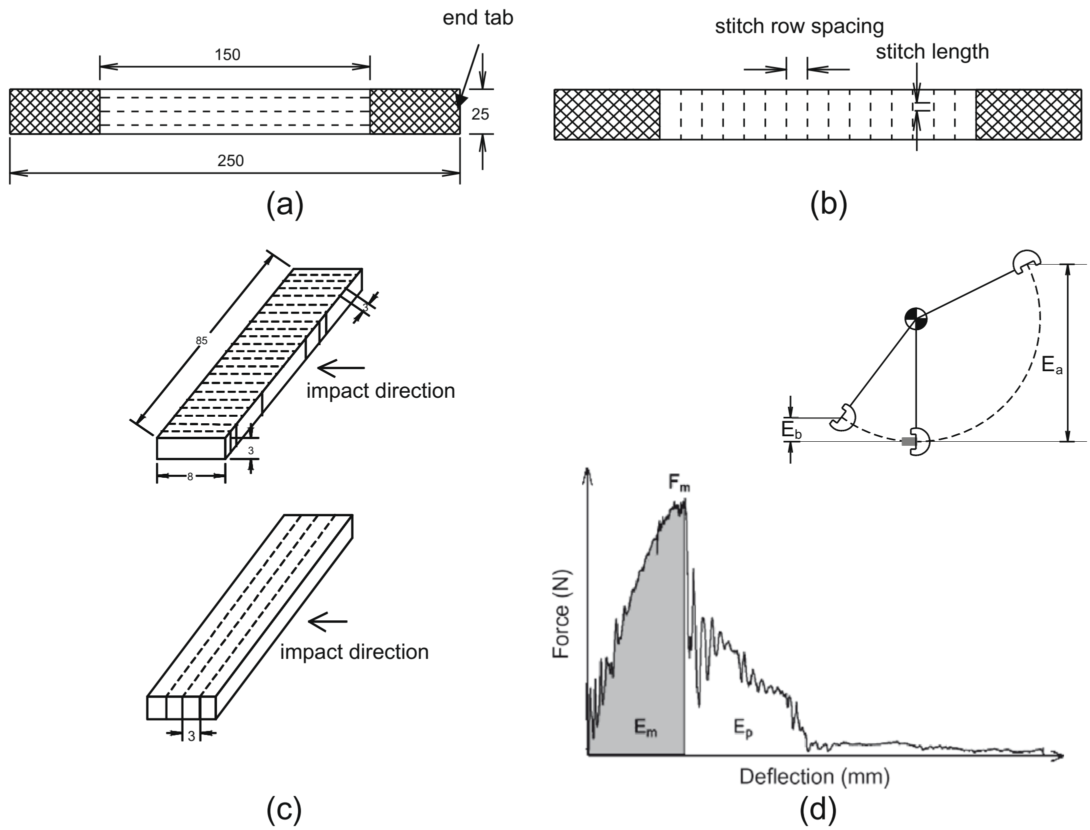

Fig. 1. Specimen dimension and stitch row orientations for tensile tests and Charpy impact tests: (a) 0° stitch row direction for tensile tests, (b) 90° stitch row direction for tensile tests, (c) 90° and 0° stitch row direction for Charpy impact tests, longitudinal and transverse with respect to the hammer edge, and (d) schematic diagram of Charpy impact measurement and schematic diagram of E_m and E_p of a force–deflection curve.

3. Results and discussion

3.1. Tensile properties

The first set of experiments investigates tensile strengths and modulus of unstitched and stitched composites. Except of sewing thread GF/PP, as shown in Fig. 2a, the stitching does not greatly change either tensile strength or modulus. It is supposed that the decrease in tensile strength of specimens with GF/PP-sewing thread arises from severe undulation around the stitches caused by its thick sewing thread (647 tex) which leads to a degradation of the laminate integrity. Generally, stitching has some drawbacks on the tensile strength like stress concentration at the stitch point, fibre misalignment, crimping of fibres, and fibre breakage arising from needle perforation. Therefore, the general degradations of in-plane strength were caused by stitching as reported by most of the literature [7,28,29]. Only one previous study reported an increased tensile strength and elastic modulus after stitching [8]. In this study, the most sewing threads do not reduce the tensile strength, which is inconsistent with the most reported cases. We believe that fibre breakage caused from stitching can be neglected in this work, since the stitching was performed on dry preforms. During tensile loading, various cracks (fibre/matrix interfacial debonding, delaminations, etc.) occur between plies and filament bundles of woven composite. Stitching in thickness direction inhibits these cracks, particularly delamination and crack propagation. Therefore, it retains the tensile strength. Importantly, our sewing thread increases the fibre volume fraction in 0° direction, which is parallel to load direction. It is believed that an increase in the fibre volume fraction resulting from additional sewing threads slightly increases the strength of a stitched composite [30]. These advantages compensate the reduction of strength due to fibre undulation. As a whole effect, stitching does not decrease the tensile strength of glass/PP woven composite.

Fig. 2b shows the effect of stitch row directions on tensile strength. As expected, the tensile strength of composite stitched in 0° (parallel to loading direction) is higher than 90° (transverse to loading direction) stitch row direction. Similar results of higher compressive and flexural strength as well as creep resistance were reported for the stitch rows aligned parallel to the loading axis in comparison of transverse [31]. The load-bearing fibre volume content in 0° direction is unchanged and matrix strength is of minor influence. In contrast, the 90° stitched specimen strength highly depends on strength of both the polymer matrix and interface adhesion. The stitching might introduce voids and poor interfacial adhesion or creates locally stress concentration leading to a reduction in strength. The specimens with 90° stitching were usually broken along the stitch lines. Besides, stitching aligned in transverse direction (90°) to the load direction causes crimping of the 0° (load-bearing) fibres which also accounts for the reduction of tensile strength [30]. It is unclear from our own data so far which of the above mechanisms are dominated, thus further research is desired.

3.2. Impact toughness

The impact toughness values of unstitched and stitched composites at different stitch row directions and temperatures are summarized in Table 2. Overall, most stitched specimens have higher impact toughness than the unstitched ones (ON). The unstitched specimens show better impact properties at higher temperature than those at lower temperature. Apart from specimens

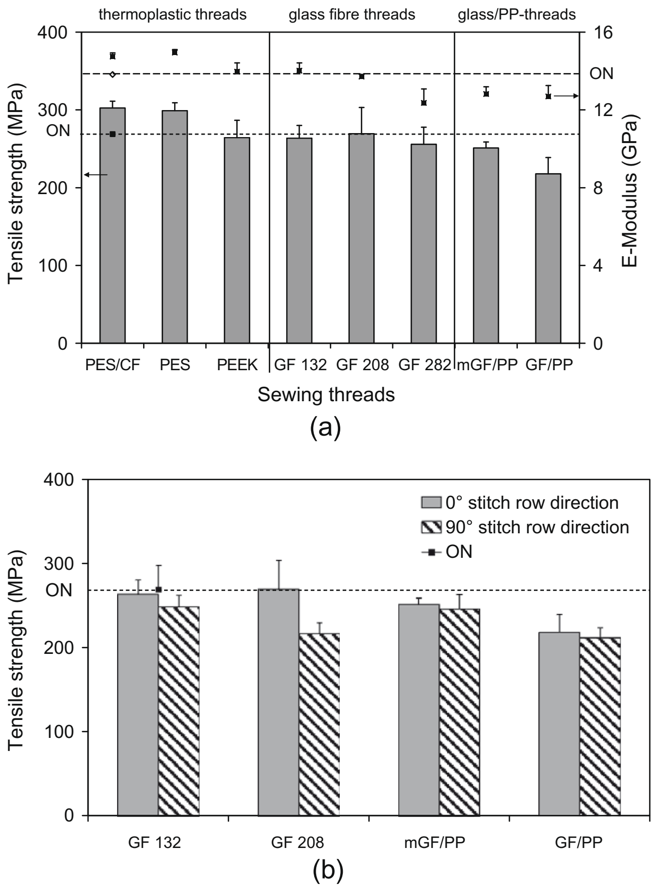

Fig. 2. Effect of (a) sewing threads on tensile strength and modulus of unstitched specimens and 0° stitched specimens, and (b) stitch row direction on tensile strength. ON for unstitched specimen in dot line.

with PBO and PES/CF sewing threads, most specimens with sewing threads show much higher values of impact toughness at 0° stitch row direction, particularly at low temperatures. Only a marginal effect was found at 90° stitch row direction for different temperatures. The stitching effect on impact responses depends on either structures or properties of sewing threads as being discussed further in following parts.

3.2.1. Effect of stitching, fibre volume fraction and mechanical properties of sewing threads

3.2.1.1. Stitching. Typical force–deflection curves from an unstitched specimen and a stitched specimen with PBO thread tested at room temperature (20 °C) are compared in Fig. 3. The traces of both unstitched (ON) and stitched specimen (PBO) show almost the same linear increase in force to the peak force (F_m) where some damage is initiated. After damage initiation, there is a sharp dropping off in force of the unstitched specimen. This implies that little energy was absorbed in the damage propagation process. However, the trace of stitched specimen shows a dropping off in several stages after the specimen reaches F_m. Hence, the gradual dropping off leads to a much higher deflection value associated with much more energy absorption. Therefore, in this case the total energy absorption of the stitched sample is more than twice higher than that of specimen without stitching. Fig. 4 illustrates fracture photographs of specimens after impact. Long delamination cracks of specimens without stitching can be clearly seen in both Fig. 4a and b. In contrast, the stitched specimens exhibit much smaller delamination (Fig. 4c and d). Fig. 5a and b illustrate sketches of fracture mechanisms, where the entire energy absorption is mainly contributed by delamination, fibre/polymer fracture work and fibre pull-out energy for specimens without stitching (Fig. 5a). Due to complex damage failures of each specimen, the scatter of the impact toughness values of unstitched specimens is quite high. For the stitched cases, the crack stops at one stitch or gets through this stitch but stops at the next one (Fig. 4c and d). Compared to the unstitched specimens where the crack spreads quickly along a straight path, tortuous path of the crack characterizes the stitched specimens. In this way, the stitching in the thickness direction inhibits the propagation of delamination and tends to reduce the delamination size and change failure mode [19]. Under impact loading, the crack grows between the plies until it is arrested by the nearest stitch. The stitching threads carry most of the load at

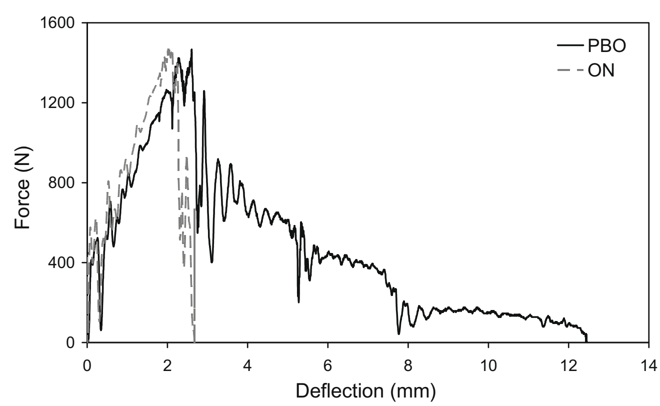

Fig. 3. Force–deflection curves of an unstitched specimen (ON) and a stitched specimen (PBO) including PBO sewing thread at room temperature (20 °C).

Table 2
Impact toughness of composites with different sewing threads at three temperature conditions.

Symbol	Impact toughness a_{cU} (kJ/m^2)					
	20 °C		0 °C		−20 °C	
	0°	90°	0°	90°	0°	90°
ON	138 (±58)		103 (±7)		103 (±11)	
GF 132	187 (±1)	198 (±12)	191 (±35)	183 (±13)	238 (±12)	210 (±13)
GF 208	202 (±12)	200 (±20)	195 (±10)	193 (±9)	241 (±25)	178 (±20)
GF 282	219 (±10)	200 (±10)	225 (±21)	192 (±16)	253 (±23)	215 (±29)
PBO	195 (±14)	175 (±10)	213 (±14)	202 (±14)	175 (±65)	168 (±66)
PES/CF	195 (±21)	193 (±16)	144 (±1)	100 (±8)	130 (±49)	154 (±71)
PES-OF, CF-UF	193 (±17)	162 (±10)	204 (±11)	203 (±18)	245 (±22)	115 (±9)
PEEK	200 (±14)	–	–	–	–	–
GF/PP	250 (±29)	–	–	–	–	–
mGF/PP	213 (±14)	–	–	–	–	–

Values in parentheses represent standard deviations.

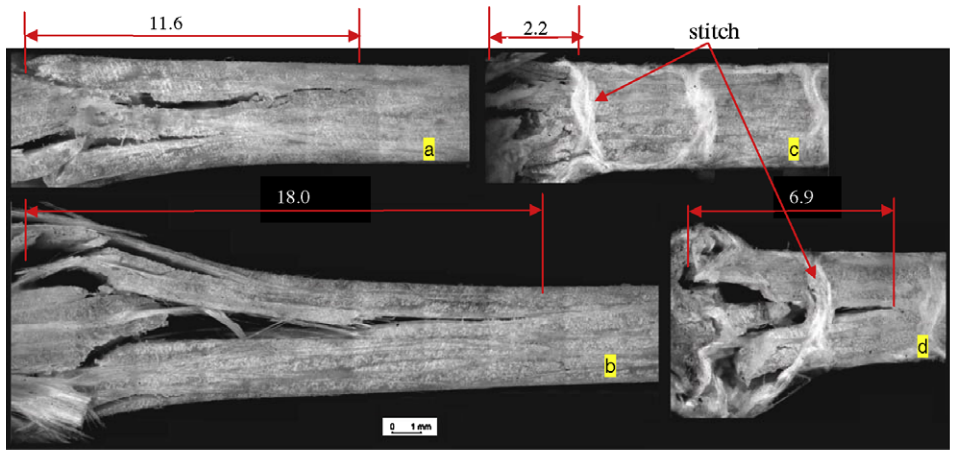

Fig. 4. Light microscope photos of specimens after impact tests: (a) +20 °C, unstitched; (b) −20 °C, unstitched; (c) +20 °C, stitched specimen with sewing thread GF 208; (d) −20 °C, stitched specimen with sewing thread GF 282.

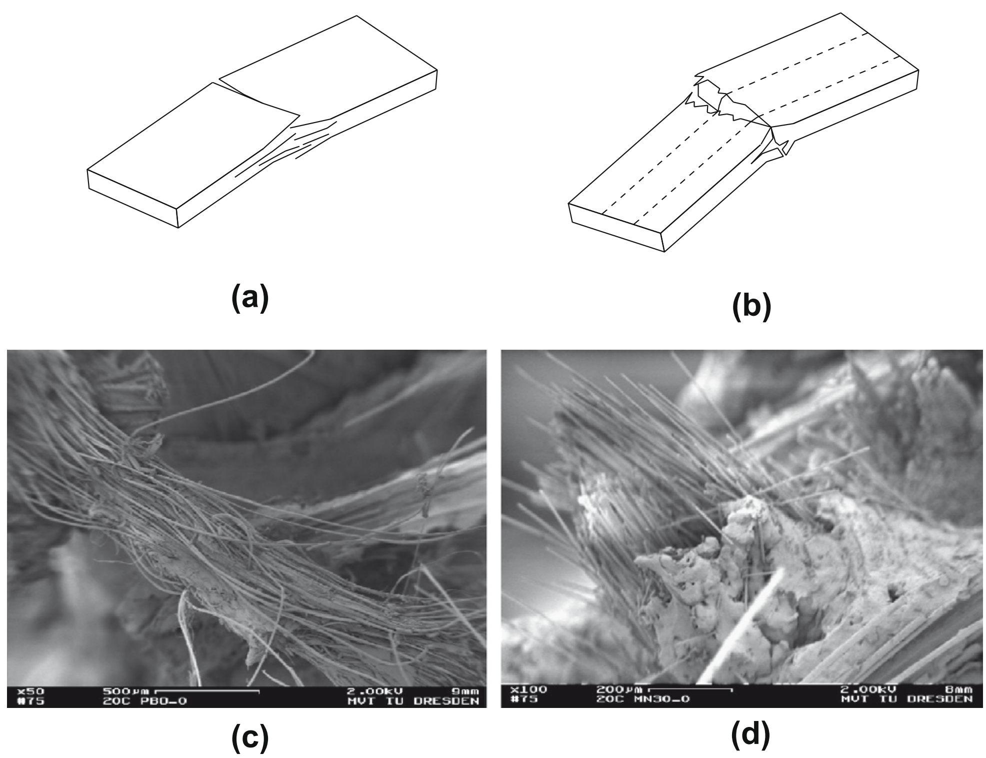

Fig. 5. Fracture mechanism and SEM micrographs taken from impact fracture surfaces of specimens at 20 °C: (a) schematic fracture mechanism of unstitched specimen, (b) schematic fracture mechanism of stitched specimen, (c) SEM micrograph of PBO sewing thread, (d) SEM micrograph of GF 132 sewing thread.

the crack tip, the so-called 'bridging effect'. As an evidence, the stitched specimen GF 282 reaches a higher maximal force (1.77 kN) compared to the unstitched one (1.49 kN) obtained from the force–deflection curve. The stitching threads reduce the stress intensity in the surrounding matrix and higher loads are required to propagate the crack through the matrix [32].

By observing impact fracture surfaces (Fig. 5c and d), the fracture of stitched specimen includes additionally sewing thread pull-out from composite and/or sewing thread breakage during loading. The two fracture behaviours are caused by the interaction of the third directional fibres with the delamination. Therefore, crack dissipates more energy during the propagation process than that of "pure" delamination in the corresponding 2D laminates [33]. Since delamination and the crack propagation process are associated with fibre breakage, interfacial debonding and pull-out, sewing thread strength and interfacial bonding strength play an important role in the energy absorption. The effect of sewing thread strength will be discussed in the next section. Very few PBO fibre breakages are found and the smooth surface of the PBO sewing thread indicates a weak bonding adhesion (Fig. 5c). In sharp contrast, the glass sewing threads show extensive fibre fracture and a shorter pull-out length (Fig. 5d) because of better interfacial adhesion with optimized surface sizing [34]. These evidentially show why the impact toughness is lower for the stitched composites containing high strength PBO sewing threads, compared with those containing glass sewing threads (see Table 2). It should be noted that the bonding effect is only achieved on the outer ply of the sewing thread (Fig. 5d). Sewing thread fibres are twisted tightly which improved load transfer from fibre to fibre. Besides, abrasion caused by friction of sewing thread through needle eye and fabric is reduced. However the twist inhibits bonding inside the sewing thread [35] especially by using matrix material like PP with relatively high viscosity. It is interesting to note that most of stitched specimens are only partially broken and many stitches on the crack location are still intact after the breakage of the specimen (Fig. 5b). It improves the safety of material, since the sewing threads hold the fracture parts of the specimen together and keep the integrity of the composite. It is well known that a large crack resulting from delamination leads to a huge shortening of lifetime of structure service. Once the damage due to impact is reduced by stitching, the residual properties should be relatively improved [19]. Overall, stitching restricts the delamination size and propagation resulting in improved impact properties.

3.2.1.2. Fibre volume fraction. It is also important to note that stitching increases slightly the fibre volume fraction in the composite. In this study volume fraction of glass fibres in composite is 35%. By using glass sewing threads GF 132, GF 208 and GF 282, increases of the fibre volume fraction of 1.6%, 2.6% and 3.5% are detected, respectively. This could also be one of the reasons that the stitched specimen reaches higher energy absorption, which is in agreement with the reported fracture energy increasing with the fibre volume fraction [36]. An increased tendency of impact toughness with respect to fibre volume fraction of GF 132, GF 208 to GF 282 can be clearly seen in Table 2.

3.2.1.3. The maximum tensile and loop forces of sewing thread. The glass sewing threads (Culimeter) with different tensile forces were chosen for this test. Both the maximum tensile and loop forces of GF 282 are significantly higher than those of GF 132 (Table 1). As presented in Table 2, impact toughness also reaches a higher value for composite containing GF 282 sewing threads than that for composite with GF 132 sewing threads. This indicates that improved impact toughness can be achieved by using stronger sewing thread.

3.2.2. Influence of stitching structures: orientation and stitch row spacing

3.2.2.1. Stitch row orientation. The typical force–deflection curves of specimens stitched with GF 282 sewing thread of both stitch row orientations (Fig. 1c) are presented in Fig. 6. It can be seen that the force of specimen having 0° stitch row orientation gradually decreases after F_m (Fig. 6a), whereas the force of the 90° oriented stitch rows shows almost a linear decrease (Fig. 6b). Therefore, the arrangement of stitch rows influences the impact failure propagation behaviour. Stitching caused localised stress concentration at stitch holes which leads to local reduction of strength properties. A splitting damage along the stitch line is observed from 90° stitch direction specimen (Fig. 6b). Because of relatively low volume concentration of stitching fibres in the composites, the impact toughness of the 90° stitch row direction is only marginally lower than that of the 0° stitch row direction (Table 2). Nevertheless, it is still significantly higher than those of unstitched specimens. It implies that the delamination is the dominate fracture mechanism during impact loading and the stitching restricts delamination significantly on the specimen regardless of the strength degradation and stitching direction.

3.2.2.2. Stitch row spacing. Since stitching in a glass/PP composite contributes marginal differences to energy absorption of E_m, we applied here two approaches by increasing E_p to improve the impact toughness. The first approach is using stronger sewing threads as described above. Another one is to decrease the slope of the force

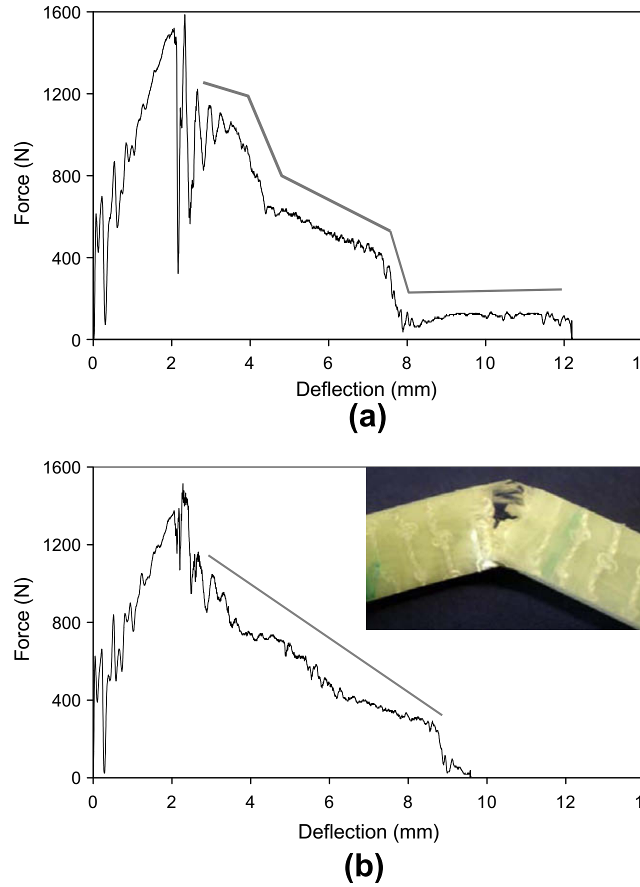

Fig. 6. Force–deflection curve of stitched specimen with sewing thread GF 282 in direction of (a) 0° and (b) 90°. Insert shows impact fractured specimen with sewing thread in 90° direction.

reduction after F_m so that a larger deflection and hence higher E_p can be achieved. This can be realized by reducing stitch row spacing, so that more stitches which are aligned transversely to the load direction can carry load. In order to compare the impact behaviour in propagation stage, stitch row spacings of 3 mm and 1.5 mm in 0° stitch row orientation were chosen. As shown in Fig. 7, the slope of force reduction of samples of 1.5 mm stitch row spacing is gradually compared to the samples containing 3 mm stitch spacing. The 1.5 mm stitch space results in double

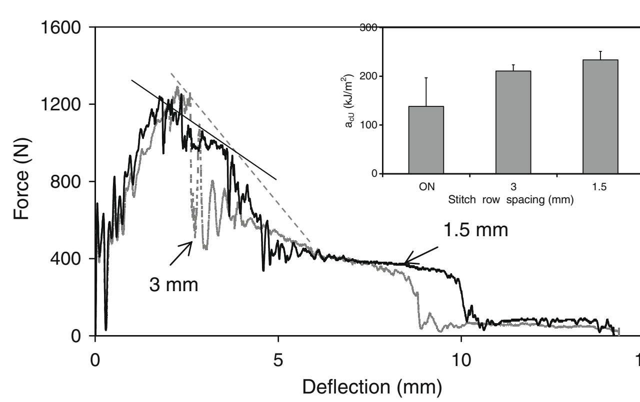

Fig. 7. Force–deflection curves of stitched specimen with sewing thread GF 208 at 20 °C, stitch row spacing of 3 mm and 1.5 mm. Insert shows comparison of impact toughness of stitched specimen with GF 208 in 3 mm and 1.5 mm stitch row spacing. Error bars represent standard deviations.

number of stitches in carrying the load, therefore more energy will be dissipated and higher impact toughness is reached. This indicates that more stitch rows, which locate perpendicular to the impact load, slow down the force reduction and thus increase the fracture toughness.

3.2.3. Effect of temperature

The impact toughness values are compared at different temperatures for both unstitched and stitched specimens. As shown in Fig. 8a, the impact toughness of specimens without stitching is lower while the temperature is decreasing because the polymer becomes more brittle. In sharp contrast, the impact toughness of stitched specimens tends to increase with decreased temperature. At −20 °C the impact toughness of stitched specimens including glass sewing thread (GF 282) is almost 2.5 times higher than that of the unstitched specimens. Such a considerable improvement is unexpectedly gained by stitching.

At low temperatures, less impact energy is supposed to be absorbed through polymer plastic deforming. The matrix material PP performs higher strength and stiffness which causes a light increase in value of E_m. A decrease in deflection results in a significant reduction of E_p (Fig. 8b). Therefore, the total energy absorption E_t of unstitched specimens decreases considerably when the temperature lowers down. Since PP polymer gets stiffer at low temperature, delamination area is much larger and the crack tends to spread more quickly. Accordingly, the area of suppressed delamination is growing for stitched composites. Associated with the larger influence area, the stitching has probably much stronger effects. This is why the impact toughness of stitched composite has positive correlation of decreasing temperature.

Fig. 9a compares E_m and E_p of both unstitched and stitched specimens with glass sewing threads at different temperatures. The values of E_m do not show apparent differences between unstitched and stitched specimens. This indicates again that stitching does not significantly influence the energy absorption before the peak force is reached. However, the values of E_p are strongly influenced by stitching at three temperature conditions. The stitched specimens exhibit much higher energy absorption E_p than specimens without stitching. Interestingly, the difference of E_p is considerably high at low temperature. Importantly, the stitched samples have E_p value which is over 10 times higher than unstitched one at low temperature. Our data implies that essential improvement on impact toughness of a fibre-reinforced thermoplastic composite at low temperatures can be achieved by stitching.

3.2.4. Ductile ratio

Comparison of ductile ratio (D.R.) of both unstitched and stitched composites is given in Fig. 9b. The higher D.R. from all stitched composites indicates that stitching considerably increases the capability of plastic deformation in crack propagation process. For unstitched composite and stitched composite with PES/CF sewing thread, the D.R. value is lower when the temperature lowers down. On the contrary, the D.R. values of stitched composites with glass sewing threads do not obviously vary according to different temperatures. It implies that the stitching with suitable sewing threads can reduce the sensitivity of ductile behaviour of composite when the temperature decreases.

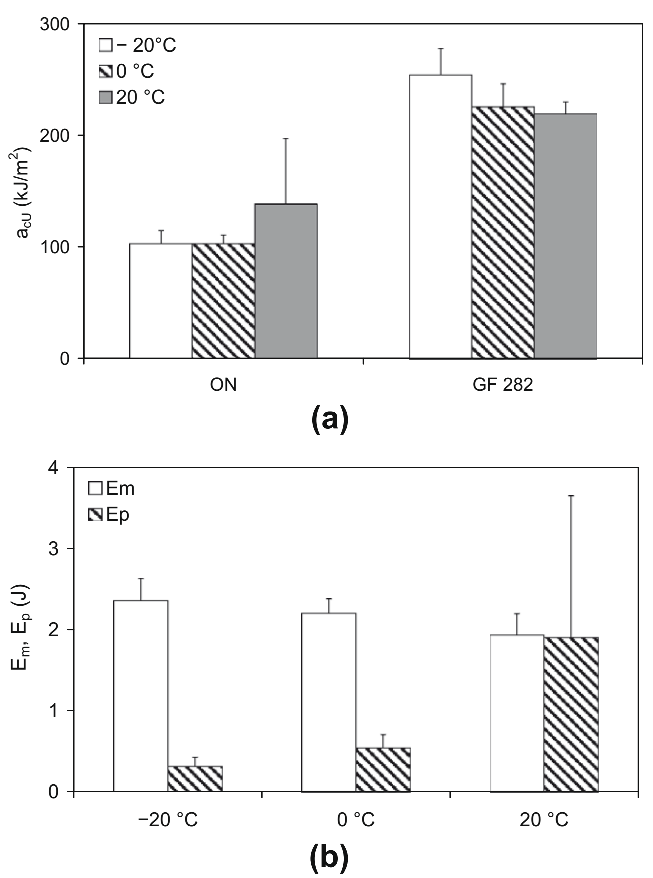

Fig. 8. (a) Impact toughness of unstitched specimen (ON) and stitched specimen (GF 282) at different temperatures (−20 °C, 0 °C and 20 °C), 0° stitch row direction. (b) Comparison of energy absorption of E_m and E_p for unstitched specimen at different temperatures.

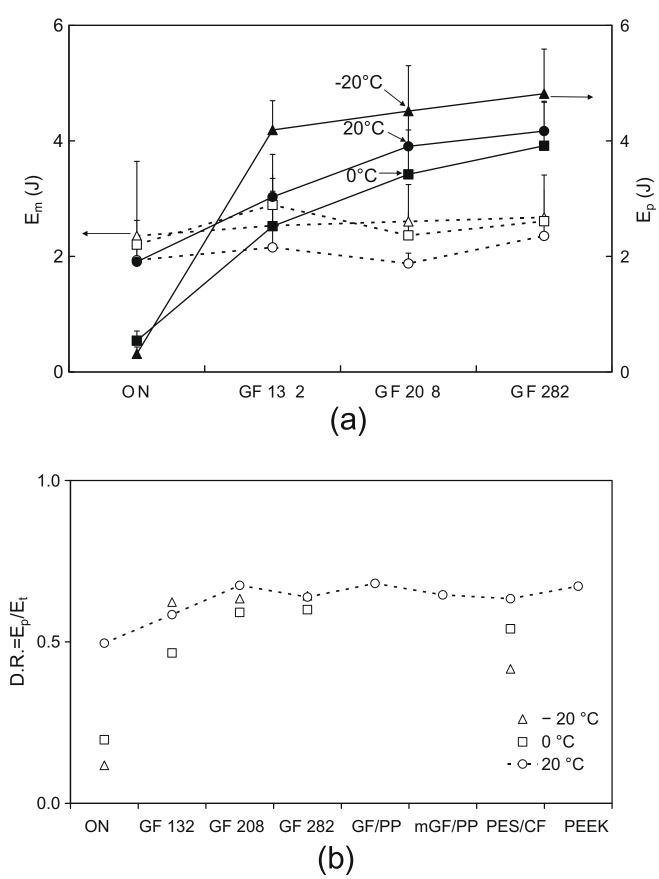

Fig. 9. Comparison of (a) E_m and E_p for unstitched and stitched specimens at different temperatures, (b) ductile ratio D.R. with respect to different sewing threads.

3.2.5. Energy absorption and sewing thread fracture work with its fibre volume fraction

The whole energy absorption (E_t) during impact fracture of stitched composites can be roughly attributed to fracture energy of base composite (E_c), and bridging mechanism of sewing thread breakage energy absorption (E_s) and its pull-out fracture energy from base composite (E_{pl}), as described by

$$E_t = f(E_c, E_s, E_{pl}). \tag{5}$$

where E_c is constant for all sewing thread systems since they have the same base composite. E_{pl} depends on bonding behaviour of sewing thread in base composite and is unknown for different sewing thread systems in this study. $E_s = W_s\varphi_s$ describes the breakage energy absorption of sewing thread by its volume fraction in base composite. W_s is the work done by tensile load on single sewing thread in Joule and φ_s is fibre volume fraction of sewing thread in percentage in base composite. The experimental data of E_t obtained from experiments against E_s are plotted in Fig. 10. Interestingly, almost all the data fall along a single straight line, showing that E_t increases linearly with E_s. It indicates that the impact toughness of a stitched composite can be increased by using high strength sewing threads and by enhancing stitch density.

Samples stitched with two sewing threads mGF/PP and GF/PP, which contain PP-filaments, show higher E_t values than the inclined line while the data from other sewing threads lie under this line. The higher values are indicative of possible higher E_{pl} which is contributed by pull-out energy of sewing thread. It is also easy to understand that PP inside sewing threads leads to a stronger bonding between sewing thread and base composite, especially for mGF/PP-sewing thread which contains 75.6% PP by volume fraction. The strong linear correlation reveals that by choosing high strength or high strain sewing thread (both of them contribute to fracture work) will enhance impact toughness of a composite. Increasing fibre volume fraction and controlling interface bonding of sewing thread will further improve impact resistance of a stitched composite.

Eq. (5) can be written as

$$E_t = f(E_c, E_{pl}) + kE_s. \tag{6}$$

The slope k of the straight line in Fig. 10 is 1.1, which indicates how strong the stitching influences impact toughness of a composite. This value depends on matrix type, fibre material and textile structure. For composites systems with other matrix materials, such as epoxy resin, the value of E_{pl} could be higher than PP matrix because epoxy could have a better bonding with strengthening fibres. This would likely lead to a higher k value. To determine how the stitching influences impact toughness of other composite materials and how k values are influenced by the interfacial adhesion, further study is needed.

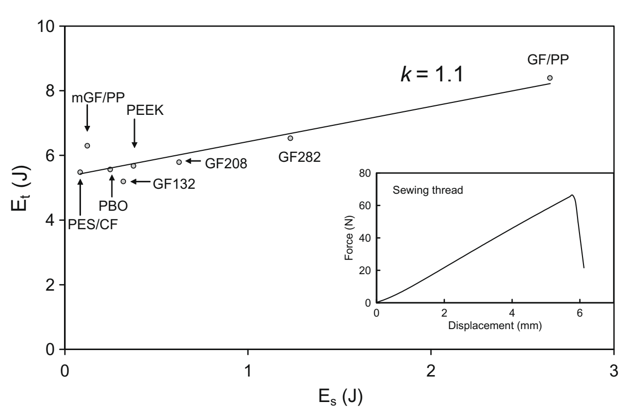

Fig. 10. Dependence of E_t on E_s of different sewing threads. The insert presents a typically tensile force versus displacement curve of sewing thread, where the fracture work of sewing thread is calculated by integrating the area under the curve.

4. Conclusions

In this study, tensile and impact properties of stitched composites made of glass and PP-filaments were investigated. Unlike most reports of literatures, we found that stitching does not reduce tensile strength. Without degradation of its in-plane tensile strength, stitching does enhance impact toughness of fibre-reinforced thermoplastic composites. Remarkable improvements at low temperature of stitched composites were achieved. Besides, stitching structures like stitch row orientation and stitch row spacings change the impact behaviour. Stitching mainly contributes to energy absorption in crack propagation phase. The improvement of ductile ratio (D.R.) by various sewing threads shows that stitching considerably increases the capability of plastic deformation during crack propagation and extra energy absorption is gained through crack bridging mechanism of sewing thread breakage and pull-out. The stitching with suitable sewing thread can reduce the sensitivity of ductile behaviour of composite to the variation of temperature. Our results reveal a positive correlation between whole energy absorption and sewing thread fracture work in relation to its fibre volume fraction. This implication could be useful for potential applications for fibre-reinforced composites by fabricating them with controlled sewing thread systems to achieve improved toughness properties.

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