Strength and failure modes in resistance welded thermoplastic composite joints: effect of fibre-matrix adhesion and fibre orientation

H. Shi*, I. Fernandez. Villegas, H.E.N. Bersee Structural Integrity & Composite, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS, Delft, The Netherlands

* Corresponding author: H.Shi (H.Shi@tudelft.nl)
Tel: +31(0)15 278 9740
Fax: +31(0)15 278 1151
Co-authors: I.FernandezVillegas@tudelft.nl; H.E.N.Bersee@tudelft.nl

Abstract

The strength and failure modes of resistance welded thermoplastic composites were investigated. Special attention was paid to the effect of basic characteristics of the adherends such as fibre-matrix adhesion and fibre orientation. 8HS woven GF/PEI composites were resistance welded. Intralaminar failure was found to be the major failure mechanism for the well welded joints, consisting of either fibre-matrix debonding or laminate tearing. An improved fibre-matrix adhesion was found to result in significantly higher lap shear strength. Besides, the main apparent orientation of the fibres on the welding surfaces was found to have an effect on the strength of the joints.

Keywords

Polymer-matrix composites (PMCs) A, Thermoplastic resin A, Fibre/matrix bond B, Joints/joining E

1. Introduction

In the latest decades, the mechanical properties of high grade thermoplastics have reached a level as good as, if not better than, thermosetting plastics, resulting in thermoplastic composites being increasingly used in the aircraft industry [1]. Due to the intrinsic properties of thermoplastic resins, thermoplastic composites can be welded in a relatively short time. And among the available welding techniques, resistance welding has been regarded as one of the most promising welding techniques because of its advantages such as low manufacturing cost and simplicity of processing. Resistance welded joints are characterised by a heterogeneous weld line composed of a heating element and some extra neat resin.

So far, research on resistance welding of thermoplastic composites has been mainly focused on understanding the influence of the welding parameters, comparative analysis of different types of heating elements and comparative analysis of different adherends. The temperature and degree of consolidation have been acknowledged as the main factors that influence the quality of the welds, and they have been found dependent on the welding parameters such as power input, welding pressure and heating time [2-4]. Processing models have been developed to predict the welding temperature and consolidation degree during the welding process [3, 5-8]. The heating element is not only responsible for heat generation during welding but it also becomes a part of the weld line of the final joints, and therefore it has an effect on the quality of the welded joints. Stavrov et al. [9] compared a metal mesh heating element with a carbon fibre heating element and concluded that the former provided better mechanical performance and weld repeatability. Further research on the effect of the characteristics of stainless steel mesh heating elements on the strength of the joints was carried out by Dubé et al.

[10]. The diameter of the metal wires and the open area were shown as the most important parameters influencing the weld quality. Likewise, the effect of different adherend materials, namely carbon fibre reinforced polyetheretherketone (CF/PEEK), carbon fibre reinforced polyetherketoneketone (CF/PEKK), glass fibre reinforced polyetherimide (GF/PEI), carbon fibre reinforced polyetherimide (CF/PEI), and glass fibre reinforced polyphenylenesulfide (GF/PPS), on the strength of the resistance joints has been investigated [10-13]. Among them unidirectional CF/PEKK welded with a metal mesh heating element resulted in the highest lap shear strength of 52MPa [10]. However, no study has been reported so far on the influence of basic characteristics of the adherends such as the fibre orientation on the welding surfaces and the fibre-matrix adhesion on the mechanical properties of the resistance welded joints, even though intralaminar failure has been acknowledged by different researchers as one of the typical failure modes in resistance welded joints [10-12]. Since fibre-matrix adhesion and fibre orientation are known to influence the intralaminar properties of the composites [14-17], those parameters are expected to have an effect on the performance of resistance welded joints.

The aim of the present work is to gain a deeper insight into the effect of fibre-matrix adhesion and fibre orientation on the mechanical performance of resistance welded joints. An analysis of the influence of those factors on the strength of resistance welded GF/PEI joints was performed with a thorough evaluation of the failure modes. The mechanical properties of the welded joints were evaluated via single lap shear testing and the failure modes of the joins were analyzed through visual inspection, optical microscopy and scanning electron microscopy (SEM).

2. Experimental

2.1. Laminates

The material used in this study was 8HS glass fibre reinforced PEI composite supplied by TenCate Advanced Composites, the Netherlands. Two types of GF/PEI prepreg, SS0303 and TC7781, were used, which only differ in the glass fibre sizing, as listed in Table 1. Due to the weave pattern of the satin woven fabric, the ratio of warp and weft yarns per unit area is different for the two sides of a single ply. In this paper, "warp side" was used to indicate the side where a higher ratio of warp yarns can be seen, while "weft side" was used to indicate the side where a higher ratio of weft yarns can be seen. Furthermore, the main apparent orientation of the fibres (the main direction of the longest visible fibre bundles) is also different on either side of a single ply. Therefore, a laminate with a stacking sequence of $[[(0^{\circ}/90^{\circ})]_n]_s$, where 0° is the direction of warp yarns and 90° is the direction of weft yarns, can be built with two different outer surfaces (see Fig. 1): (1) "Type I" - the main apparent orientation of the fibres in the 0° direction of the laminate and (2) "Type II" - the main apparent orientation of the fibres in the 90° direction of the laminate. Similarly, the laminate: $[[(90^{\circ}/0^{\circ})]_n]_s$ can also be built either Type I or Type II. Since both Type I $[[(0^{\circ}/90^{\circ})]_n]_s$ and Type II $[[(90^{\circ}/0^{\circ})]_n]_s$ laminates have warp outer surfaces while both Type II $[[(0^{\circ}/90^{\circ})]_n]_s$ and Type I $[[(90^{\circ}/0^{\circ})]_n]_s$ laminates have weft outer surfaces, in this paper, Type I-warp, Type IIwarp, Type I-weft and Type II-weft were used to refer to these four types of laminates, respectively.

A hot platen press was used to fabricate the laminates. Before consolidation, the prepreg plies were dried in an oven at 260 °C for 3 hours in order to fully remove any residual moisture and N-Methyl-2-pyrrolidone (NMP, a solvent used in the impregnation process). Then, the plies were laminated and consolidated in the hot platen press at 320 °C under 2.0 MPa pressure for 20 min. After the consolidation process, the adherends were immediately cut out from the laminates using a water cooled diamond saw and then welded or tested. If welding was not performed immediately after the cutting operation, the composite adherends were stored in a desiccator.

2.2. *Heating element*

A stainless steel (AISI 304L) mesh with a plain woven pattern was used as the heating element. In this study, a M200 metal mesh (0.04 mm wire diameter and 0.09 mm open gap width) was used since it is known to provide resistance welded joints with excellent properties [10]. The heating elements were cut out from the mesh sheet into strips of 13mm in width and 250 mm in length. In order to fill the open areas of the mesh and provide a resin rich area between the heating element and the laminates, the mesh was sandwiched between two layers of 60 μ m thick PEI resin films prior to the welding process (no pre-consolidation of the mesh and the extra resin was carried out).

2.3. Resistance welding

The in-house developed resistance welding setup was used in this study, and it was described in detail in literature [18]. A constant power input of 80 kW/m² and a constant pressure of 0.8 MPa were used for the welding. A computer controlled power supply unit (maximum DC output of 45 A and 70 V, Delta Elektronika) was used to provide the welding energy, and two pneumatic cylinders were used to provide the welding pressure. Two blocks of high-density fibre (HDF) wood covered with a layer of 127 μ m thick polyimide film were used as thermal insulators. Adherends with dimensions of 100 mm × 192 mm were single lap welded with an overlap length of 13mm, where the 0° direction of the original laminates was kept parallel to the shortest side of the

adherends, as shown in Fig. 2. Different welding times of 30s, 40s, 55s, 90s, 100s and 120s, corresponding to welding energies of 2.4 MJ/m², 3.2 MJ/m², 4.4 MJ/m², 7.2 MJ/m², 8.0 MJ/m² and 9.6 MJ/m², were used for the analysis of basic failure modes of the resistance welded joints. Later, the heating time was set to 55s for the investigation on the effect of fibre-matrix adhesion and fibre orientation.

Extra welds were performed in order to determine the welding temperatures at each heating time. In these welds two K-type thermocouples (Φ0.1 mm), insulated with polyimide tape, were placed in the middle of the overlap, as schematically shown in Fig.
2. The welding temperature for each heating time was calculated by using the average of the maximum reading of the two thermocouples in at least three different experiments.

2.4. Mechanical testing and characterization methods

Single lap shear tests were used to evaluate the strength of the resistance welded joints. The preferred propagation paths for cracks at the weldline were assessed via both Mode I and Mode II interlaminar fracture tests. The effect of fibre sizing on the laminate properties was quantified through flexural and short-beam shear tests. Detailed information on each type of test as well as the samples used is given below and summarized in Table 2.

2.4.1. Single lap shear test

Single lap shear tests were performed according to the ASTM D1002 standard. Six test specimens were cut from each weld using a water cooled diamond saw into final dimensions of 187.3 mm long and 25.4 mm wide. The tests were performed at room temperature (23±3°C) and relative humidity of 50±5%. A Zwick/Roell 250KN testing machine was used with a constant crosshead speed of 1.3 mm/min. At least six samples

were tested for each individual welding setting. The apparent lap shear strength (LSS) of the joints was calculated as the maximum load divided by the total overlap area. The facture surfaces of the welded specimens were examined visually and by SEM.

GF/PEI laminates made of different types of prepreg and with various stacking sequences were used in this study. For the analysis of the basic failure modes, SS0303 Type I laminates with a $[(0^{\circ}/90^{\circ})]_{4S}$ stacking sequence (Type I-Warp) were used, as shown in Fig. 3. For the investigation of the effect of fibre-matrix adhesion, SS0303 and TC7781 Type I laminates with a $[(0^{\circ}/90^{\circ})]_{4S}$ stacking sequence (Type I-Warp) were used. Finally, for the analysis of the effect of fibre orientation, SS0303 Type I and Type II laminates with both $[(0^{\circ}/90^{\circ})]_{4S}$ and $[(90^{\circ}/0^{\circ})]_{4S}$ stacking sequences (Type I-warp, Type I-weft, Type II-warp and Type II-weft joints) were used.

2.4.2. Fracture toughness tests

Mode I and mode II interlaminar fracture toughness energies, G_{IC} and G_{IIC} , were measured through double cantilever beam (DCB) and end notched flexure (ENF) tests following the ASTM D 5528-01 and Airbus AITM 1.0006 standards, respectively. The modified beam theory was used for calculating G_{IC} values as recommended by the ASTM D 5528-01 standard. A pre-crack, 40 mm long for DCB or 50mm long for ENF, was created by inserting a layer of 25 µm thick Kapton film in the middle plane of the specimens. The longitudinal edges of the DBC and ENF specimens were coated with a thin layer of water-based white fluid to make the visual detection of crack tip more obvious. A Zwick/Roell 20KN testing machine was used for the tests with cross-head speeds of 3 mm/min and 1 mm/min for DCB and ENF tests, respectively. Six samples were tested for each type of specimen.

7

Two types of tests were carried out (see Fig. 4), namely fracture toughness measurements for cracks propagating through the laminate and fracture toughness measurements for cracks propagating within the weld line. For the analysis of cracks propagating through the laminate, both SS0303 and TC7781 GF/PEI laminates with stacking sequences of $[[(0^{\circ}/90^{\circ})]_{4s}]_{s}$ and $[[(90^{\circ}/0^{\circ})]_{4s}]_{s}$ were built, with either Type I or Type II surfaces at the crack opening interfaces, namely Type I-warp, Type II-warp, Type I-weft and Type II-weft. For the analysis of cracks propagating within the weld line, press consolidated instead of welded samples were used in order to exclude the undesirable effects caused by a non-uniform weld quality in crack propagation [19]. SS0303 laminates with a $[[(0^{\circ}/90^{\circ})]_{4s}/M200/PEI]_{s}$ stacking sequence were built for this purpose, where PEI denotes one layer of 60 µm thick PEI resin film. In order to keep the cracks propagating along the mesh-matrix interface and to keep the specimen symmetric, two metal meshes were consolidated inside the GF/PEI laminates with two PEI films in between (middle line). The pre-crack was created in between the two PEI layers.

2.4.3. Flexural and short beam shear tests

The effect of fibre sizing on the laminate properties was quantified through flexural test (3PB, according to the ASTM D790-07 standard) and short-beam shear test (SBS, according to the ASTM D2344 standard). Specimens for the flexural tests were 1.9 mm thick, 12.7 mm wide and 70 mm long, and they were cut out from the SS0303 and TC7781 Type I laminates with $[(0^{\circ}/90^{\circ})]_{4s}$ stacking sequence (Type I-Warp). Following the standard, a span-to-depth ratio of 32:1 and 1mm/min crosshead speed were used. Specimens for the short-beam shear tests were 3.7 mm thick, 7.2 mm wide and 23 mm long, cut out from the SS0303 and TC7781 Type I laminates with $[[(0^{\circ}/90^{\circ})]_{4s}]_s$

stacking sequence(Type I-Warp). According to the standard, a span-to-depth ratio of 4:1 was used, and the test speed was 1mm/min. A Zwick/Roell 20KN testing machine was used in both cases, and at least 6 samples per laminate were tested.

3. Results and discussion

3.1. Failure modes analysis

SS0303 Type I-Warp joints welded with different heating times were tested and their failure modes were analysed. Fig. 5 shows the LSS of the joints, as well as the maximum temperatures measured during the welding process (referred to as "welding temperature" hereafter). The welding temperatures for all the joints were higher than 215 °C (glass transition temperature of PEI) and below 450 °C (temperature at which the PEI polymer starts decomposing [20]). As expected, the welding temperature increased with increasing welding time. The LSS was found to be strongly related to the heating time and showed a similar trend as what has been found in literature [12, 21]. The LSS increased up to a maximum of 32.04 ± 1.7 MPa for the 55 s heating time and subsequently decreased for longer heating times. If the optimum processing interval is defined by LSS values above 80% of the maximum LSS yielded by the welded joints, the optimum heating times for this specific material and set-up fall between 40s and 90s. Due to the influence of the heating element and the non-uniform temperature distribution at the overlap [8], the failure mechanisms of the resistance welded joints significantly differ from the ones of adhesive bonded joints [11, 12]. In this study, the different types of failure modes are organized as follows: (1) interfacial failure, which happens between interfaces not yet affected by the welding process: either the interfaces between the metal mesh and the neat resin or the interfaces between the extra resin and the adherends; (2) mesh tearing; (3) cohesive failure or failure within the weld line,

consisting of mesh-resin debonding and resin rupture and (4) intralaminar failure, consisting of fibre-matrix debonding and/or tearing of the laminates. It follows a detailed description of the failure modes for each distinct welding scenario.

3.1.1. Underheated welds

For the joints welded with a heating time below the minimum processing time, i.e. 30s, the main failure modes are found to be interfacial failure (between mesh-PEI and PEIlaminate interfaces) and mesh tearing. As shown in Fig. 6, interfacial failure can be clearly seen at the fracture surfaces, especially near the edges of the joint overlap. Interfacial failure implies a poor consolidation quality, which is caused by the relatively low processing temperature [8], and it will result in low lap shear strength values.

3.1.2. Welds within the processing interval

Relatively high LSS values (above 28 MPa) were obtained for the joints welded with heating times between 40 s and 90 s. Intralaminar failure (fibre-matrix debonding) accompanied by mesh tearing was found to be the dominant failure mode for all the specimens within this group (see Fig. 7(a)). As a result of the non-uniform temperature distribution across the overlap in resistance welded joints [8], other minor failure modes could also be found, especially for the shortest and longest welding times within this group. These were interfacial failure at the relatively colder edges of the overlap for the 40 s welding time (see Fig. 7(b)) and cohesive failure (matrix-mesh debonding with resin rupture) towards the relatively hotter centre of the overlap for the 90 s welding time (see Fig. 7(c)). This is believed to cause the reduction in LSS as compared to 55 s heating time.

The fact that fibre-matrix debonding was found to be the dominant failure mechanism for joints welded within the processing interval was somewhat surprising given the poor

10

adhesion between the metal and the PEI polymer [22]. However, as explained in what follows, fracture toughness tests confirmed that the glass fibre-PEI matrix interface is the preferred path for crack propagation in both load cases present in the lap shear test, i.e. peel and shear. The fracture toughness tests were performed on press-consolidated samples in order to avoid potential noise in the results caused by a non-uniform quality of the welds.

As shown in Fig. 8 and Fig. 9, Mode I crack propagation occurred along the fibrematrix interface and required significantly less energy compared to crack propagation forced to occur within the resin rich surroundings of the metal mesh. In the latter case, cracks propagated through the tough resin towards the metal mesh. Occasional mesh bridging followed by mesh tearing caused a sudden increment in the fracture toughness energy. Similar results were obtained for Mode II loading. The energy required for cracks to propagate between the resin and the mesh was so high that flexural failure of the laminates occurred before any crack propagation could be observed.

3.1.3. Overheated welds

For an overheated weld, i.e. heating times of 100 s and 120 s in this study, cohesive failure (matrix-mesh debonding with resin rupture) accompanied by mesh tearing was found to be predominant. Obvious changes in the PEI resin were observed on the fracture surfaces (see Fig. 10) consisting of a darker resin colour and small resin rupture-flakes. These changes are believed to be related to thermal degradation of PEI [23]. Besides, voids attributed as well to the degradation of the polymer, were also found within the weld line. The changes in the resin as well as the voids are believed to drive failure towards the weld line and hence to lead to cohesive failure, as shown in Fig. 11.

3.1.4. Effect of moisture

Even though the majority of the laminates used in this study were dried before being welded, welds performed on laminates exposed to moisture showed some interesting changes in the failure modes. Significant porosity in the adherends was found in the latter case, which occasionally shifted fibre-matrix debonding into cracks that propagated along the void paths and caused relatively deep tearing of the composite substrates (see Fig. 12 and Fig. 13). Since this effect was observed for intermediate heating times and, as opposed to the adherends, no voids could be found in the hotter weld line, porosity was attributed in this case to the evaporation of the moisture dissolved in the PEI resin rather than to thermal degradation. For moderate void contents, the effect of fibre tearing and a longer and more tortuous crack path was offset by a decreased contact area as a result of the voids, and hence no big changes in LSS could be associated to this new failure mode (31.7±1.3 MPa LSS for approximately 0.1% moisture content and 55 s heating time). However, increased void content eventually caused significant losses in LSS (26.6±0.8 MPa LSS for approximately 0.3% moisture content and with a heating time of 55s).

3.2. Effect of fibre sizing

Since fibre-matrix debonding was found to be the dominant failure mode for the joints welded within the processing interval, the effect of fibre-matrix adhesion on the strength of the welded joints was investigated. Two different fibre sizings (see Fig. 14 [24]), namely a chromium methacrylate coupling agent (Volan A) as used in the SS0303 prepreg and aminosilane sizing (TF970) as used in the TC7881 prepreg, were compared. The mechanical properties of the SS0303 and TC7881 composites were characterized by flexural tests, short beam shear tests and Mode I fracture toughness tests. Similar

flexural strengths and fracture modes were obtained for both fibre sizings, as shown in Fig. 15. However, SS0303 specimens yielded higher short beam shear strength than TC7781 specimens, different failure modes were also observed. Tensile fracture was found to be the main failure type for SS0303 samples, while delamination was found for TC7781 samples. The lower short beam shear strength and the delamination failure mode indicate a weaker fibre-matrix adhesion in the TC7781 laminates as compared to the SS0303 laminates. Likewise, the Mode I interlaminar fracture toughness was found to be considerably higher for the SS0303 laminates (see Fig. 16).

Fig. 17 shows the LSS and fracture surfaces of the welded joints for these two types of laminates with an optimum heating time of 55s. TC7781 joints resulted in a LSS 56% lower than that of SS0303 joints and showed clean fibres on the fracture surfaces without any resin residue. The significant impact of fibre-matrix adhesion on the LSS of the joints is attributed to the fact that more energy is needed to cause fibre-matrix debonding in welded joints between laminates with stronger fibre-matrix adhesion.

3.3. Effect of fibre orientation

Four types of SS0303 GF/PEI joints welded with an optimum heating time of 55s and with different fibre orientations on the surfaces of the welding surfaces, i.e. Type I-warp, Type I-weft, Type II-warp and Type II-weft, were single lap shear tested. As shown in Fig. 18, Type II joints resulted in a decreased LSS as compared to Type I joints with LSS decrements ranging from 13% to 20% (weft and warp joints, respectively). Likewise weft joints yielded higher LSS than warp joints, with LSS increments ranging between 6% and 16% (Type I- and Type II- joints, respectively).

Fractography analysis of the joints confirmed fibre-matrix debonding as the primary failure mode for warp joints, whereas weft joints showed deep laminate tearing (see Fig.

19). The higher LSS for the weft joints can be explained by the higher energy involved in the failure: the occurrence of deep laminate tearing in weft joints is attributed to the higher waviness of the weft fibres, which creates more tortuous debonding paths and gives way to tearing of the fibre bundles. It must be noted, however, that, especially in Type I joints, the differences of LSS between weft joints presenting laminate tearing and warp joints presenting fibre-matrix debonding are not big. This indicates a fairly strong fibre matrix interface of the SS0303 laminates. Model I and Mode II fracture toughness tests of plain composite samples (see Fig. 20) yielded as well higher fracture toughness values for samples with weft surfaces at the crack opening plane.

The higher LSS of Type I joints is attributed to their higher resistance to crack initiation in the lap shear tests in spite of a lower energy required for crack propagation as stated in literature [15, 25] and confirmed by the Mode I and Mode II fracture tests in this research (Fig. 20). Owing to the stress concentrations at the edges of the overlap in single lap shear tests [18], crack initiation is expected to play a prevalent role in the apparent lap shear strength. Type II joints, with the main fibre orientation perpendicular to the load direction will, similarly to 90° UD composites, easily crack under loading thereby giving way to failure at a lower load than Type I joints. Additionally, having more fibres parallel to the load direction on the welding surfaces (Type I joints) could result in a better load transfer from the overlap area to the rest of the substrate, and thus lead to a more favourable stress distributions.

4. Conclusion

In this study, the LSS and the failure modes of resistance welded joints in 8 harness satin GF/PEI composites with a metal mesh heating element were analyzed. The

influence of heating time, fibre-matrix adhesion and fabric orientation were investigated. The following main conclusions can be drawn from this investigation:

- 1) Intralaminar failure is found to be the main failure mode for a joint welded with an optimal heating time. Two different types of intralaminar failures are found depending on the type of fibres primarily present on the welding surfaces. Fibrematrix debonding is the main failure mode when the majority of the fibres on the welding surfaces are warp yarns, while laminate tearing is the main failure mode when the majority of the fibres are weft yarns. The more tortuous fracture path in the second case, promoted by the higher waviness of the weft fibres, leads to moderate increments amounting to 6-16% in the LSS.
- 2) When fibre-matrix debonding is the main failure mode, fibre-matrix adhesion has a significant effect on the LSS of the welded joints. Using GF/PEI laminates with aminosilane glass fibre sizing results in a 56% decrease of LSS as compared to laminates with chromium methacrylate glass fibre sizing.
- 3) The main apparent orientation of the fibres on the welding surfaces also has an effect on the LSS of the welded joints. Having the main apparent orientation of the fibres perpendicular to the load direction causes the LSS of the welds to decrease, with reductions ranging between 13% and 20% in the present study.
- 4) The presence of moisture in the laminates leads to process-induced porosity during welding that shows negative effect on the LSS and induces changes in the failure modes.

Acknowledgements

The authors would like to express their gratitude for the support provided by TenCate

Advanced Composites, The Netherlands. H. Shi thanks the PhD Scholarship Fund from

China Scholarship Council (CSC) for overseas study.

References

[1] Offringa A. Thermoplastics in Aerospace, New Products Through Innovative Technology. SAMPE Journal. 2005;41(7):19-27.

[2] Mantell SC, Springer GS. Manufacturing Process Models for Thermoplastic Composites. Journal of Composite Materials. 1992;26(16):2348-77.

[3] Ageorges C, Ye L, Mai Y-W, Hou M. Characteristics of resistance welding of lap shear coupons. Part I: Heat transfer. Composites Part A: Applied Science and Manufacturing. 1998;29(8):899-909.

[4] Ageorges C, Ye L, Mai Y-W, Hou M. Characteristics of resistance welding of lap shear coupons.: Part II. Consolidation. Composites Part A: Applied Science and Manufacturing. 1998;29(8):911-9.

[5] Jakobsen TB, Don RC, Gillespie JW. Two-Dimensional thermal analysis of resistance welded thermoplastic composites. Polymer Engineering & Science. 1989;29(23):1722-9.

[6] Maffezzoli AM, Kenny JM, Nicolais L. Welding of PEEK/Carbon Fiber Composite Laminates. SAMPE Journal. 1989;25(1):5.

[7] Xiao XR, Hoa SV, Street KN. Processing and Modelling of Resistance Welding of APC-2 Composite. Journal of Composite Materials. 1992;26(7):1031-49.

[8] Shi H, Villegas IF, Bersee HEN. Modelling of Heat Transfer and Consolidation For Thermoplastic Composites Resistance Welding. 18th International Conference on Composites Materials. Jeju, South Korea2011.

[9] Stavrov D, Bersee HEN, Beukers A. The Influence of the heating element on resistance welding of thermoplastic composite materials. ICCM-14 Conference. 2003.

[10] Dubé M, Hubert P, Gallet JN, Stavrov D, Bersee HE, Yousefpour A. Metal mesh heating element size effect in resistance welding of thermoplastic composites. Journal of Composite Materials. 2012;46(8):911-9.

[11] Hou M, Ye L, Mai YW. An Experimental Study of Resistance Welding of Carbon Fibre Fabric Reinforced Polyetherimide (CF Fabric/PEI) Composite Material. Applied Composite Materials. 1999;6(1):35-49.

[12] Ageorges C, Ye L, Hou M. Experimental investigation of the resistance welding of thermoplastic-matrix composites. Part II: optimum processing window and mechanical performance. Composites Science and Technology. 2000;60(8):1191-202.

[13] Stavrov D, Bersee HEN. Experimental Study on Mechanical Testing Techniques for Resistance Welding of Thermoplastic Composites. SAMPE Europe International Conference. 2006.

[14] Briscoe BJ, Court RS, Williams DR. The effects of fabric weave and surface texture on the interlaminar fracture toughness of aramid/epoxy laminates. Composites Science and Technology. 1993;47(3):261-70.

[15] Kotaki M, Hamada H. Effect of interfacial properties and weave structure on mode I interlaminar fracture behaviour of glass satin woven fabric composites. Composites Part A: Applied Science and Manufacturing. 1997;28(3):257-66.

[16] Alif N, Carlsson LA, Boogh L. The effect of weave pattern and crack propagation direction on mode I delamination resistance of woven glass and carbon composites. Composites Part B: Engineering. 1998;29(5):603-11.

[17] Suppakul P, Bandyopadhyay S. The effect of weave pattern on the mode-I interlaminar fracture energy of E-glass/vinyl ester composites. Composites Science and Technology. 2002;62(5):709-17.

[18] Shi H, Villegas IF, Bersee HEN. An investigation on the strain distribution of resistance welded thermoplastic composite joints. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. Honolulu, Hawaii.: AIAA; 2012.

[19] Hamer W. An experimental study on the influence of the metal mesh heating element on the mechanical performance in resistance welded joints. Delft: Delft University of Technology; 2011.

[20] Carroccio S, Puglisi C, Montaudo G. Thermal degradation mechanisms of polyetherimide investigated by direct pyrolysis mass spectrometry. Macromolecular Chemistry and Physics. 1999;200(10):2345-55.

[21] Stavrov D, Bersee HEN. Experimental investigation of resistance welding of thermoplastic composites with metal mesh heating element. SAMPE-Europe conference proceedings. Paris, France2004.

[22] Dubé M, Hubert P, Gallet JNAH, Stavrov D, Bersee HEN, Yousefpour A. Fatigue performance characterisation of resistance-welded thermoplastic composites. Composites Science and Technology. 2008;68(7-8):1759-65.

[23] Augh L, Gillespie JW, Fink BK. Degradation of Continuous Carbon Fiber Reinforced Polyetherimide Composites During Induction Heating. Journal of Thermoplastic Composite Materials. 2001;14(2):96-115. [24] Sterman S, Bradley HB. A new interpretation of the glass-coupling agent surface through use of electron microscopy. Polymer Engineering & Science. 1961;1(4):224-33.

[25] Ogasawara T, Yoshimura A, Ishikawa T, Takahashi R, Sasaki N, Ogawa T. Interlaminar Fracture Toughness of 5 Harness Satin Woven Fabric Carbon Fiber/Epoxy Composites. Advanced Composite Materials. 2012;21(1):45-56.

Figure captions:

Fig. 1. Schematic drawing of $[[(0^{\circ}/90^{\circ})]_n]_s$ and $[[(90^{\circ}/0^{\circ})]_n]_s$ laminates stacked with different surface sides: Type I-Warp, Type I-Weft, Type II-Warp and Type II-Weft

Fig. 2. Positions of the thermocouples used for the temperature measurements during the resistance welding of GF/PEI

Fig. 3 Schematic drawing of single lap shear GF/PEI samples with different fibre orientations at the welding surfaces (warp yarn shown as black and weft yarn shown as grey in the figure)

Fig. 4. Schematic diagrams of the DCB and ENF samples for plain GF/PEI specimen and mesh embedded GF/PEI specimen (a), and the four different fibre orientations at the crack propagation interfaces for plain GF/PEI specimens (b) (warp yarn shown as black and weft yarn shown as grey in the figure)

Fig. 5. The welding temperatures (maximum temperatures measured during the welding) and lap shear strength values for the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with different heating times (using 80% of the maximum weld strength as the benchmark)

Fig. 6. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time of 30s (under welded joints)

Fig. 7. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time within the processing interval: (a) a joint welded for 55s, (b) a joint welded for 40s, (c) a joint welded for 90s

Fig. 8. Crack resistance curves (R curves) of plain SS0303 GF/PEI specimens and mesh embedded SS0303GF/PEI specimens

Fig. 9. SEM micrographs for the fracture surfaces of Mode I specimens: (a) SS0303 GF/PEI laminate, (b) mesh embedded SS0303 GF/PEI

Fig. 10. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time of 100s (over heated joints)

Fig. 11. Cross-section micrograph of a SS0303 GF/PEI joint (Type I-Warp) welded at 80kW/m² and 100s that shows how the crack is deviated towards the mesh in the centre of the overlap

Fig. 12. Fracture surfaces of SS0303 GF/PEI joints (Type I-Warp) made of adherends with residual moisture and welded at 80kW/m² for 55s. The SEM micrograph (right) evidences the presence of porosity in the crack path

Fig. 13. Cross-section micrographs of SS0303 GF/PEI joints (Type I-Warp) welded at 80kW/m² for 55s by using laminates of different moisture conditions: (a) laminate with residual moisture, (b) fully dried laminate

Fig. 14. Different fibre sizings for the glass fabrics of GF/PEI prepreg [24]: (a) Chromium methacrylate (b) Aminosilane

Fig. 15. The flexural strength, short beam shear strength (a) and the failure modes (b) of the GF/PEI laminates with different fibre sizings

Fig. 16. R-curves of DCB tests for GF/PEI specimens with different fibre sizings

Fig. 17. (a) Lap shear strength of SS0303 and TC7781 GF/PEI joints (Type I-Warp) welded with 80kW/m² and 55s, and (b) SEM micrographs for the fracture surfaces of both types of joints

Fig. 18. Lap shear strengths of SS0303 GF/PEI joints with different fibre orientations welded with 80kW/m² and 55s

Fig. 19. Fracture surfaces and SEM micrographs for the SS0303 GF/PEI joints with different fibre orientations on the joining surfaces and welded with 80kW/m² and 55s: (a) Type I-warp, (b) Type II-warp, (c) Type I-weft, and (d) Type II-weft

Fig. 20. Comparison of interlaminar fracture toughness for the SS0303 GF/PEI laminates with different fibre orientations at the crack propagating interfaces

Tables:

Product code	SS0303 (050 003 8463 34000)	TC7781 (P127 001 8463 34000)	
Resin type	Ultem 1000 PEI	Ultem 1000 PEI	
Glass fabric style	US Style 7781	US Style 7781	
5	5	5	
Varn type	EC6 68tex	FC6 68tex	
i ani type	Leo oolex		
Maga of folgie	200~/~~2	200~/~2	
Wass of fabric	500g/1112	300g/III2	
_ / /	_ ~		
Fabric manufacturer	TenCate	Hexcel	
Fibre treatment	Volan A (chromium methacrylate)	Hexcel TF970 (aminosilane)	
	· · · · · · · · · · · · · · · · · · ·		

Table 1. Characteristics of the two types of GF/PEI prepregs used in this study

Table 2. Mechanical tests performed in this study (LSS: lap shear strength test; DCB: double cantilever beam test; ENF: end notched flexure test; 3PB: three point flexure test; SBS: short beam shear test)

		F ¹ 1 1 ¹	Effect of fibre-matrix	Effect of fibre
		Failure mode analysis	adhesion	orientation
LSS	Type of samples	Welded	Welded	Welded
	Prepreg type	SS0303	SS0303 & TC7781	SS0303
	Stacking sequence	[(0°/90°)] _{4s}	[(0°/90°)] _{4s}	$[(0^{\circ}/90^{\circ})]_{4s}$ &
	Main apparent fibre orientation	Type I	Туре І	Type I & Type II
DCB & ENF ^a	Type of samples	Press-consolidated	Press-consolidated	Press-consolidated
	Prepreg type	SS0303	SS0303 & TC7781	SS0303
	Stacking sequence	[[(0°/90°)] _{4s}] _s & [[(0°/90°)] _{4s} /M200/PEI] _s	[[(0°/90°)] _{4s}] _s	[[(0°/90°)] _{4s}] _s &
	Main apparent fibre orientation (crack opening surfaces)	Туре І	Type I	Type I & Type II
3РВ	Type of samples		Press-consolidated	-
	Prepreg type		SS0303 & TC7781	
	Stacking sequence	-	[(0°/90°)] _{4s}	-
	Main apparent fibre orientation	-	Туре І	-
SBS	Type of samples	-	Press-consolidated	-
	Prepreg type		SS0303 & TC7781	
	Stacking sequence	-	$[[(0^{\circ}/90^{\circ})]_{4s}]_{s}$	-
	Main apparent fibre	-	Type I	-

a Only DCB tests were performed for the analysis of the effect of the fibre-matrix adhesion



Fig.1 Click here to download high resolution image



Fig.6 Click here to download high resolution image

Fig.7 Click here to download high resolution image

Fig.10 Click here to download high resolution image

Fig.11 Click here to download high resolution image

Fig.12 Click here to download high resolution image

Fig.18 Click here to download high resolution image

Fig.19 Click here to download high resolution image

Fracture toughness (kJ/m²)

Figure captions:

Fig. 1. Schematic drawing of $[[(0^{\circ}/90^{\circ})]_n]_s$ and $[[(90^{\circ}/0^{\circ})]_n]_s$ laminates stacked with different surface sides: Type I-Warp, Type I-Weft, Type II-Warp and Type II-Weft Fig. 2. Positions of the thermocouples used for the temperature measurements during the resistance welding of GF/PEI

Fig. 3 Schematic drawing of single lap shear GF/PEI samples with different fibre orientations at the welding surfaces (warp yarn shown as black and weft yarn shown as grey in the figure)

Fig. 4. Schematic diagrams of the DCB and ENF samples for plain GF/PEI specimen and mesh embedded GF/PEI specimen (a), and the four different fibre orientations at the crack propagation interfaces for plain GF/PEI specimens (b) (warp yarn shown as black and weft yarn shown as grey in the figure)

Fig. 5. The welding temperatures (maximum temperatures measured during the welding) and lap shear strength values for the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with different heating times (using 80% of the maximum weld strength as the benchmark)

Fig. 6. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time of 30s (under welded joints)

Fig. 7. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time within the processing interval: (a) a joint welded for 55s, (b) a joint welded for 40s, (c) a joint welded for 90s

Fig. 8. Crack resistance curves (R curves) of plain SS0303 GF/PEI specimens and mesh embedded SS0303 GF/PEI specimens

Fig. 9. SEM micrographs for the fracture surfaces of Mode I specimens: (a) SS0303 GF/PEI laminate, (b) mesh embedded SS0303 GF/PEI

Fig. 10. Fracture surfaces and SEM micrographs of the fracture surfaces of the SS0303 GF/PEI joints (Type I-Warp) welded under a constant power input of 80kW/m² and with a heating time of 100s (over heated joints)

Fig. 11. Cross-section micrograph of a SS0303 GF/PEI joint (Type I-Warp) welded at 80kW/m² and 100s that shows how the crack is deviated towards the mesh in the centre of the overlap

Fig. 12. Fracture surfaces and SEM micrographs of SS0303 GF/PEI joints (Type I-Warp) made of adherends with residual moisture and welded at 80kW/m² for 55s. The SEM micrograph (right) evidences the presence of porosity in the crack path

Fig. 13. Cross-section micrographs of SS0303 GF/PEI joints (Type I-Warp) welded at 80kW/m² for 55s by using laminates of different moisture conditions: (a) laminate with residual moisture, (b) fully dried laminate

Fig. 14. Different fibre sizings for the glass fabrics of GF/PEI prepreg [24]: (a) Chromium methacrylate (b) Aminosilane

Fig. 15. The flexural strength, short beam shear strength (a) and the failure modes (b) of the GF/PEI laminates with different fibre sizings

Fig. 16. R-curves of DCB tests for GF/PEI specimens with different fibre sizings

Fig. 17. (a) Lap shear strength of SS0303 and TC7781 GF/PEI joints (Type I-Warp) welded with 80kW/m² and 55s, and (b) SEM micrographs for the fracture surfaces of both types of joints

Fig. 18. Lap shear strengths of SS0303 GF/PEI joints with different fibre orientations welded with 80kW/m² and 55s

Fig. 19. Fracture surfaces and SEM micrographs for the SS0303 GF/PEI joints with different fibre orientations on the joining surfaces and welded with 80kW/m² and 55s:
(a) Type I-warp, (b) Type II-warp, (c) Type I-weft, and (d) Type II-weft

Fig. 20. Comparison of interlaminar fracture toughness for the SS0303 GF/PEI laminates with different fibre orientations at the crack propagating interfaces