Co-consolidation of CF/PEEK tape-preforms and CF/PEEK organo sheets to manufacture reinforcements in stamp-forming process

Julian Weber and Jens Schlimbach

Manufacturing Science, Institut für Verbundwerkstoffe GmbH, Kaiserslautern, Germany

ABSTRACT
Co-consolidation is considered one effective joining method to allow novel types of integral structures to be manufactured. In this study, carbon fiber reinforced Polyether-Ether-Ketone partially consolidated tape preforms were co-consolidated with carbon fiber reinforced Polyether-Ether-Ketone organo sheets in stamp-forming process. Interlaminar bond quality of both joining partners is validated in double cantilever beam test. Results exhibit average interlaminar fracture toughness of 2.54 kJ/m² for stamp-forming specimen, which exceeds interlaminar fracture toughness of reference samples manufactured in autoclave being 1.79 kJ/m². Further examinations on specimen morphology and mechanical properties indicate distinct assignments to process characteristic cooling rates, which coincides with studies from literature. Accordingly, high cooling rates—as evident in stamp-forming process—are allocated to high toughness, low crystallinity and low bending modulus, causing high interlaminar fracture toughness. Investigations on laminate quality reveal maximum void content of 1.58%.

GRAPHICAL ABSTRACT

Abbreviations: α: fiber weight fraction; ΔHf: enthalpy of fusion; ϕ: fiber volume content; a: propagated crack length; CF/PEEK: carbon fiber/polyether-ether-ketone; CF/PPS: carbon fiber/polyphenylene sulfide; DCB: double cantilever beam; DSC: differential scanning calorimetry; EHT: electron high tension; F: force; GIC: interlaminar fracture toughness; IR: infrared; PI: polyimide; Q: heat-flow rate; SEM: scanning electron microscopy; tCPT: cured ply thickness; tOrganoSheet: organo sheet thickness; UD: unidirectional; w: specimen width; X: degree of crystallization.

CONTACT
Julian Weber
Julian.weber@ivw.uni-kl.de
Institut für Verbundwerkstoffe GmbH, Erwin-Schroedinger-Strasse 58, 67663 Kaiserslautern, Germany

© 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

By launching the programs A350 XWB and B787, the two major civil aircraft manufacturers have expressed their focus in fiber-reinforced plastics as the material of choice to make aircraft operation more efficient through drastic emission savings. Considering production costs, these new structures cannot yet compete with conventional aluminum design, since time and cost consuming autoclave curing and manual assembly steps dominate. To tackle this, the use of out-of-autoclave processes and thermoplastic components shall be extended [1–3].

Up to now, the latter are confined to mainly secondary structures or small primary structures like clips, ribs, leading edges or small panels, that are manufactured in stamp forming, where cycle times of <2 min are already achievable [2,4]. To exploit nature of thermoplastics at most extent and make efficient use of their characteristic features, production of large structures with integrated stiffeners, manufactured in stamp forming, are aimed to develop. Usage of direct bonding method co-consolidation allows hybridization of stamp forming process and joining of reinforcements in one step. Thereby, no extra joining material is needed, cycle time is decreased, and the joint strength matches that of the bulk material, creating a seamless transition [5,6]. From a process engineering point of view, direct bonding is achieved by heating the interface and cooling down under pressure [6–8].

Consolidation in fusion bonding requires polymer-polymer interface healing [9]. Wool and O’Connor [10,11] described this procedure with five sequential stages, namely surface rearrangement, surface approach, wetting, diffusion, and randomization. The first three stages, until diffusion of molecules begins, is known as intimate contact development and was originally developed by Loos and Dara [12]. Thereby, resin flow causes squeezing of air and resin out of the interface, network deformation takes place, and potential barriers associated with inhomogeneities at the interface disappear [13–15]. The time until full intimate contact is reached can be considered as a function of polymer viscosity, depending on the polymer temperature, initial surface roughness, and the applied pressure. Subsequently, molecules begin to migrate through the interface and entangle with the ones of the counterparty (interdiffusion or autohesion). Strength of the bond increases until full bonding is achieved, which is when the interface cannot be distinguished from the bulk material [16]. Cooling under pressure completes the bonding process, whereas cooling rate is of high influence on both morphological and mechanical properties of the bonded part [9,17,18]. In this present study of stamp forming— in relation to autoclave consolidation—short time to form intimate contact as well as high cooling rates predominate, which is why direct bonding, assuming polymer healing and consolidation, is challenging.

Previous research has revealed several dependencies between cooling rate on matrix morphology, fiber/matrix interaction and interface structure [19–22]. Gao and Kim [21], Lustiger et al. [23] and Khanh et al. [22] relate high cooling rates to low crystallinity and high toughness due to enhanced matrix ductility. Gao and Kim did measurements on $G_{IC}$ to determine interlaminar fracture toughness in double cantilever beam (DCB) test and specified values of 2.6 $kJ/m^2$ for a cooling rate of 80 K/min, respectively, 1.8 $kJ/m^2$ for a cooling rate of 1 K/min [24]. Thereby, the two crucial properties matrix ductility and fiber-matrix interface bond strength are opposed to the cooling rate. Ductility increases and fiber-matrix interface bond strength decreases with higher cooling rates, which ultimately has the effect of composite toughness increase. Thereby, an adequate interface bond is key to allow matrix deformation. In further works of Gao and Kim [20,21], effects of cooling rate on fiber-matrix interface adhesion with correlations to the degree of crystallinity and bulk mechanical properties were determined. Thus, interface bond strength decreases with increasing cooling rate, tensile strength and elastic modulus of PEEK decreases. Due to dominant effects on crystallinity and spherulite size, ductility increases. It was found that fast cooling revealed mixtures of isolated and graphite fiber nucleated spherulites and low cooling rates solely lead to larger fiber nucleated spherulites. Studies undertaken by Saiello et al. [25] reveal effects on interphase morphology. Ray et al. [26] quantified $G_{IC} = 2.15 kJ/m^2$ for laser-assisted automated tape placement specimen, expecting cooling rates of 14,700 K/min to 20,000 K/min [27] and $G_{IC} = 1.32 kJ/m^2$ for autoclave cured specimen with cooling rates of 2 K/min. Sacchetti et al. [28] did investigations on influence of cooling rates on the interlaminar fracture toughness of unidirectional (UD) CF/PPS laminates. Thereby, strong dependencies between high cooling rates and interlaminar fracture toughness were identified [29]. In further investigations, Sacchetti determined plastic deformation of CF/PEEK laminates as the mechanism effecting interlaminar fracture toughness at most, when laminates are heated as a stack in the oven and are stamp-formed subsequently. Investigations showed increase in interlaminar fracture toughness as interleaving thicknesses of neat resin between joined laminates was heightened. Measurements on morphology in Differential Scanning Calorimetry (DSC) revealed same levels of crystallinity (35%) for press consolidated specimen (slow cooling rate) and stamp-
forming specimen (high cooling rate), offering no effect on laminate toughness [29].

In this present study, direct bonding of CF/PEEK organo sheets and CF/PEEK tape preforms is examined. Contrary to existing studies of direct bonding in stamp forming process, joining surfaces are brought into the molten state separately, providing short time intimate contact development in combination with high cooling rates. Thereto, organo sheets are placed in a countersink tool, in-situ heated via IR and co-consolidated with a partially consolidated tape-preform by stamp-forming. The strength of the joint is validated in DCB-test by determining interlaminar fracture toughness. Autoclave curing of the same specimen composition was used as the benchmark process. Hereby, direct bonding is achieved under long time intimate contact development, offering sufficient duration to let molecules diffuse through the interface to form polymer healing and in the end create a fully developed bond.

This procedure is considered one effective method to manufacture integral components in short cycle times by exploiting thermoplastics advantageous characteristic of meltability. The partially consolidated, load path optimized tape-preform may represent a structural part that shall be thermoformed, locally reinforced by an organo sheet that is co-consolidated in stamp forming.

2. Experimental

2.1. Materials and manufacturing of tape-preform and organo sheets

The material used for both, the partially consolidated tape-preform and the organo sheet, is Solvay’s APC-2 polyether ether kethone (PEEK) with an AS4 C-fiber. The fiber volume content according to data is \( \varphi = 0.58 \). Cured ply thickness is specified to be \( t_{c,\text{pt}} = 0.138 \text{ mm} \).

The tape preform is manufactured in automated tape-laying by using a Coriolis Tape-Placement Head that is attached on a six-axis KUKA robot. Eleven layers of UD \( 1/4 \) in tapes in an arrangement of eight tapes side by side are placed by means of laser heating. Lay-up speed is set to 0.2 m/s, laser power is 2000 W and compaction force of the roller is 400 N. Contact area is 68 \( \times \) 26.8 mm², resulting in a compaction pressure of 2.2 bar. Detected temperature in the nip-point is 425 °C. In-situ consolidation is not an object of interest at this point, since the full consolidation is to take place during stamp-forming process. The organo sheet is processed in autoclave, comprising eleven hand-laid-up tapes. Process data is given in Table 1. As with the tape preform, ply scheme is \( [0^\circ]_{11} \) (UD). Individual specimens are cut from a single plate by means of waterjet cutting to a size of 260 \( \times \) 35 mm².

2.2. Stamp-forming setup and manufacturing DCB-specimen

Stamp-forming test setup to manufacture DCB-specimen comprises a tool equipped with five rectangular cutouts to insert the organo sheets and two IR-radiator panels I and II to heat both laminates separately (see Figure 1). Position of panel I is fixed and located next to the press, whereas panel II is installed on a sliding carriage, that can be moved inside the press over the tool. The press, on a laboratory scale, has a maximum press force of 800 kN, a table size of 1000 \( \times \) 1200 mm² and a maximum closing speed of 850 mm/s.

The tape-preform is clamped between two aluminum frame covers, fastened with brackets, suspended with springs on each corner, and attached to the sliding carriage that holds IR-radiator panel II (see Figures 1 and 2). Aluminum frame covers ensure that UD-laminates do not melt in the area where suspension points are located, to prevent loss of shape during deconsolidation during melting. The springs allow the tape-preform to travel vertically without tension, when the mold is closing. A thermocouple (type K) is mounted on the top of the laminate—out of the projected tool area—to detect temperature during melting (see Figure 3).

Each organo sheet is equipped with a polyimide release film in accordance to ISO 15024 on one end of the specimen of the joining surface. One organo sheet is equipped with a thermocouple (type K) on the opposite end of the DCB testing area (see Figure 3). The heating behavior of the organo sheets was investigated in preliminary tests. Based on those results, it was decided to use glass-fiber reinforced polytetrafluoroethylene (PTFE) strips in order to reduce heat flow between the organo sheet and the tool.

Both radiator panels I and II are preheated. To begin melting process of both joining partners, the sliding carriage is moved to its end stop, when IR panel I covers the tape-preform and IR panel II covers the organo sheets (see Figure 1, top). One representative temperature log is shown in Figure 4. The surface appearances as well as the logged

Table 1. Autoclave processing data.

| Parameter               | Value          |
|-------------------------|----------------|
| Heat-up rate (°C/min)   | 5.9            |
| Pressure ramp (bar/min) | 0.17           |
| Dwell temperature (°C)  | 380            |
| Dwell Pressure (bar)    | 10             |
| Dwell time (s)          | 1800           |
| Cooling rate (°C/min)   | 6.2            |
The temperature of both laminates were taken as indicators for matrix being melted. Figure 5 shows the melted surface of the organo sheets offering distinct unevenness on the entire surface, which was taken as an indicator of melted surfaces. The set-temperature was determined in preliminary tests, of 390°C.

The sliding carriage with the tape-preform and IR-radiator panel II is moved to its opposite end stop where the tape-preform covers the organo sheets (see Figure 1, bottom). The press is closed in rapid motion and then closed with a force of 80 t in a force-controlled manner. With the tool projected contact surface, a pressing pressure of 6.3 bar results. As seen in Figure 4 temperature at both thermocouples drops rapidly, when mold is closed. Temperature just before first contact is ≈ 375°C. Thermocouple of the organo sheet is then located in the joining zone, between the tape preform and the organo sheet (see Figure 3), measuring a temperature drop of 155°C in the first 10 s after contact. Tool temperature is reached rapidly there. Thermocouple of the tape-preform is outside the mold to detect temperature loss of the unpressed laminate due to thermal radiation to the environment. The demolding process is started after dwell time of 120 s.

Benchmark DCB specimen were manufactured in autoclave process whereas the joining partners are also on the one hand partially consolidated tape preforms and on the other hand autoclave processed

Figure 1. Stamp-forming test setup to manufacture DCB specimen; top: clamping frame position during heating of both partners, bottom: clamping frame position during moulding.

Figure 2. Clamping frame with tape-preform covering tool with organo sheets.
organo sheets (see Figure 6). The process data corresponds to that given in Table 1.

2.3. Characterization

2.3.1. DCB-test

The mode I interlaminar fracture toughness is measured in DCB test to assess adhesion between both laminates on peel loading. Specimen geometry as well as test parameters were chosen in accordance with ISO 15024. 25 DCB-specimen manufactured in stamp-forming and ten specimen manufactured in autoclave with dimensions of $250 \times 25 \times 3.1 \text{ mm}^3$ were tested with a ZwickRoell universal testing machine (see Figure 7). Specimen width and height were measured in accordance to ISO 15024. Those values are used for the calculation of interlaminar fracture toughness $G_{IC}$. Aluminum load-blocks are attached on the top and bottom of the sample at the end with the release film. One side of each specimen was inked with a white guideline for the initial crack length $a_i$ and final crack length $a_{i+1}$. An initial crack, starting at the end of the release film and exhibiting a minimum length of $a_i = 10 \text{ mm}$, is induced with a
testing speed of 5 mm/min without recording data but observing crack propagation with a stereomicroscope. Tip of the crack is marked on the guideline and specimen is removed from the test rig. After that, specimen is marked with a stroke 60 mm in distance to initial crack, representing final crack length. During phase two of DCB-test, constant crosshead speed of 10 mm/min is chosen until final crack length \( a_{i+1} \) is reached by propagating crack, while load is recorded as a function of crosshead displacement.

### 2.3.2. DSC-analysis

In DSC, grade of crystallinity is determined since stamp-forming process and autoclave curing exhibit different thermal treatment, which is why different morphological structures were expected. Thereto, samples of \(~20\) mg were heated with a rate of 10 K/min up to 400°C. Heat flux flow to a reference sample is detected as a function of temperature.

### 2.3.3. Scanning electron microscopy (SEM)

The microstructure formation and the interfaces between fiber and matrix were investigated with a Zeiss Supra 40 VP SEM. Having cooled post-DCB test specimen in nitrogen, small samples were broken off with a pair of pliers parallel to the fibers. Sputtering with gold with a BALZERS SCD 050 was to avoid electrostatic charging. The accelerating voltage of the electrons (EHT) was set to 5 kV. The intention of SEM analysis was to assess laminates microstructure formation. Samples were not taken from DCB-crack surfaces but perpendicular to this surface.

### 2.3.4. Three-point bending test

Three-point-bending tests of post-DCB test specimen were performed with the objective to examine mechanical performance in terms of toughness under bending load of the individual laminates that were joined in stamp-forming, respectively, autoclave. In accordance to DIN EN ISO 14125 coupons of 15 mm width and 80–90 mm length (as a function...
of thickness) were loaded with a testing speed of 5 mm/min.

2.3.5. Microscopic analysis
Microsection specimen of post-DCB test specimen was prepared by bandsaw cutting, neat resin embedding, grinding, and polishing. The examination of the micrographs was done with a transmitted light microscope DM6 by Leica. The joining area was observed in order to assess crack propagation path.

3. Results
3.1. DCB results
Applicable to a large proportion of both autoclave cured specimen and stamp-formed specimen, discontinuous crack growth was evident. In the load-deflection curve, slipping is identifiable as abrupt loss of loading; areas of adhesion reveal continuous decrease of load. In Figure 8, two diagrams of continuous and discontinuous crack growth in case of autoclave processed specimen is shown. This is to highlight the impact of discontinuous crack growth on the area A, that is used to calculate $G_{IC}$ (see Equation (1)).

In Figure 9, fracture surfaces with areas of stick and slip of both investigated processes are shown. Fiber eruption and fiber fracture is detectable all over specimen width, indicating excellent adhesion between both joining partners, inferring polymer diffusion throughout the interface. Noticeably, autoclave specimen exhibit sharp borders between stick...
and slip areas and higher contrast between those zones than that observed at stamp-forming specimen. To assess performance of tested specimen in DCB-test, exemplary load-deflection curves for each of both types are given in Figure 10.

Since discontinuous crack growth affects the size of the calculated area $A$ and in the end the results of the determined $G_{IC}$, all tested specimen were sorted by the occurrence of discontinuous crack growth and continuous crack growth in the testing zone. Doing so, five stamp-formed specimen and five autoclave-processed specimen whose measurement curve deviates least from an ideal load curve were chosen for evaluation. The ideal load curve is assumed to be one load deflection curve with continuous crack growth, running through the local load-maximums of the individual measurements. Values for interlaminar fracture toughness $G_{IC}$ were determined by means of Equation (1) according to DIN EN ISO 15024. Thereby, $A$ is the energy to achieve total propagated crack length (see Figure 8). $a$ is the propagated crack length, $w$ the width of the sample.

$$G_{IC} = \frac{A}{a \cdot w} \cdot 10^6 \quad (1)$$

DCB-test results reveal average interlaminar fracture toughness of 2.54 kJ/m² with a nominal standard deviation of 0.18 kJ/m² in case of stamp-forming specimen. Autoclave processed specimen do exhibit an average value of 1.79 kJ/m² and a nominal standard deviation of 0.092 kJ/m² (see Figure 11). In the case of autoclave specimen, fully developed polymer healing due to long dwell time in the molten state under compression is assumed, which is why full interlaminar bond is expected. In the case of stamp-forming, short dwell time to develop intimate contact development and subsequent polymer healing to form an interlaminar bond is evident. Based on the gathered results on interlaminar fracture toughness measurements in DCB test, it is assumed that this short time of intimate contact development is sufficient to form an interlaminar bond and thus polymer healing between both laminates in stamp forming is assumed. Bond quality on autoclave level, respectively, full interlaminar bond between both joining partners in stamp-forming process is expected.

$G_{IC}$ values of stamp-forming specimen exceeding $G_{IC}$ values of autoclave consolidation specimen matches previous research [26]. Following this, low cooling rates, as given in autoclave consolidation, are related to low toughness and high cooling rates, as given in stamp-forming process, are linked to high toughness as a result of different morphological structures [20,21,24]. In this study, cooling rates of 15 K/s in case of stamp forming and 0.1 K/s in case of autoclave consolidation are evident.

Further investigations were conducted to reveal relations between autoclave consolidation characteristic process properties and stamp forming characteristic process properties and specimen properties that may
affect interlaminar fracture toughness. Doing so, morphological analysis was done in DSC, fracture surfaces parallel to fiber longitudinal direction were examined in SEM to validate fiber-matrix adhesion as well as matrix morphological structure, three-point-bending tests were conducted to compare toughness of the bulk material of stamp-forming specimen and autoclave specimen. Microsection analysis was done to analyze crack path course in post-DCB specimen as well as analysis of the interface between both laminates with regard to fiber migration and air entrapment.

### 3.2. DSC-analysis results

DSC analysis was done to measure degree of crystallization since strongly deviating cooling rates at autoclave consolidation are evident and may affect morphological structure. The degree of crystallization $X$ was measured using Equation (2). Thereby, $\Delta H_m$ is the normalized enthalpy of fusion, representing the absorbed or released energy of the sample during transformation. 130 J/g [30] is the normalized enthalpy of fusion of fully crystalline PEEK and $1 - \alpha$ is the weight fraction of matrix of the corresponding specimen. $\Delta H_m$ equals the area under the endothermic peak.

Average results for six specimen of each process (stamp-forming and autoclave) reveal 28% average crystallinity for stamp-formed specimen and 38% average crystallinity for autoclave-processed specimen.

$$X = \frac{\Delta H_m}{\Delta H_f (1 - \alpha)} \tag{2}$$

---

**Figure 12.** SEM images of post-DCB test specimen, parallel to fiber direction.
Nominal standard deviations of 3.2% for autoclave processed specimen, 5.7% for stamp-forming specimen, respectively, do reveal high fluctuation, which is why results of DSC-analysis should be considered only qualitatively. This matches previous research relating higher cooling rates to lower degree of crystallization and vice versa [21,24,26]. To identify differences in physical morphological structure of processed specimen, SEM images were analyzed.

### 3.3. SEM analysis results

In Figure 12, SEM images of post-DCB test specimens, parallel to fibers and perpendicular to fracture surface of the DCB-test with a magnification of 5000 are shown.

Stamp-formed specimen reveal a rather fine fracture surface featuring little development of surface asperity, comprising arrays of many small bumps indicating a pronounced micro-ductility, which implicates a tough matrix. Fracture surface of the autoclave specimen exhibit a rather coarse micro-structure, featuring plate-like fracture elements and strongly pronounced crack edges, which suggests the material to be more brittle implicating abrupt failure.

SEM analysis was not done to validate DCB-crack surface in terms of failure behavior in DCB-test. Higher toughness of the bulk material does affect the failure behavior under bending load as evident in DCB-test and in the end does contribute to higher $G_{IC}$ values, since energy dissipation is supported by fracture formation in the bulk material. To quantify the difference in bulk material toughness three point bending tests of post-DCB specimen were conducted.

### 3.4. Three-point bending test results

In total 12 post-DCB test specimen, six of each process autoclave and stamp-forming, were tested in
three point bending test. Accordingly, average bending modulus is 91.1 GPa for stamp-forming specimen and 103.6 GPa for autoclave processed specimen. Nominal standard deviations are 4 GPa in case of stamp-forming specimen and 3.2 GPa in case of autoclave processed specimen. Expressed relatively, results are 12% higher flexural modulus and 21% higher failure stress for autoclave processed specimen. Average toughness of the tested specimen was determined by calculating the area between the measured load deflection curve and a fictitious load deflection curve of an ideally elastic specimen, connecting the origin and the last measuring point in the load-deflection diagram. This was done determine the plastic energy exclusively that is generated during bending load of both individual laminates of the DCB specimen as it appears in DCB test (see Figure 13). Doing so, average toughness of 33.78 J/m³ in case of stamp-forming specimen and 21.00 J/m³ in case of autoclave processed specimen were determined.

Results match findings of the aforementioned SEM-analysis, which was laminates manufactured with high cooling rates offering fracture patterns typical of tough materials. This assignment corresponds to what was found in existing studies [20,21,24,26].

3.5. Microsection analysis results

Analyze of the interface area indicates locally migrating of the crack path away from the interface inside the bulk material (see Figure 14). Greater strength of the joint than that of the bulk material can be deduced from this, allowing the conclusion of fully developed polymer healing and thus molecular entanglement throughout the interface.

4. Conclusion and outlook

In this study, a novel joining method of thermoplastics by means of co-consolidation in stamp-forming processes was investigated. On the basis of this feasibility test, direct bonding by means of co-consolidation of a tape-preform and an organo sheet in stamp-forming was validated by determination of interlaminar fracture toughness. The challenge was to create an interlaminar bond with short time intimate contact, offering also short time to realize polymer healing.

Results of the DCB-test reveal higher interlaminar fracture toughness of stamp-forming specimen than benchmark specimen processed in autoclave as well as those of previous research found in literature with similar conditions. Accordingly, interlaminar bond based on molecule chain movement throughout the interface is assumed. Post-DCB specimen analyze indicate high strength of bonding, showing bulk material fracture in consequence of crack propagation apart from the joining zone as well as fiber fracture at the interface, meaning strength of bonding is even higher than that of the bulk material (Figure 14).

Investigations on morphology and mechanical performance revealed distinct assignments of identified laminate properties to the investigated processes with their characteristic thermal treatment, being high cooling rates in stamp forming process and low cooling rates during autoclave consolidation. In particular, correlations are high interlaminar fracture toughness in combination with low crystallinity, high toughness, low strength and stiffness in the case of stamp-forming and the opposite for autoclave processed specimen.

In further studies, the dependency between tape-preform pre-consolidation and void content of the obtained laminates will be investigated. The aim is to find out whether it is necessary to start with, a fully consolidated tape preform to manufacture co-consolidated laminates at autoclave level in stamp forming process, whereas consolidation of the tape-preform between one side metal and one side organo sheet is the challenging part.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The project ‘OSFIT—One-Shot Fully Integrated Thermoplastic-Frame’ is funded by the Federal Ministry of Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag (funding reference 20W1706C).

ORCID

Julian Weber http://orcid.org/0000-0002-8108-4423

References

[1] Offringa AR. Thermoplastic composites—rapid processing applications. Compos A. 1996;27:329–336.
[2] Breuer UP. Commercial aircraft composite technology. Cham: Springer International Publishing; 2016.

[3] van Ingen JW. Thermoplastic orthogrid fuselage shell. Sampe J. 2016;52(5):7–15.

[4] Brauner C, Herrmann AS. Analysis of the Thermoforming Process of Thermoplastic Composite Parts: Conference Proceedings, 2nd International Conference & Exhibition on Thermoplastic Composites; 2014 Oct 27–28; Congress Center Bremen, Germany.

[5] Yousefpour A, Hojjati M, Immarigeon J-P. Fusion bonding/welding of thermoplastic composites. J Thermoplastic Compos Mater. 2004;17:303–341.

[6] Amanat N, James NL, McKenzie DR. Welding methods for joining thermoplastic polymers for the hermetic enclosure of medical devices,” Med Eng Phys. 2010;32:690–699.

[7] da Costa AP, Botelho EC, Costa ML, et al. A review of welding technologies or thermoplastic composites in aerospace applications. JATM. 2012;4:255.

[8] Davies P, Cantwell WJ, Jar P-Y, et al. Joining and repair of a carbon fibre/PEEK composites. In: O’Brien TK, editor. Composite Materials: Fatigue and Fracture. Vol. 3. West Conshohocken, PA 19428-2959: ASTM International; 1991. p. 70–19.

[9] Gao S-L, Kim J-K. Effect of cooling rate on interphase properties of carbon fibre/peek composites. J Soc Mater Sci Jpn. 1999;48:157–162.

[10] Moser L. Experimental analysis and modeling of susceptoerless induction welding of high performance thermoplastic polymer composites. Zugl. Kaiserslautern: Institut für Verbundwerkstoffe, 2012.

[11] Mantell SC, Springer GS. Manufacturing process models for thermoplastic composites. J Compos Mater. 1992;26:2348–2377.

[12] Gao S-L, Kim J-K. Cooling rate influences in carbon fibre/PEEK composites. Part I. Crystallinity and interface adhesion. Compos A. 2000;31:517–530.

[13] Vu-Khanh T, Frikha S. Influence of processing on morphology, interface, and delamination in PEEK/ carbon composites. J Thermoplast Compos Mater. 1999;12:84–95.

[14] Lustiger A, Uralil FS, Newaz GM. Processing and structural optimization of PEEK composites. Polym Compos. 1990;11:65–75.

[15] Gao S-L, Kim J-K. Cooling rate influences in carbon fibre/PEEK composites. Part II: interlaminar fracture toughness. Compos A. 2001;32:763–774.

[16] Sajiello S, Kenny J, Nicolais L. Interface morphology of carbon fibre/PEEK composites. J Mater Sci. 1990;25:3493–3496.

[17] Sacchetti F, Grouve WJB, Warnet LL, et al. Effect of resin-rich bond line thickness and fibre migration on the toughness of unidirectional Carbon/PEEK joints. Compos A. 2018;109:197–206.

[18] Blundell DJ, Osborn BN. The morphology of poly(aryl-ether-ketone). Polymer. 1983;24:953–958.