Real-time observation of waviness formation during C/PEEK consolidation

E.T.M. Krämera,b, W.J.B. Grouve b, S. Koussios a, L.L. Warnet b, R. Akkerman a,b,⁎

a ThermoPlastic composites Research Center (TPRC), Palatijn 15, 7521PN Enschede, Netherlands
b University of Twente, Drienerlolaan 5, 7522NB Enschede, Netherlands

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ABSTRACT
Defects such as fiber waviness can occur during the production of thermoplastic composite parts. It is desirable to prevent or minimize fiber waviness as it causes a knockdown in the part’s mechanical properties. However, the mechanisms governing the formation of fiber waviness are currently not fully understood. A setup for the real-time observation of waviness formation during flat laminate consolidation is presented in this paper. For C/PEEK unidirectional composites, it was observed that waviness forms during cooling between the maximum process temperature and the crystallization temperature. A higher processing temperature leads to waviness with a larger misalignment angle. No such trends were observed for the wavelength. Waviness does not form or increase in severity after crystallization. The driving force for waviness formation in flat laminate consolidation was determined to be tool shrinkage transferred to the laminate via tool-ply friction.

1. Introduction

1.1. Background

Thermoplastic composites (TPC) are increasingly used in the aerospace industry because of their excellent specific stiffness and strength, as well as their potential for cost-effective and automated manufacturing. However, there are still some challenges in manufacturing. A prominent one is the occurrence of defects such as fiber waviness during part production. Two examples of such parts are shown in Fig. 1. Fiber waviness causes a knockdown in mechanical properties that depends on the shape of the wave and the number of affected plies [1–6].

Fiber waviness in thermoplastic composite parts can originate from the manufacturing stage, even when the part has been made following the design and manufacturing specifications. Components with such nonconformities need expensive additional non-destructive inspection (NDI). These parts are generally scrapped, as the influence of fiber waviness on the mechanical performance is poorly understood. The scrap rate can be reduced by minimizing or even preventing fiber waviness, which requires a proper understanding of the governing mechanisms.

A flat laminate consolidated using a heated press or an autoclave may already suffer from fiber waviness, even in the absence of compressive fiber loads due to forming of the laminate. The formation of in-plane waviness during consolidation of a flat laminate is investigated in this paper, with a particular focus on the description of the governing mechanisms. A short literature review is presented before setting the objectives.

1.2. Literature review

The imperfection of fiber straightness has been studied extensively in the past, with multiple designations in the literature: waviness, misalignment, marcelling, chicken tracks and wrinkles. The groundwork for the effects of fiber misalignment on the mechanical properties in thermoset composites (TSC) dates back as early as 1965 [1]. The significance on the knockdown of part properties in high-performance TSCs has been established for out-of-plane waviness [3] and in-plane waviness [4]. Generally, waviness is considered unacceptable due to the large negative influence on part performance and uncertainties in accurately determining the knockdown [3]. Unfortunately, the amount of literature on the formation of waviness is less abundant. Moreover, a very limited amount of literature is available when focussing on TPCs. The available entries focus mainly on the forming process.

The mechanisms for the formation of fiber waviness in the literature can be divided into two loading conditions: axial compressive fiber stresses and transverse fiber stresses. Not all mechanisms have been investigated with respect to TPCs. However, a lot can be learned from research into their thermosetting counterparts.

1.2.1. Axial compressive fiber stress

The most reported loading condition for the formation of fiber
waviness is an axial compressive force on the fiber reinforcement. Fibers may buckle when subjected to such forces, causing waviness in the ply [7]. Three scales of buckling can be distinguished: bucking on the macroscale (laminate), mesoscale (ply/tow) and microscale (fiber).

Macroscopic buckling may arise during stamp forming of both commodity TPCs [8] and high performance TPCs [9]. Compressive fiber stresses originate from bending of the laminates in this process. laminate bending may also cause waviness in TSC parts that are produced with high tool temperatures [10] or double diaphragm forming [11]. Important associated aspects are ply-ply friction and the lay-up sequence, as they have a large influence on the formation of wrinkles for TSCs [12] and TPCs [13]. Nowadays macro-scale wrinkling can be predicted reasonably well [14] and software for wrinkling prediction is commercially available [15]. However, the simulation results are limited to large wrinkles [13]. It was demonstrated that the prediction of wrinkle formation in forming processes on the scale of a fiber or tow is in fact possible [16]. However, the authors used indirect indicators such as the shear angle, while a reliable prediction requires models based on the underlying physics.

Mesoscopic buckling can occur due to compressive fiber stresses in TSC processing when a stack of plies is debulked over a convex surface [17], during lay-up with automated fiber placement (AFP) [18], or during curing of stepped laminates, tapered laminates and laminates with gaps and overlaps from the AFP process, shown by modelling [19] and with experiments [20]. Similar studies for TPCs have not been reported in the literature.

Tool-ply interaction is another mechanism reported in the literature to cause an axial compressive stress in the fiber reinforcement on the mesoscale. A laminate can be strained when the coefficient of thermal expansion (CTE) of the tool is higher than the CTE of the fiber reinforcement. In TSCs this CTE mismatch may lead to fibers being stretched by the hot tool during curing, which cause shape distortions at room temperature [7]. Conversely, a CTE mismatch may lead to compressive fiber stresses by the shrinking tool in TPC processing, causing waviness. This was shown by observing fiber waviness after the production of T300/P1700 carbon fiber/polysulfone (C/PSU) laminates with a fiber volume fraction (Vf) of 60%, using tools with a varying CTE [21]. The use of tool plates with a high CTE yielded wavy laminates, while tool plates with a low CTE produced no observable waviness. It has been hypothesized that waviness must form while cooling through the glass transition temperature, since the processing temperature had no influence on waviness severity in C/PSU laminates [22]. C/PSU is a TPC with an amorphous matrix. It is unknown if the same conclusions hold for semi-crystalline TPCs, as they have a different solidification mechanism. The influence of tool-ply interaction on the formation of waviness in TPCs with a semi-crystalline matrix has not yet been reported in the literature.

In TSC processing, matrix shrinkage is often considered a source of axial compressive fiber stresses on the microscale. Researchers have modelled a single fiber embedded in thermoset resin during curing and concluded that matrix shrinkage may cause a fiber to buckle [23]. This effect has also been observed in-situ [24]. Buckling of a single fiber is highly dependent on the temperature evolution [25]. However, results from the single fiber experiments research are not directly transferable to laminate production. The stabilization surrounding a fiber in a ply is very different from a single fiber embedded in resin, because of the high Vf and fiber-fiber interaction [26]. Matrix shrinkage is a suggested mechanism for waviness formation in TPCs [27], although no evidence for this mechanism has been reported in the literature.

Axial compressive fiber stresses are more prone to cause waviness when a laminate has deconsolidated or decompacted. This can occur during the heating phase of the stamp forming process [28]. Similarly, TPC prepreg tapes desolidify during the heating phase of AFP lay-up [29]. Moisture release from the matrix and the release of residual stresses have been identified as the underlying mechanisms.

1.2.2. Transverse fiber stress

The other loading condition for waviness formation is a stress transverse to the fiber. The prominent mechanism reported in the literature is flow of material. Resin flow, which is inherent to the resin transfer molding (RTM) process for TSCs, may produce waviness in the fiber reinforcement [30]. Flow of material during production of laminates may originate from a pressure gradient during processing [31]. In TPC processing these can be caused by an improper thickness distribution or mold cavity mismatch in the case of matched mold consolidation [32]. However, transverse fiber stresses are not expected to play a role in the processes considered in this research.

1.3. Objective

Full control of the process is needed to reduce the occurrence of waviness in TPC parts. Therefore, the objective of this research is to describe the governing mechanisms for waviness formation in semi-crystalline TPCs during flat laminate consolidation. This is a prerequisite for the development of a predictive model. Furthermore, the relevant temperature interval for waviness formation must be determined, as it is yet unclear at which temperatures waviness is formed. This enables characterization of the required material properties for modeling purposes and leads to identification of the processing parameters that could be improved for the production of waviness-free laminates. This may readily lead to processing guidelines for minimization of waviness formation.

2. Experimental work

The proposed waviness formation mechanisms mentioned in literature could only be deducted a posteriori since observation of an actual part during processing has not been performed. Therefore, an
experimental setup has been designed to visually observe the formation of waviness during consolidation of flat TPC laminates. The physical mechanisms governing the formation of waviness may possibly be deduced from the visual observation.

2.1. Description of the vacuum assisted glass plate consolidation setup

The setup is built on a custom hotplate designed for vacuum bag consolidation of TPCs. An overview of the setup is shown in Fig. 2. An aluminum thermal diffuser plate is placed on top of the hotplate, followed by a graphite sheet and an aluminum caul sheet. The graphite sheet provides a slip plane between the aluminum heat diffuser and the caul sheet. This slip plane ensures that the thermal expansion of the aluminum caul sheet is not constrained by the layers below the caul sheet. Aluminum was selected as the caul sheet material for its high thermal expansion, which is associated with waviness formation [21]. The temperature was measured next to the glass plate using two thermocouples. Cooling was provided by compressed air flowing through cooling channels in the hotplate. Pressure was applied to the laminate by a vacuum bag. A small square was cut out of the vacuum film to create an observation window, which enables real-time observation of the composite. A camera was used to record the composite during processing. Details about these parts are listed in Table 1.

The glass plate was treated with Frekote NC700, a releasing agent designed for low friction surfaces during processing [33,34]. A Uplex 25S polyimide film was placed between the caul sheet and the composite. This film enables release of the composite from the caul sheet after processing, while retaining a high tool-ply friction during processing. This effect has been validated with the friction measurement device as described in [35] and shown in Fig. 3. A coefficient of Coulomb friction of 0.42 was found between the caul sheet and the composite, for a temperature of 385°C and a pressure of 1 bar. The high friction ensured that the composite followed the thermal expansion of the caul sheet, while moving freely along the glass surface.

Table 1

| Component        | Details                                                                 |
|------------------|-------------------------------------------------------------------------|
| Hotplate         | 400 × 400 mm Brass plate, 4 kW heating rods                            |
| Cooling          | Cooling channels with compressed air                                   |
| Aluminum diffuser| Aluminum 1050 alloy                                                    |
| Vacuum sealant   | Airtech A800-3G                                                        |
| Vacuum film      | Airtech Thermalimide E 50 μm                                            |
| Graphite plate   | Egraflex NR, 1 mm                                                       |
| Caul sheet       | Aluminum 1050 alloy, 304 × 304 × 1.5 mm                                 |
| Release media    | UBE Uplex 25S                                                           |
| Composite        | C/PEEK, 0.15 mm UD ply, 59 %V_f                                        |
| Glass plate      | Duran borosilicate 11 mm thickness                                     |
| Glass breather   | Airtech UHT 800                                                        |
| Camera           | IDS uEye U549xSE-M                                                      |

2.2. Materials

The caul sheet is a 1.5 mm thick aluminum 1050 alloy sheet with a CTE of 22·10^{-6} K^{-1} at room temperature. The glass plate is an 11 mm thick borosilicate plate with a CTE of 3.3·10^{-6} K^{-1} [36]. The composite material is C/PEEK, a unidirectional (UD) carbon fiber thermoplastic composite prepreg tape with a V_f of 59%. C/PEEK UD prepregs were supplied by Toray Advanced Composites (supplier T) [37] and Solvay (supplier S) [38]. Both prepregs contain AS4 fibers, with a small negative CTE of −0.63·10^{-6} K^{-1} [39]. The PEEK matrix in both prepregs has a glass transition temperature (T_g) of 143 °C and a melting point (T_m) of 343 °C. The CTE of neat PEEK resin is 55·10^{-6} K^{-1} at room temperature and 140·10^{-6} K^{-1} in melt [40]. Prepregs from different suppliers were tested to investigate the effect of a difference in fiber–matrix distribution between the material from these suppliers [29], since a resin-rich surface can potentially decrease the tool-ply interaction through a lubrication mechanism [41]. A cross section of both prepregs is shown in Fig. 4, where the differences in fiber–matrix distribution and the resin-rich layer are clearly visible between the two materials.

2.3. Method

Two types of experiments were performed. The first set of experiments was designed to observe the consolidation of the laminate using the setup shown in Fig. 2. The second series of experiments was designed to study the effect of processing conditions on wrinkle formation, using prepregs from both suppliers. Here, the glass plate was replaced by an aluminum caul sheet.
2.3.1. Real-time observation of the laminate surface during consolidation

Three single ply laminates of 300 mm x 300 mm were consolidated with the setup as described in Section 2.1, using the Toray Cetex TC1200 prepreg material without any pre-treatment. The following procedure was used as a baseline and is visualized in Fig. 5.

1. Apply vacuum to generate a pressure difference of 1 bar
2. Heat to $T_{\text{max}}$ (385 °C) at a rate of 8 °C/min
3. Dwell for 10 min at $T_{\text{max}}$
4. Cool to room temperature at a rate of 8 °C/min
5. Release vacuum and demould

The temperature was logged throughout the cycle and a picture from the camera was saved every 10 s. A time-lapse video was composed from the pictures with their corresponding temperature values embedded. Therefore, detection of waviness formation and other visual events becomes straightforward and the waviness formation temperature interval could be determined.

2.3.2. Influence of processing temperature and transverse plies

Kugler et al. observed that the maximum process temperature did not influence waviness formation for amorphous TPCs [22]. Therefore, experiments were performed to investigate if this also holds for semi-crystalline TPCs. The glass plate has been replaced with an aluminum caul sheet as visual observation is not necessary in these additional experiments. This ensured an equal tool-ply interaction on both sides of the laminate. The maximum temperature ($T_{\text{max}}$) was varied between 360–400 °C. Single ply [0] and four-ply [0/90] laminates were processed to investigate the effect of transverse plies in the lay-up. Prepregs from two different suppliers were tested to rule out supplier specific effects. No pre-treatments were performed on the material. The test matrix is available in Table 2. Three laminates were processed for each combination of parameters.

Surface micrographs were taken for nine patches of wavy fibers, evenly selected from each laminate, using a Keyence VHX-5000 microscope at a magnification of 200x. The micrographs were processed with a fiber tracing algorithm to determine the wavelength and maximum misalignment angle for the wavy fibers [42]. These wave parameters have been correlated to compressive strength [5], hence they quantify the severity of the produced waviness. Cross sectional micrographs of wavy patches were taken using aforementioned microscope, to study the through thickness propagation of the waviness for the four-ply laminates.

Table 2

| # | S & L | $T_{\text{max}}$ [°C] | $\lambda$ [mm] | $\theta$ [°] | $\lambda$ [mm] | $\theta$ [°] |
|---|---|---|---|---|---|---|
| 1 | T [0] | 360 | 3.40 ± 0.26 | 9.66 ± 1.37 | 3.30 ± 0.41 | 9.75 ± 1.48 |
| 2 | T [0] | 385 | 4.19 ± 0.62 | 15.44 ± 2.69 | 4.12 ± 0.53 | 15.14 ± 2.55 |
| 3 | S [0] | 385 | 4.91 ± 0.68 | 15.42 ± 1.03 | 4.91 ± 0.62 | 15.30 ± 1.89 |
| 4 | T [0] | 400 | 4.34 ± 0.35 | 17.84 ± 2.52 | 4.02 ± 0.45 | 17.18 ± 2.01 |
| 5 | T [0/90] | 385 | 3.58 ± 0.28 | 13.60 ± 1.75 | 3.82 ± 0.46 | 14.02 ± 1.59 |

3. Results

3.1. Real-time observation of the laminate surface during consolidation

Four pictures of key moments during the consolidation of a single ply are shown in Fig. 6 with their according temperature. The following observations were made:

(Fig. 6.1 $\rightarrow$ 6.2) No waviness formation was observed during heating from room temperature to $T_{\text{max}}$.

(Fig. 6.2 $\rightarrow$ 6.3) Formation of waviness was observed during cooling down from $T_{\text{max}}$. New waves were formed and existing waves gradually increased in severity. The movement of fibers had completely stopped at approximately 285 °C. The reflection of light on the ply changed around this temperature.

(Fig. 6.3 $\rightarrow$ 6.4) During cooling from 285 °C down to room temperature, no more formation of waviness was observed while existing waves did not change in shape anymore.

Waviness appeared at all places in the observation window, despite it being only visible at the edges in these pictures. This is due to difficulties with capturing waviness with the camera, since observation is only possible from a specific angle related to the incoming light.

3.2. Influence of processing temperature and transverse plies

The resulting wave parameters for all laminates that were consolidated between two caul sheets are shown in Table 2. Each experiment was performed three times and nine patches of wavy fibers were analyzed per laminate, to obtain the wavelength ($\lambda$) and maximum misalignment angle ($\theta$). The averaged wave parameters ($\bar{\lambda}, \bar{\theta}$) were determined by averaging all wavy patches in an experiment. Fig. 7

![Fig. 5. Temperature profile during consolidation.](image-url)
shows the surface of a four-ply laminate in which multiple patches of wavy fibers are visible. Although the picture may suggest otherwise, all patches solely exhibit in-plane waviness. The surface micrograph (outlined in red) is processed with the fiber tracing algorithm. All laminates exhibit fiber waviness in a similar way: patches of wavy fibers, scattered all over the surface with a waviness-free margin of approximately 3 cm from the edge, as illustrated in Fig. 8. These waves resemble sinusoids consisting of 1.5–2 periods. A bundle of fibers typically passes through three to five wavy patches when it is traced from one edge of the laminate to the other edge. The difference between the curvilinear length and span length of a fiber in one patch of waviness is approximately 0.15 mm.

Cross-sectional micrographs of a wavy patch in a four-ply laminate are shown in Fig. 9. The top image shows a cross section parallel to the surface fiber direction, where waviness is clearly visible in the bottom layer. Although waviness appeared in the outer ply on both sides of these laminates, the location of a wavy patch on one side of the laminate does not necessarily match the location of a wavy patch on the other side of the laminate. The bottom image shows a cross section perpendicular to the surface fiber direction. No waviness was observed in the middle plies.

The results for the experiments can be compared in Fig. 10, based on the results in Table 2. No significant differences in misalignment angle have been observed between the wavy patches in a single-ply and a four-ply laminate, and between both manufacturers. A significant increase in misalignment angle was observed with an increasing $T_{\text{max}}$ between 360–400 °C. No clear trend was observed for the wavelength.

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**Fig. 6.** Pictures of the observation window during a consolidation cycle of a single ply C/PEEK. (1) Start of cycle. (2) Maximum temperature, start of waviness formation during cooling. (3) End of waviness formation during cooling. (4) End of cycle. Please note that the edges of the observation window as illustrated in Fig. 2 are shown, not the laminate edges.

**Fig. 7.** Background: Picture of the surface of a four-ply laminate (#5 in Table 2). Patches of wavy fibers are clearly visible. Foreground: Surface micrograph with typical waviness as found by the experiments. A traced fiber is shown as a bold line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
4. Discussion

4.1. Real-time observation of consolidation through glass plate

Waviness formation was only observed during the cooling stage between $T_{\text{max}}$ and 285 °C. Waviness formation stopped at around 285 °C in all experiments. DSC measurements were performed using a Mettler Toledo DSC822E differential scanning calorimeter to explain this. Three samples of approximately 15 mg C/PEEK prepreg were analyzed in a nitrogen environment, to prevent degradation. The temperature profile from Fig. 5 was used.

The traces of the DSC measurements are shown in Fig. 11. This graph shows that crystallization of the C/PEEK composite took place between 305–285 °C. The latter temperature is the crystallization endset ($T_{\text{cryst}}$), which corresponds with the change in reflection of light on the ply during the observation experiments. This is a good estimate for the temperature where the matrix has fully solidified [43].

The difference between $T_{\text{max}}$ and $T_{\text{cryst}}$ will be called the waviness formation temperature interval:

$$\Delta T_w = T_{\text{max}} - T_{\text{cryst}}$$

(1)

4.2. Waviness formation mechanisms in the waviness formation temperature interval

An overview of the possible waviness formation mechanisms was given in Section 1.2. Deconsolidation and material flow have not been observed in the experiments. The remaining mechanisms are discussed next.

4.2.1. Matrix shrinkage

The matrix is in a molten, viscous state between $T_{\text{max}}$ and $T_{\text{cryst}}$. The storage modulus and viscosity of the matrix are low in this interval. Compressive fiber stresses arise from the CTE mismatch between the matrix and the fiber during cooling. However, when the matrix is in a viscous state, it is able to relax its internal stresses to some extent. Consequently, compressive fiber stresses are relaxed as well. Stress relaxation is much more difficult when the matrix is crystalline. Therefore, it is argued that if compressive fiber stresses are caused by differential shrinkage of the fiber and the matrix, they would primarily arise when the matrix is crystalline. However, no waviness formation has been observed in the experiments after crystallization.

Furthermore, no increased waviness formation or intensification has been observed during crystallization, when significant shrinkage of the matrix is taking place [44]. Hence, the contribution of matrix shrinkage to the formation of fiber waviness is considered negligible.

4.2.2. Tool shrinkage

The aluminum cauls sheets expand during heating and shrink during cooling. With the presence of tool-ply friction and a tool-ply CTE mismatch, the fibers will experience a tensile force during tool expansion. However, this tensile fiber force is limited by tool-ply slip when the maximum attainable tool-ply friction force is reached. During cooling the tool shrinks, imposing a compressive stress on the fibers. These compressive fiber stresses are the presumed driving force for fiber buckling and the observed patches of waviness. Evidence is found in the experimental results shown in Fig. 10. A higher $T_{\text{max}}$ leads to more tool shrinkage, which leads to a larger misalignment angle. The cross sections in Fig. 9 show that the waviness is a surface effect: it does not propagate through the thickness in a [0/90]$_s$ laminate. Furthermore, the amount of shrinkage for the 300 mm wide caul sheet is 0.66 mm when considering its linear CTE of $22 \cdot 10^{-6}$ K$^{-1}$ and a $\Delta T_w$ of 100 °C. The difference between the curvilinear length and span length of a fiber in a patch of waviness was approximately 0.15 mm. Since a fiber typically passes through three to five wavy patches, the total length difference is between 0.45–0.75 mm, which is roughly equal to the tool shrinkage.

Therefore, the conclusion in the literature, that $T_{\text{max}}$ has no influence on waviness formation in amorphous TPCs [22], is not applicable to semi-crystalline TPCs. The absence of crystallization in amorphous TPCs leads to a different solidification mechanism and a much more gradual increase of matrix viscosity and storage modulus during cooling.

4.2.3. Buckling resistance of the fiber–matrix system

The storage modulus of the matrix dictates the transverse stabilization of the fibers. A higher modulus provides a better quasi-static buckling resistance [45]. During $\Delta T_w$ the storage modulus of the matrix is low, hence the buckling resistance is low. At $T_{\text{cryst}}$ the matrix modulus is high, therefore the buckling resistance is also high.

Two situations occur during cooling: Below $T_{\text{cryst}}$ the buckling resistance is high and compressive fiber forces due to matrix shrinkage are high. Above $T_{\text{cryst}}$ the matrix is in melt: the buckling resistance is low and compressive fiber stresses can be dissipated through the viscous matrix. In the experiments described in this paper, waviness
formation is only observed above $T_{\text{cryst}}$ where the buckling resistance of the fiber-matrix system is low. Therefore it is argued that formation of waviness in semi-crystalline TPCs takes place during cooling, before crystallization, with tool shrinkage imposing a compressive axial force on the fibers. This statement motivates further investigation into the role of tool-ply friction and tool material CTE on the formation of fiber waviness during semi-crystalline TPC processing. Improving these aspects of the process could minimize or eliminate fiber waviness in TPC laminate consolidation. Ongoing experiments using low CTE Kovar tool plates yielded no waviness, which is in line with the proposed mechanisms. A more elaborate investigation concerning multiple tool materials, tool-ply friction coefficients and laminate lengths will be submitted for publication in due time.

5. Conclusions

An experimental setup for real-time observation of waviness formation during the production of thermoplastic composite laminates has been presented in this paper. It was successfully used to produce laminates with patches of wavy fibers, to observe the formation of waviness and to determine the temperature interval in which waviness formation takes place in C/PEEK prepregs.

It can be concluded that fiber waviness in TPCs forms during cooling between the maximum process temperature ($T_{\text{max}}$) and the crystallization temperature ($T_{\text{cryst}}$). This temperature interval is called the waviness formation temperature interval and has been defined as $\Delta T_w = T_{\text{max}} - T_{\text{cryst}}$. It should be mentioned that the waviness severity did not increase below $T_{\text{cryst}}$ and no new waviness formation was observed. One key observation was that the maximum misalignment angle of the wavy fibers increased when $\Delta T_w$ increases.

The driving force for waviness formation during C/PEEK consolidation was determined to be an axial compressive stress on the fiber, caused by tool displacements that are transferred to the laminate via tool-ply friction. The waviness can be considered a surface phenomenon, as it was not observed in plies below the surface. Matrix dominated mechanisms, such as matrix shrinkage, were considered negligible since the formation of fiber waviness was only observed in the temperature interval with a low matrix storage modulus.

The determined waviness formation temperature interval and governing mechanisms can now be used in a modelling approach, with the objective of producing guidelines for waviness-free laminates. The tool-ply friction, the coefficient of thermal expansion of the tool material and the maximum processing temperature were the identified parameters that can be altered to decrease the waviness severity.

CRediT authorship contribution statement

**E.T.M. Krämer:** Conceptualization, Methodology, Investigation, Writing - original draft. **W.J.B. Grouve:** Conceptualization, Supervision, Writing - review & editing. **S. Koussios:** Resources, Writing - review & editing. **L.L. Warnet:** Conceptualization, Supervision. **R. Akkerman:** Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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![Graph of Heat flux vs. Temperature](image)

**Fig. 11.** Relevant part of the DSC heating and cooling trace for three C/PEEK samples. The temperature profile from **Fig. 5** is used in these experiments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
