

Solid-state stamp forming of UD CF/PA6: Forming window and defect evolution

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Abstract

Solid-state stamp forming offers a route to retain fibre and ply support in unidirectional carbon-fibre-reinforced thermoplastics (UD CFRTs), but insufficient matrix softening increases forming resistance and defect formation. This study investigates the solid-state forming window of cross-ply UD carbon fibre/polyamide 6 (CF/PA6) through finite-element analysis, dome-forming experiments and X-ray computed tomography (CT). Blank shape and ply blocking were examined as controlled comparisons, while temperature was treated as the principal process variable. The simulations predicted progressively less wrinkling with increasing temperature, whereas the experiments showed that overall forming quality did not improve monotonically as the laminate softened. At 180 °C, high forming resistance resulted in extensive surface cracking and severe local deformation. Among the temperatures tested, the 195 and 205 °C conditions provided the most favourable surface response, whereas at 215 °C and in the 260 °C melt-state reference, fibre waviness, inter-ply movement and shape instability became more pronounced as fibre and ply support decreased. CT further showed that the cleaner surface of the 195 °C component did not correspond to better internal quality, with more pronounced delamination in the examined CT sections than in the 205 °C component. The numerical model reproduced the global component dimensions with differences of 1.62–9.91% and captured the principal wrinkle regions. These results show that the useful solid-state forming window is governed by competing temperature-dependent mechanisms: excessive forming resistance at the lower-temperature side and insufficient fibre and ply support at the higher-temperature side.

Keywords

UD CF/PA6; Solid-state stamp forming; Temperature-dependent defect evolution; Ply blocking; X-ray computed tomography

1 Introduction

Continuous-fibre-reinforced thermoplastic composites are attractive for lightweight structures because they combine high specific mechanical properties with short processing cycles and the potential for automated manufacturing [1,2]. Stamp forming provides a high-rate route for converting pre-consolidated thermoplastic laminates into complex components [1,3–5]. Among these materials, unidirectional (UD) tape laminates offer additional design flexibility because fibre orientations can be tailored to structural loading, but their forming behaviour is more difficult to control. Their high longitudinal stiffness, low transverse strength and strong anisotropy make the forming response sensitive to material draw-in, bending, inter-ply sliding and local compression [6–10].

Wrinkling is one of the main limitations in forming UD thermoplastic laminates, particularly for doubly curved geometries. It develops when the laminate cannot conform to the tool geometry through the available in-plane deformation, bending and inter-ply movement [7,11,12]. Recent press-forming studies have shown that blank geometry and lay-up strongly influence wrinkle development and local deformation [10,13], while surface quality and fibre waviness are also sensitive to forming parameters and deformation history [14,15]. These observations indicate that overall forming quality cannot be assessed from wrinkling alone.

Other defect modes become important when deformation is accommodated through excessive local movement. Inter-ply sliding influences load transfer and relative movement between adjacent plies [8,16,17], while recent work on compressed UD CF/PA6 interfaces has shown that frictional sliding resistance can remain active after local cohesive load transfer is lost [18,19]. Tool-ply sliding additionally affects material draw-in at the tooling interface [20]. Excessive relative movement can promote local thickness variation and fibre waviness; the latter can reduce compressive strength [21]. Fibre splitting provides an additional limitation because the transverse strength of UD laminates is much lower than the fibre-direction strength [9]. Successful forming therefore requires sufficient material mobility to conform to the tool while retaining enough fibre and ply support to suppress wrinkling, splitting, waviness and excessive inter-ply movement.

Temperature controls the balance between material mobility and fibre and ply support during UD thermoplastic forming. Most reported stamp-forming studies of UD thermoplastic laminates heat the matrix to, or close to, the melt state to reduce forming resistance [3,4,6,22,23]. This increases material mobility and facilitates rapid shaping, but can also promote inter-ply sliding and reduce the support provided by the polymer matrix [17,24,25]. For the UD CF/PA6 studied here, previous material characterisation showed strong temperature dependence of the transverse tensile and intra-ply shear responses between 180 and 220 °C, whereas the strain-rate effect was smaller over the tested range [26]. The solid-state response of PA6 is likewise strongly temperature dependent [27]. Together, these findings indicate two competing effects of temperature: insufficient softening restricts deformation and promotes cracking or wrinkling, whereas excessive softening reduces fibre and ply support and promotes fibre waviness and inter-ply movement.

Solid-state forming has been demonstrated for thermoplastic laminates [28,29], and a constitutive model has been developed for the present UD CF/PA6 under solid-state forming conditions [26]. However, it remains unclear how this material behaviour translates to the forming of a doubly curved cross-ply laminate and how the useful solid-state forming window is governed at its lower- and higher-temperature sides. In particular, reducing forming resistance with increasing temperature does not necessarily lead to a monotonic improvement in forming quality, because the dominant defect mode may change as the laminate softens. Recent UD press-forming studies have examined wrinkling, local deformation, surface quality and numerical validation in detail [3,4,10,13,14], but internal quality has been less commonly incorporated into forming assessments. This leaves two closely related questions: which mechanisms govern the lower- and higher-temperature sides of the useful solid-state forming window, and whether surface quality alone is sufficient to identify favourable forming conditions.

The present study therefore combines finite-element investigation, forming experiments and internal-quality assessment for cross-ply UD CF/PA6. A previously developed constitutive model [26] is implemented in a dome-forming finite-element model to examine the effects of blank shape and ply blocking as controlled comparisons, while temperature is treated as the principal process variable. Forming experiments are then conducted using a rapid cold-tool route over 180–260 °C to determine how the predicted reduction in wrinkling with increasing temperature relates to the experimentally observed evolution of cracking, fibre waviness and inter-ply movement. Surface inspection and X-ray CT are used together to assess surface and

internal quality, including internal delamination, followed by numerical–experimental comparison of the selected forming condition. The central contribution is to show that the dominant defect mode changes with temperature and to identify the different mechanisms governing the two sides of the useful solid-state forming window: high forming resistance at the lower-temperature side and insufficient fibre and ply support at the higher-temperature side.

The remainder of the paper is organised as follows. Section 2 presents the numerical investigation; Sections 3 and 4 describe the experimental methodology and forming response, respectively; Section 5 evaluates internal quality and validates the numerical model for the selected forming condition; Section 6 discusses the solid-state forming window, the roles of blank shape and ply blocking, and the resulting process implications; and Section 7 summarises the main conclusions.

2 Numerical investigation

The numerical investigation used Abaqus/Explicit to examine the effects of blank shape, ply blocking and temperature on the deformation and wrinkling of cross-ply UD CF/PA6. Blank shape and ply blocking were first compared to establish a consistent geometric and laminate configuration for the subsequent temperature study. Temperature was then investigated using the Type B blank and three-ply-blocked laminate, with the preceding variables held fixed.

2.1 Model setup

The finite-element model was constructed to reproduce the dome-forming geometry, laminate configuration and loading conditions used in the experiments. The model setup included the tool geometry and boundary conditions, the bending formulation for the UD laminate, the temperature-dependent material properties and the contact conditions.

2.1.1 Geometry and boundary conditions

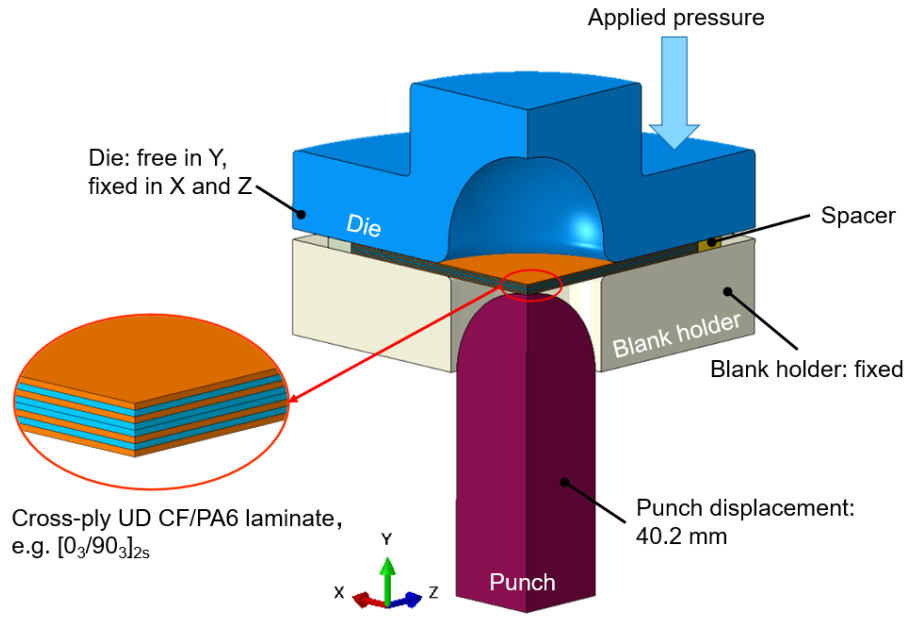


Figure 1. Finite-element assembly and boundary conditions for dome forming, including the representation of the cross-ply UD CF/PA6 laminate.

Figure 1 shows the finite-element assembly and boundary conditions. The punch, die, blank holder and spacers were modelled as rigid tools, while the workpiece represented the corresponding cross-ply UD CF/PA6 laminate. For the three-ply-blocked laminate, each three-ply block of the same fibre orientation was represented by one effective numerical layer with a thickness of 0.4125 mm, giving a total laminate thickness of 3.3 mm. A 40.2 mm punch displacement was applied in the forming direction at a speed of 100 mm/s, corresponding to a loading duration of 0.402 s. The die was free to move in this direction and constrained in the remaining degrees of freedom, while the blank holder was fully constrained. A pressure of 2.77 MPa was applied to the die, corresponding to a total experimental blank-holding force of 60 kN. Owing to the geometric and laminate symmetry, one quarter of the forming assembly was modelled using symmetry conditions on the X-Y and Y-Z planes.

2.1.2 Bending formulation

The bending resistance of UD prepreg plies is substantially lower than that implied by their in-plane stiffness [30]. A conventional continuum formulation can therefore over-couple the membrane and bending responses, suppressing the local bending deformation associated with wrinkle formation. Separate representations of the in-plane and bending responses have consequently been adopted in composite-forming simulations [31–33].

Following the approach of Dörr et al. [33], superimposed membrane and shell elements sharing the same nodes were used to represent the in-plane and bending responses of the UD CF/PA6 laminate.

The effect of the bending formulation is illustrated in Figure 2 using simulations conducted at 200 °C. The conventional solid-element model (Figure 2a) produced a comparatively smooth deformation field and did not capture the local wrinkling predicted by the superimposed formulation. In contrast, the combined membrane–shell model (Figure 2b) developed pronounced local wrinkles in the formed region. The superimposed membrane–shell formulation was therefore adopted for all subsequent simulations.

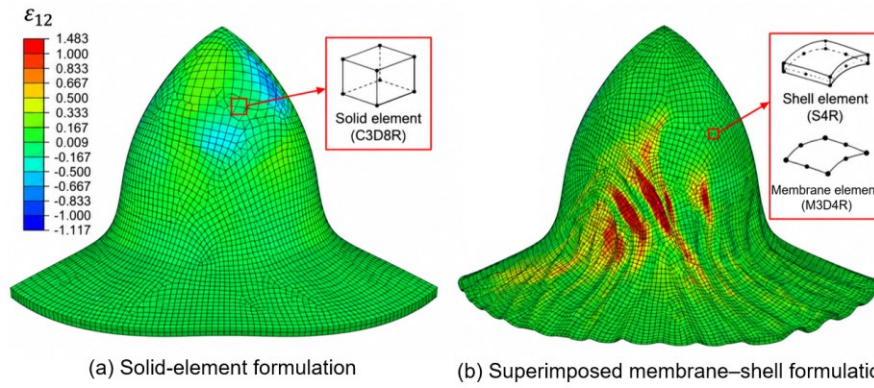


Figure 2. Effect of bending formulation on the predicted forming response at 200 °C: (a) conventional solid-element formulation and (b) superimposed membrane–shell formulation.

2.1.3 Model inputs

The main model inputs are summarised in Table 1. A density of 1.15×10^{-9} tonne/mm³ was used in the simulations [34]. The in-plane response was described using the temperature-dependent constitutive model and corresponding VUMAT previously developed for the same UD CF/PA6 material [26]. The bending response was represented by temperature-dependent linear-elastic engineering constants, with the transverse modulus E_{22} estimated from the PA6 data reported in Ref. [27]. Inter-ply and tool-ply friction coefficients were adopted from Ref. [35].

Table 1. Main inputs for the finite-element model.

Category	Parameter	Value / description
UD	Density, ρ	1.15×10^{-9} tonne/mm ³
CF/PA6	In-plane response	M3D4R; temperature-dependent VUMAT [26]
	Bending response	S4R; temperature-dependent linear-elastic engineering constants
	Transverse modulus, E_{22}	115.57 MPa at 180 °C; 93.55 MPa at 190 °C; 72.61 MPa at 200 °C; 52.65 MPa at 210 °C [27]
Contact	Poisson's ratios	$\nu_{12} = \nu_{13} = \nu_{23} = 0.32$
	Inter-ply friction coefficient	0.3812 [35]
	Tool-ply friction coefficient	0.1218 [35]
Tools	Tool representation	Rigid bodies
Process	Initial laminate temperature	180–210 °C
	Blank-holding pressure	2.77 MPa (60 kN total)

2.2 Effects of forming variables

The numerical results are presented for blank shape, ply blocking and temperature. Blank shape and ply blocking are examined first, followed by temperature.

2.2.1 Blank shape

Blank shape affects both the material available for draw-in and the flange area over which blank-holder restraint is applied. Previous UD press-forming studies have similarly shown that blank geometry can strongly influence local deformation and wrinkle development [10,13]. Three blank geometries were therefore compared (Figure 3). Type A was a circular blank with a diameter of 150 mm. Type B removed material from the regions where excess flange material accumulated in Type A, while Type C introduced further trimming that reduced both the local flange width and the maximum blank dimension to 140 mm.

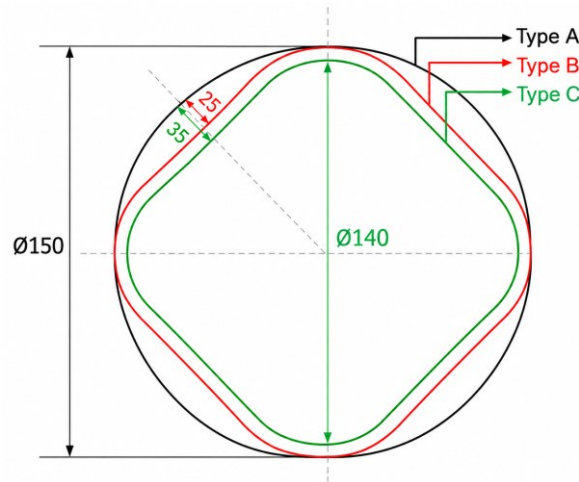


Figure 3. Blank geometries used in the numerical and experimental comparisons. Type A is a circular blank with a diameter of 150 mm; Types B and C are obtained by trimming the Type A blank by 25 mm and 35 mm, respectively, in the indicated regions; Type C has a maximum blank dimension of 140 mm.

Figure 4 compares the predicted in-plane shear strain, ε_{12} , distributions and the corresponding deformed flange geometries for the three blank shapes. The strain contours are used to compare the distribution and localisation of deformation rather than as a failure criterion. Type A retained excess material in region ① and developed pronounced localised deformation. Type B reduced this flange accumulation and produced a more uniform deformed profile around the dome. Further trimming in Type C reduced the local flange width near region ③ and the maximum blank dimension to 140 mm, with increased wrinkling in this region. These results indicate that removing excess flange material promotes more balanced material draw-in, whereas excessive trimming reduces the area available for blank-holder control and increases local wrinkling. Type B was therefore selected for the subsequent temperature study.

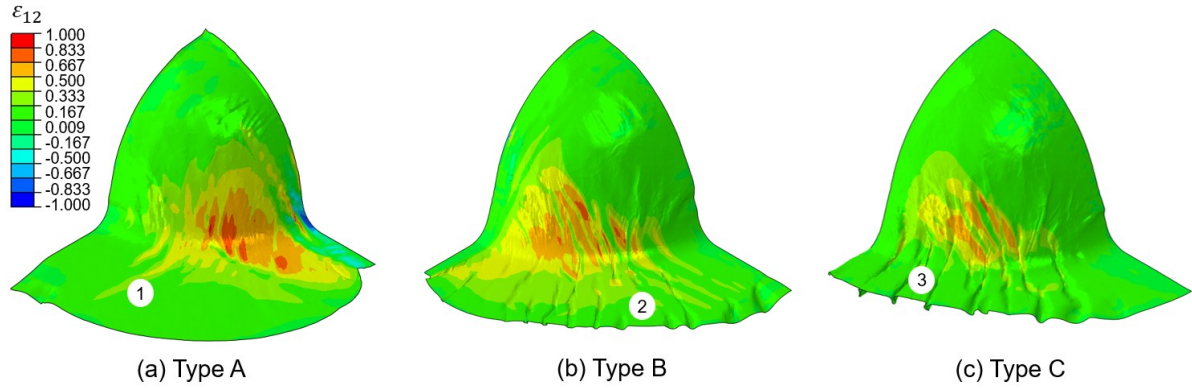


Figure 4. Effect of blank geometry on the predicted in-plane shear strain distribution and corresponding deformed flange geometry: (a) Type A, (b) Type B and (c) Type C.

2.2.2 Ply blocking

Ply blocking groups adjacent plies with the same fibre orientation into thicker blocks while keeping the overall laminate thickness unchanged. In the FE model, each same-orientation block was represented by one effective numerical layer, giving 8, 12 and 24 numerical layers for the three-ply-blocked, two-ply-blocked and single-ply-blocked configurations, respectively. Increasing the number of plies within each block alters how deformation is accommodated within the same-orientation plies and reduces the number of interfaces available for relative sliding between neighbouring blocks. Because bending, in-plane deformation and inter-ply sliding all contribute to wrinkle formation in multilayer thermoplastic laminates [17,36], the ply-blocking configuration can directly affect the resulting deformation pattern. Three cross-ply configurations were compared: $[0_3/90_3]_{2S}$, $[0_2/90_2]_{3S}$ and $[0/90]_{6S}$, hereafter referred to as the three-ply-blocked laminate, two-ply-blocked laminate and single-ply-blocked laminate, respectively. Here, single-ply-blocked means that each same-orientation block contains one ply, rather than that the laminate consists of only one ply.

Complete temperature-dependent failure data were not available for all relevant deformation modes. The maximum in-plane principal stress was therefore used only as a comparative indicator of local stress concentration, rather than as a failure criterion. Figure 5 shows that the two- and three-ply-blocked laminates developed lower local stress concentrations than the single-ply-blocked laminate, with the three-ply-blocked laminate showing the lowest levels among the three cases. In contrast, the through-thickness profiles in Figure 6 show that inter-ply wrinkling became more persistent as the ply-block thickness increased. Wrinkles remained evident at the 10 and 15 mm sections in the two- and three-ply-blocked configurations, whereas they were substantially reduced in the single-ply-blocked laminate. Ply blocking therefore changes the balance between local stress concentration and inter-ply wrinkling rather than uniformly improving the forming response.

The numerical comparison therefore revealed competing effects of ply blocking rather than a uniformly superior configuration. The three-ply-blocked laminate was carried forward for subsequent study because it showed the lowest local stress concentration, while the single-ply-blocked laminate was retained for a direct experimental comparison of surface integrity. The two-ply-blocked laminate was used only to establish the intermediate numerical trend.

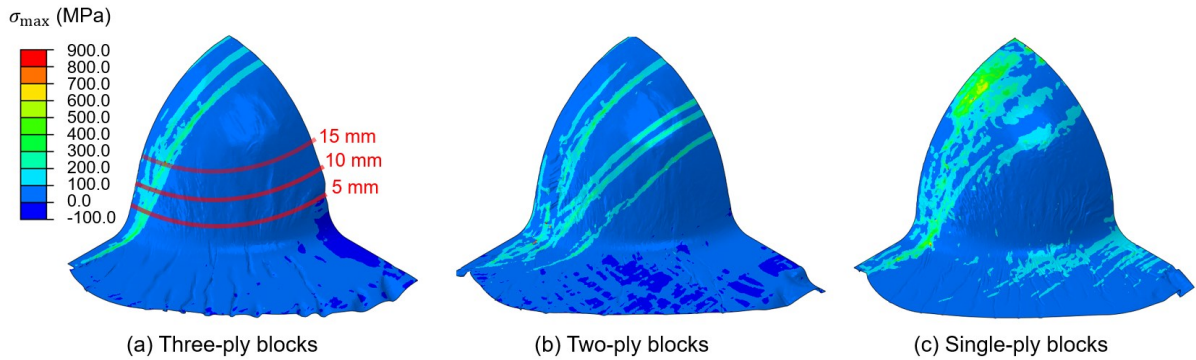


Figure 5. Predicted maximum in-plane principal stress distributions for different ply-blocking configurations: (a) three-ply-blocked laminate, (b) two-ply-blocked laminate and (c) single-ply-blocked laminate.

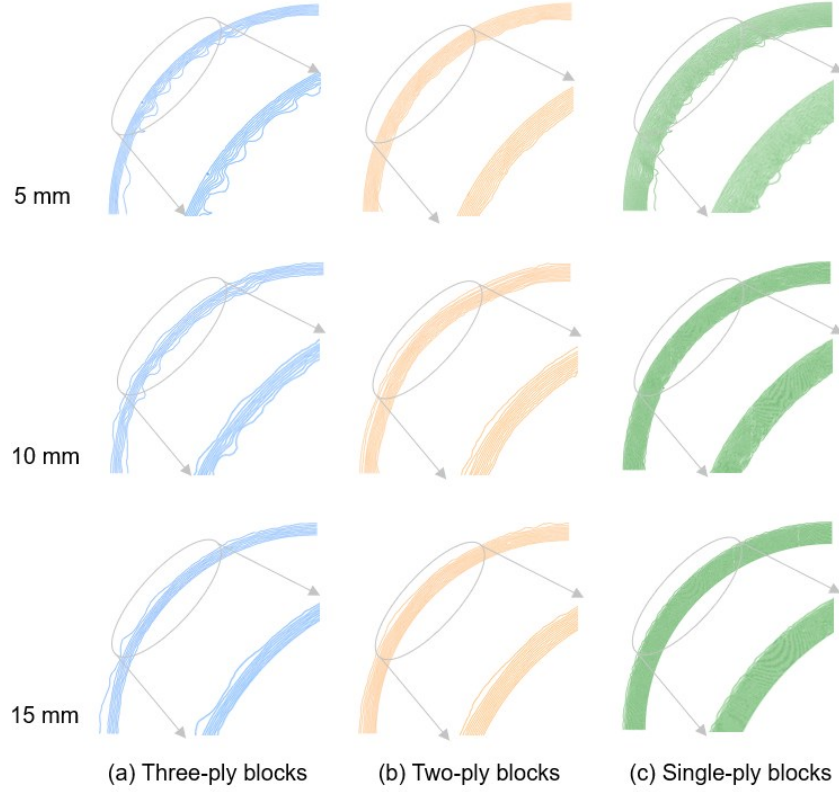


Figure 6. Through-thickness deformation profiles for different ply-blocking configurations at 5, 10 and 15 mm from the dome base. Columns correspond to (a) three-ply-blocked laminate, (b) two-ply-blocked laminate and (c) single-ply-blocked laminate, while rows indicate the three section locations.

2.2.3 Temperature

Temperature was varied from 180 to 210 °C using the Type B blank and the three-ply-blocked laminate. This range covers the strong temperature-dependent response previously measured for the same UD CF/PA6 material [26]. Figure 7 shows that regions of relatively high in-plane shear strain, ε_{12} , became more extensive as temperature increased. This indicates that a larger proportion of the forming deformation occurred through in-plane shear as the material softened and the forming resistance decreased. The strain contours are used here to compare the deformation response rather than as a failure criterion.

Wrinkling was evaluated separately using the modified mean curvature proposed by Dörr [35]:

$$\bar{\kappa} = (|SK_1| + |SK_2|) / 2, \quad (1)$$

where $\bar{\kappa}$ is the modified mean curvature, and SK_1 and SK_2 are the changes in curvature in the local material 1- and 2-directions, respectively. The curvature quantities have units of inverse length.

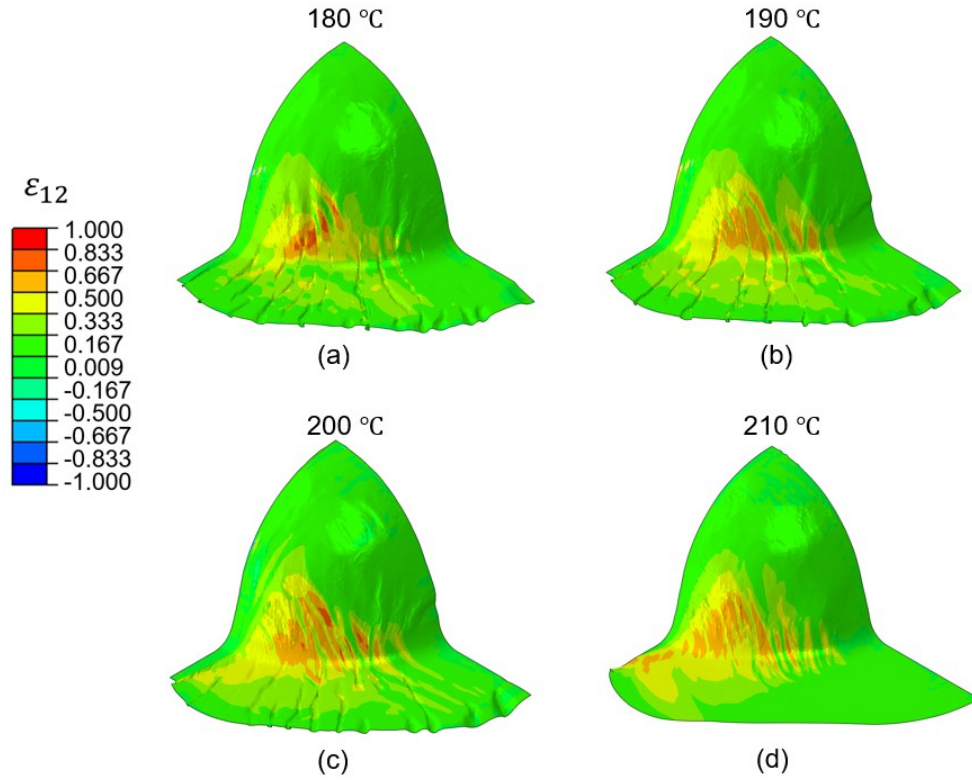


Figure 7. Effect of temperature on the predicted in-plane shear strain distribution: (a) 180 °C, (b) 190 °C, (c) 200 °C and (d) 210 °C.

The modified mean curvature distributions in Figure 8 show a progressive reduction in wrinkling with increasing temperature. Regions of high curvature are pronounced at 180 and 190 °C, become less evident at 200 °C, and are largely suppressed at 210 °C. If forming quality were assessed from wrinkling alone, the numerical results would therefore favour the higher end of the investigated temperature range. However, the temperature-dependent material response [26] and bending properties in Table 1 indicate substantial softening as temperature increases. Increasing temperature reduces forming resistance but simultaneously reduces the fibre and ply support available to control local deformation. The numerical model therefore captures the temperature-driven reduction in wrinkling but cannot, by itself, establish whether overall forming quality continues to improve, because fibre splitting and delamination are not represented in the present model.

The Type B blank and three-ply-blocked laminate were therefore carried forward to the experimental temperature series. The single-ply-blocked laminate was retained for the separate ply-blocking comparison, while a melt-state trial was included to provide a reference for comparison with the solid-state conditions.

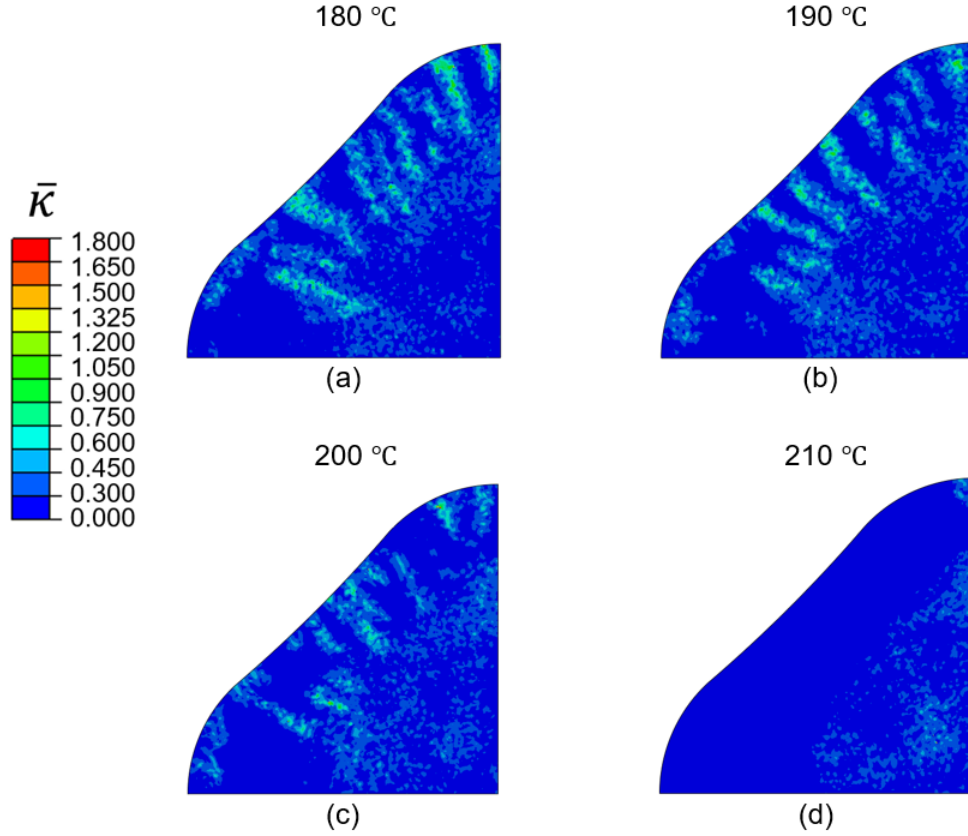


Figure 8. Effect of temperature on the predicted modified mean curvature distribution for the top blocked layer, mapped onto the initial blank: (a) 180 °C, (b) 190 °C, (c) 200 °C and (d) 210 °C.

3 Forming experiments

Blank shape and ply blocking were first compared with the corresponding numerical trends. The Type B blank and three-ply-blocked laminate were then used for the main temperature series, allowing cracking, wrinkling, fibre waviness and inter-ply movement to be compared primarily as a function of forming temperature.

3.1 Setup and specimens

The experimental setup comprised a high-rate forming system, room-temperature dome-forming tools and pre-consolidated UD CF/PA6 laminates. The forming system and specimen preparation are described below.

3.1.1 Forming setup

The forming experiments were conducted using a 250 kN high-rate forming machine (Figure 9a). A furnace positioned adjacent to the machine was used to heat the UD CF/PA6 blanks before rapid transfer to the forming tools. The laminate temperature was monitored using K-

type thermocouples connected to a data logger, allowing the heating and transfer conditions to be calibrated for each target forming temperature.

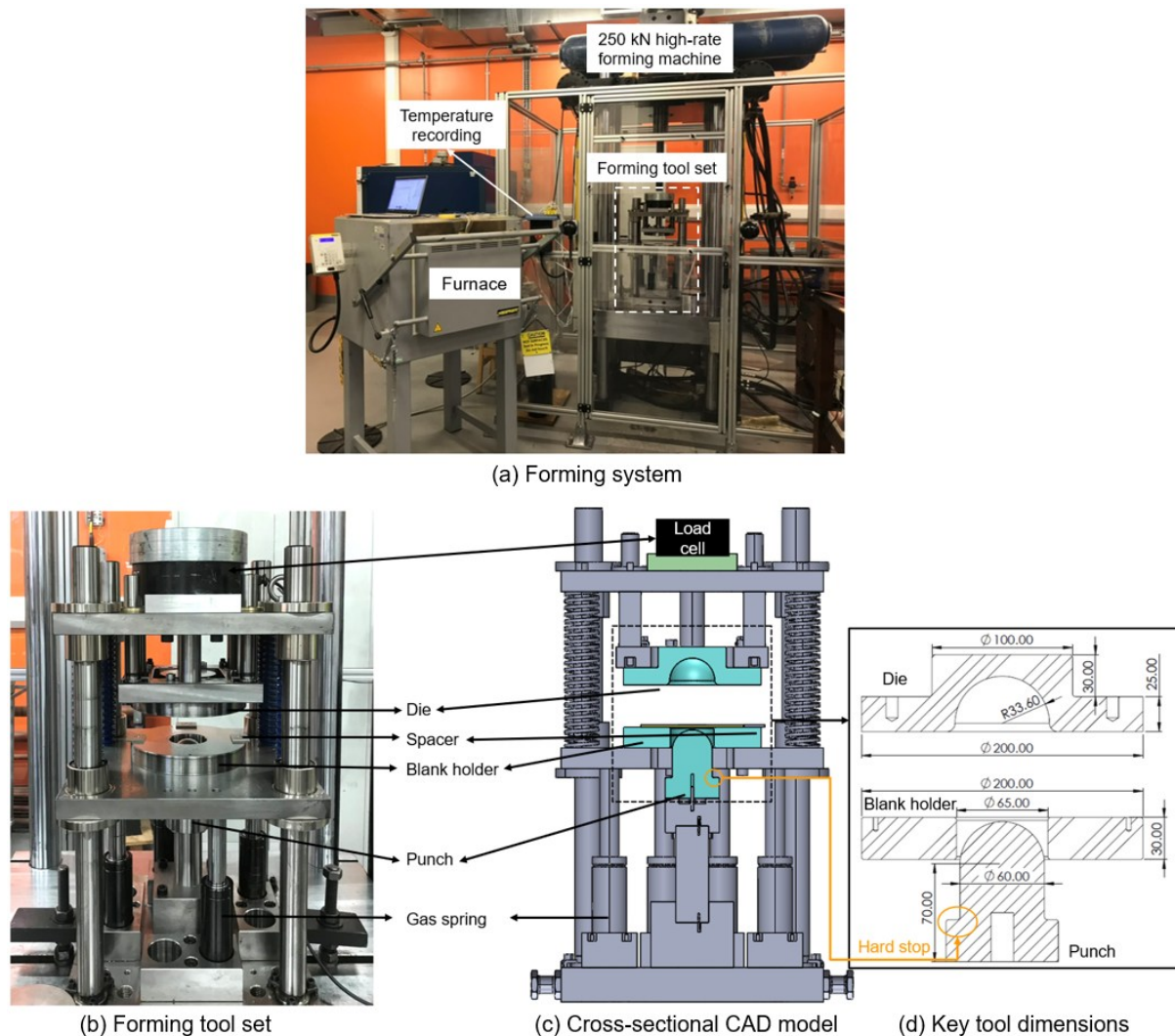


Figure 9. Experimental setup for UD CF/PA6 stamp forming: (a) high-rate forming system, (b) forming tool set, (c) cross-sectional CAD model of the tool assembly, and (d) key dimensions of the dome-forming tools.

The tool set comprised a forming frame and H13 steel dome-forming tools (Figure 9b–d). The frame incorporated a movable upper assembly and a fixed lower assembly, with four gas springs, each providing 15 kN, giving a total blank-holding force of 60 kN. The dome-forming punch had a diameter of 60 mm. The die geometry incorporated a clearance allowance of 10% relative to the laminate thickness, while 3.4 mm spacers limited the final tool closure and prevented excessive through-thickness compression.

During forming, the upper die moved downward while the punch remained fixed relative to the lower frame. A hard stop prevented further closure once the blank holder contacted the hard

stop. The forming tools were initially at room temperature, and forming and subsequent cooling were carried out in the same cold-tool operation.

3.1.2 Laminate preparation

Commercial UD CF/PA6 prepreg (Toray Cetex TC910 [34]) with an initial ply thickness of 0.16 mm [26] was used. The 24-ply laminates had a consolidated thickness of 3.3 mm, corresponding to an average consolidated ply thickness of 0.1375 mm. Previous differential scanning calorimetry (DSC) measurements for this material reported a PA6 melting peak at approximately 221 °C [18,19]. The 180–215 °C forming conditions are therefore referred to here as the below-melting-peak, or solid-state, range, while 260 °C provides a melt-state reference.

Three-ply-blocked and single-ply-blocked laminates were consolidated before forming using the hot-press cycle reported in Ref. [26]. The consolidation temperature was 250 ± 10 °C. An initial pressure of 0.2 MPa was applied during heating; once the target temperature was reached, the pressure was increased to 0.4 MPa and maintained for 20 min. The laminates were subsequently cooled to 80 °C under a sustained pressure of 0.4 MPa. The consolidated laminates were inspected by ultrasonic C-scan to verify the consolidation quality and subsequently water-jet cut into the required blank geometries.

3.2 Temperature calibration and test matrix

The Type B blank and three-ply-blocked laminate were used for the main temperature series. Because the heated laminate cooled during transfer from the furnace to the room-temperature tools, the furnace set point did not directly represent the actual forming temperature. The furnace set point required for each target forming temperature was therefore calibrated experimentally using the laminate temperature measured at the start of forming.

A calibration laminate was instrumented with four 0.076 mm-diameter K-type thermocouples inserted into 2 mm-diameter holes drilled from the laminate edge to a depth of approximately 10 mm. Figure 10 shows a representative temperature history for the 205 °C forming condition. The forming temperature was defined as the mean temperature measured by the four thermocouples at the end of transfer, immediately before forming. Video analysis showed that transfer from the furnace to the forming tools took approximately 8 s.

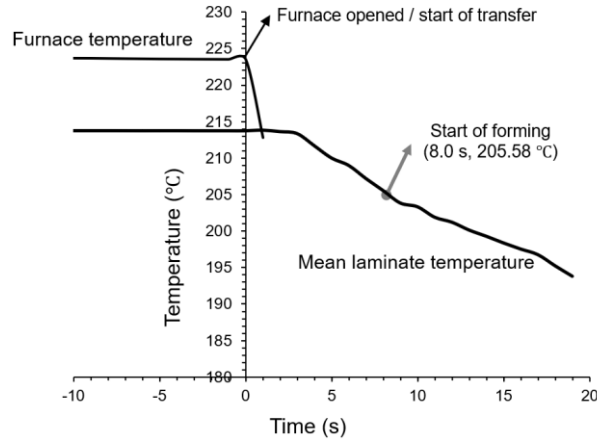


Figure 10. Representative laminate temperature history during transfer for the target 205 °C forming condition. The forming temperature was defined as the mean laminate temperature at the end of transfer, immediately before forming.

The experimental conditions are summarised in Table 2. The die moved at 100 mm/s, giving a forming time of approximately 0.4 s, followed by a holding period of 30 s. Trials 1–3 compared the three blank geometries at a target forming temperature of 205 °C, while Trials 3 and 4 compared the three-ply-blocked and single-ply-blocked laminates under otherwise identical conditions. Trials 2 and 5–7 constituted the solid-state temperature series from 180 to 215 °C using the Type B blank and three-ply-blocked laminate. Trial 8 provided a 260 °C melt-state reference using the same rapid cold-tool route.

Table 2. Experimental matrix for the UD CF/PA6 stamp-forming trials.

Trial	Target forming temperature (°C)	Blank type	Laminate configuration
1	205	Type A	$[0_3/90_3]_{2s}$
2	205	Type B	$[0_3/90_3]_{2s}$
3	205	Type C	$[0_3/90_3]_{2s}$
4	205	Type C	$[0/90]_{6s}$
5	180	Type B	$[0_3/90_3]_{2s}$
6	195	Type B	$[0_3/90_3]_{2s}$
7	215	Type B	$[0_3/90_3]_{2s}$
8	260 (melt state)	Type B	$[0_3/90_3]_{2s}$

4 Forming response

The forming results are presented first for blank shape and ply blocking, followed by the temperature series. The first two comparisons assess whether the experimental forming response is consistent with the corresponding numerical trends, while the temperature series addresses the main process question: whether lowering the forming resistance continues to improve overall forming quality, or whether the dominant defect mode changes as the laminate softens.

4.1 Blank shape

Figure 11 compares the components formed from the three blank geometries at a target forming temperature of 205 °C. Type A retained excess material in the flange region (①) and developed pronounced local wrinkling along the side wall (②). Type B reduced the flange accumulation and produced a more uniform deformed profile around the dome, although local wrinkles remained in regions (③) and (④). Further trimming in Type C reduced the local flange width in region (⑦) and the overall blank dimension, while local wrinkling remained evident in regions (⑤) and (⑥). Compared with Type B, the additional trimming did not provide a further improvement in the formed profile, suggesting that the reduced flange area limited the effectiveness of blank-holder restraint. These observations are consistent with the numerical trends and indicate that blank geometry must balance excess flange material against sufficient area for blank-holder control. Type B was therefore retained for the subsequent temperature series.

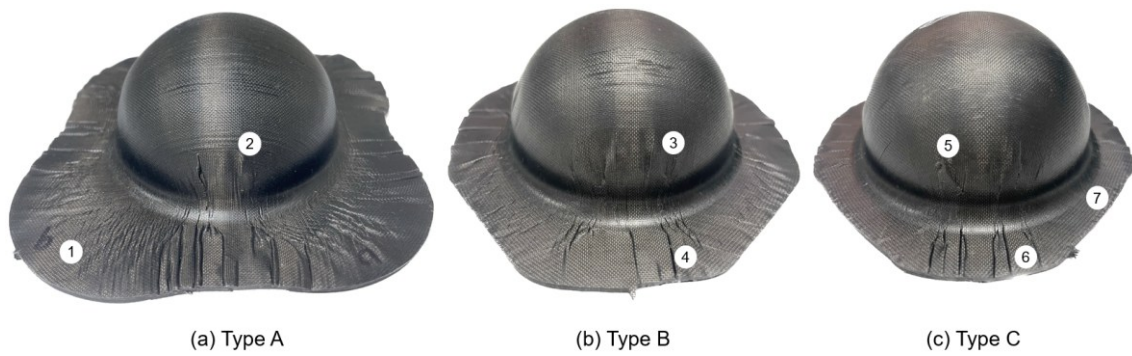


Figure 11. Effect of blank geometry on the formed components: (a) Type A, (b) Type B and (c) Type C. Region ① indicates excess flange material, regions ②–⑥ indicate local wrinkling, and region ⑦ indicates the locally reduced flange width.

4.2 Ply blocking

Figure 12 compares the three-ply-blocked laminate with the single-ply-blocked laminate using the same Type C blank at 205 °C. The single-ply-blocked laminate developed several visible surface splits on the dome, whereas no comparable splitting was observed on the three-ply-blocked laminate. Although both configurations exhibited local wrinkling, no clear reduction in overall wrinkle severity could be established from the experimental comparison. The most distinct experimental difference was therefore the better surface integrity of the three-ply-blocked laminate. This observation is consistent with the lower local stress concentration predicted for the three-ply-blocked laminate in Section 2.2.2. The three-ply-blocked laminate was therefore retained as the fixed laminate configuration for the subsequent temperature study.

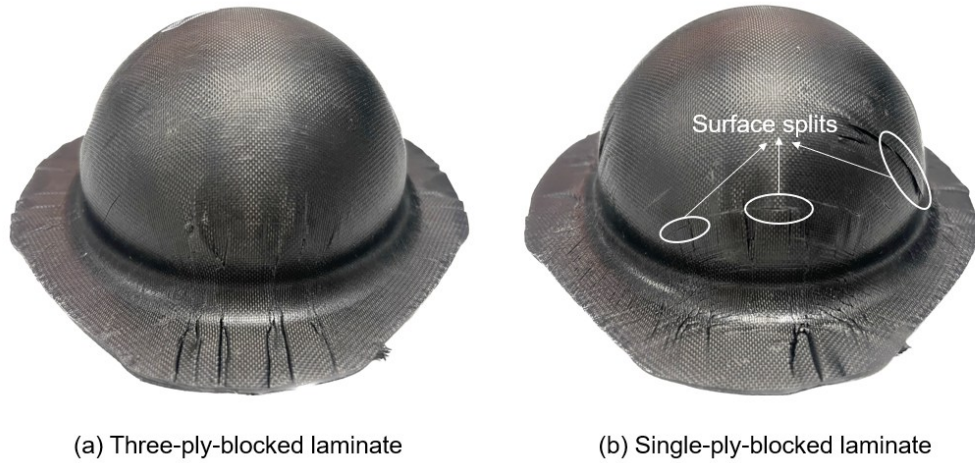


Figure 12. Effect of ply blocking on surface defect formation at 205 °C: (a) three-ply-blocked laminate and (b) single-ply-blocked laminate.

4.3 Temperature

Figure 13 compares the Type B, three-ply-blocked parts formed at 180, 195, 205, 215 and 260 °C. The numerical results in Section 2.2.3 predicted progressively less wrinkling as temperature increased because the reduction in forming resistance allowed the laminate to deform more readily. However, the model does not represent fibre splitting, fibre waviness or delamination. The experiments therefore examined whether the numerical reduction in wrinkling translated into a corresponding improvement in overall forming quality when these additional defect modes were considered.

At 180 °C, the component suffered extensive surface cracking on both sides (regions ① and ②) together with severe local deformation. This response is consistent with the high forming resistance measured for the material at low temperature [26], where insufficient softening restricts deformation and increases local loading. The 180 °C result therefore represents the low-temperature failure regime and indicates that the useful forming range lies above this condition.

At 195 and 205 °C, the extensive cracking observed at 180 °C disappeared and both components retained the intended dome geometry. The 195 °C part showed no obvious surface splitting, although local wrinkling remained on the outer and inner surfaces (regions ③–⑤). The 205 °C part exhibited a small surface split in region ⑥ together with local wrinkling in regions ⑦ and ⑧, but showed no pronounced fibre waviness or relative ply movement. Both conditions therefore showed a more favourable surface response than the 180 °C condition. Although the 195 °C component showed no visible surface splitting, comparison of overall forming quality also required assessment of internal quality.

A different defect pattern emerged at 215 °C. Pronounced fibre waviness appeared on the dome surface (region ⑨), together with local wrinkling (regions ⑩ and ⑫) and visible relative movement between plies (region ⑪). These defects are consistent with further softening and a reduction in the fibre and ply support available to maintain local stability. The 260 °C melt-state reference showed extensive fibre waviness, local fibre splitting, inter-ply movement, ply folding, severe wrinkling and distortion of the inner dome contour (regions ⑬–⑯). The 30 s holding period was also insufficient for the melt-state component to cool sufficiently, contributing to the distorted inner dome contour.

Taken together, the experiments show that forming quality does not improve monotonically as forming resistance decreases. Instead, the dominant defect mode changes with temperature. At the low-temperature end, insufficient softening produces high forming resistance and promotes cracking, whereas at the high-temperature end, excessive softening reduces fibre and ply support and promotes fibre waviness, inter-ply movement and shape instability. Among the conditions tested, 195 and 205 °C provided the most favourable surface response. Internal quality was therefore examined next to determine whether the apparently similar surface performance of these two conditions was also reflected through the laminate thickness.

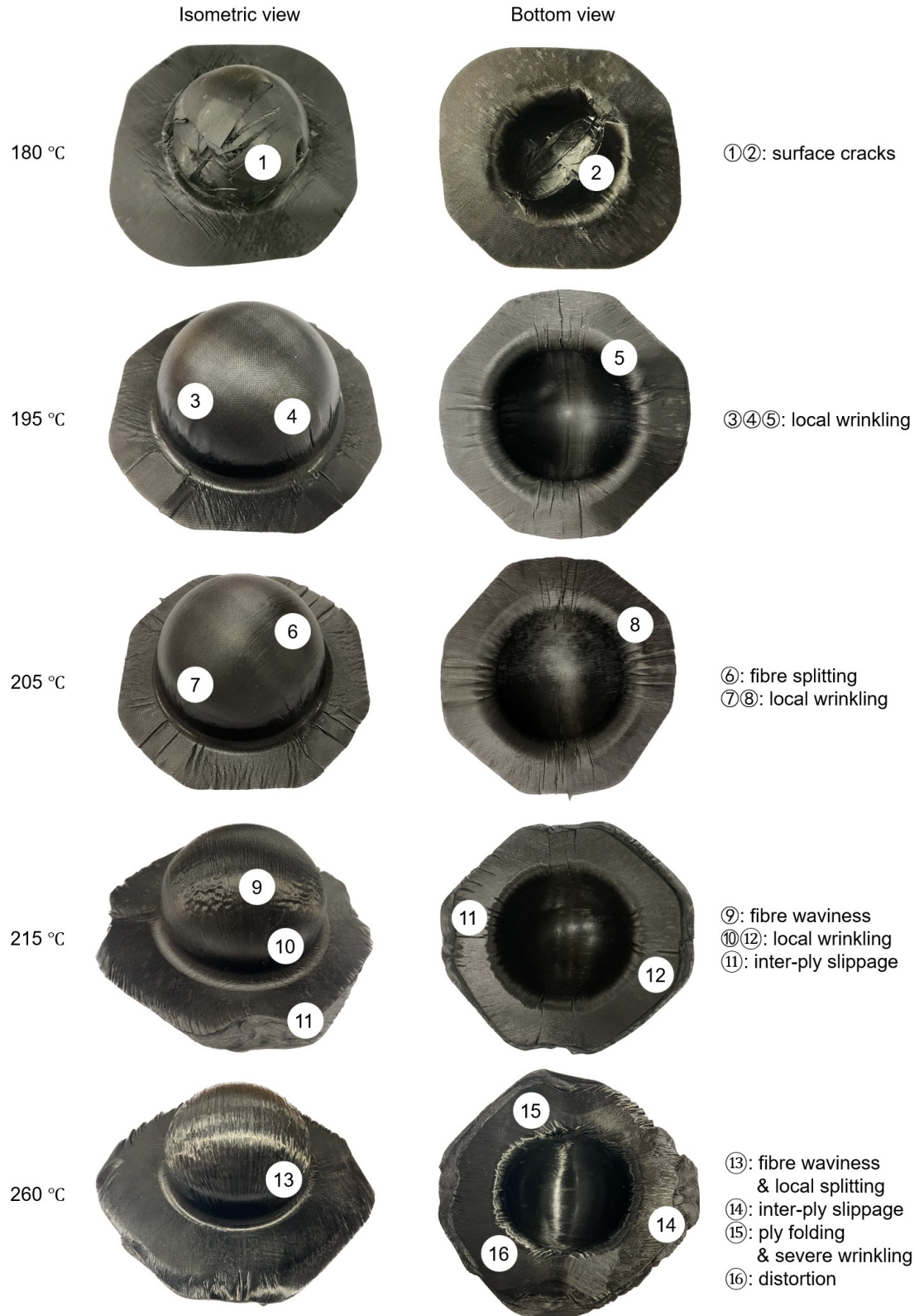


Figure 13. Temperature-dependent defect development in Type B, three-ply-blocked components formed at 180, 195, 205, 215 and 260 °C, shown in isometric and bottom views. Regions ①–② indicate surface cracking at 180 °C; regions ③–⑤ local wrinkling at 195 °C; regions ⑥–⑧ fibre splitting and local wrinkling at 205 °C; regions ⑨–⑫ fibre waviness, local wrinkling and inter-ply movement at 215 °C; and regions ⑬–⑯ fibre waviness, local fibre splitting, inter-ply movement, ply folding, severe wrinkling and inner-dome distortion at 260 °C.

5 Internal quality and model validation

Surface observations identified 195 and 205 °C as the most favourable forming conditions among those tested, but did not establish their internal quality. Two questions therefore remained: whether the visible surface features were associated with internal defects, particularly delamination, and whether the finite-element model could reproduce the global deformation and wrinkle locations of the condition selected after combined surface and internal assessment. These questions were addressed using optical microscopy and X-ray CT, followed by numerical–experimental comparison.

5.1 Internal quality

Optical microscopy was used to characterise representative local surface defects in the Type A component from Trial 1; the corresponding observations are provided in Figure A.1 in Appendix A. X-ray CT was then used to compare the internal quality of the 195 and 205 °C Type B components, which showed the most favourable surface response among the tested conditions. The components were scanned using a DeskTom 150 industrial CT system at a voxel resolution of 40 µm and analysed using myVGL (Figure 14). Although the 195 °C component showed a cleaner outer surface, its 0° and 90° cross-sections revealed more pronounced internal delamination, particularly in regions ④–⑥. Delamination was also observed in the 205 °C component in regions ② and ③, but was less pronounced in the sections examined. No comparable delamination was evident in the examined 45° sections of either component. The spatial association between visible wrinkle regions and the internal separations suggests that local surface wrinkling can be accompanied by inter-ply delamination. The CT sections revealed more pronounced internal delamination in the 195 °C component despite its cleaner surface appearance. Considering the combined surface and internal quality, the 205 °C condition was therefore selected for the subsequent numerical–experimental comparison.

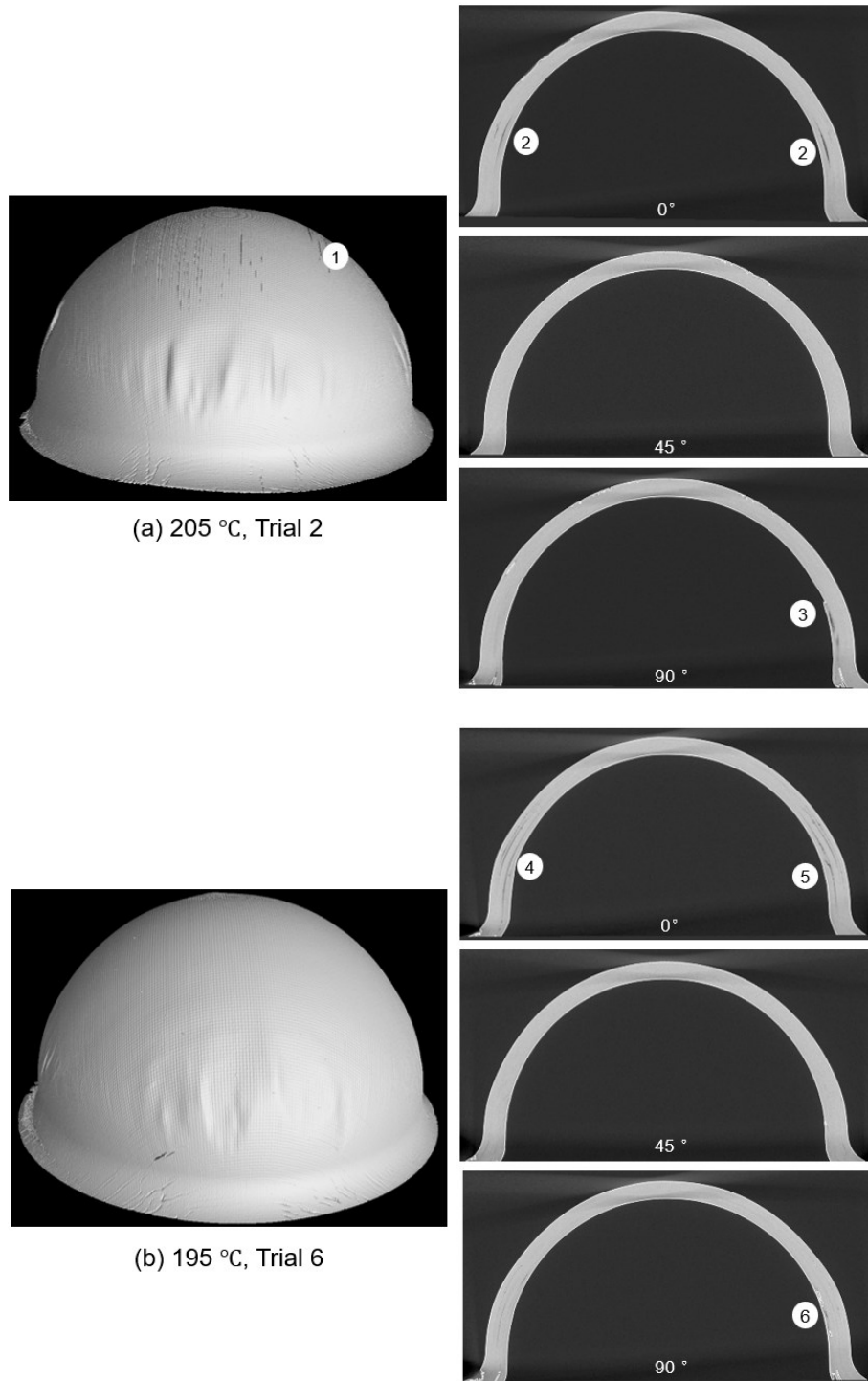


Figure 14. X-ray CT comparison of the (a) 205 °C component (Trial 2) and (b) 195 °C component (Trial 6), including rendered surface views and corresponding 0°, 45° and 90° cross-sections. Region ① indicates the visible surface split on the 205 °C component; regions ②–③ and ④–⑥ indicate local internal delamination in the 205 and 195 °C components, respectively.

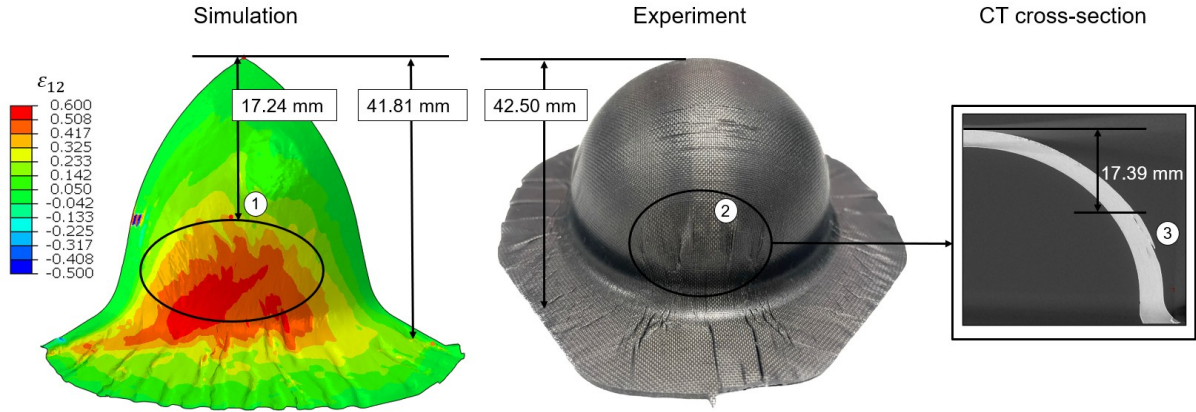
5.2 Model validation

The numerical result for the selected 205 °C condition, obtained using the temperature-dependent constitutive model reported in Ref. [26], was compared with the corresponding

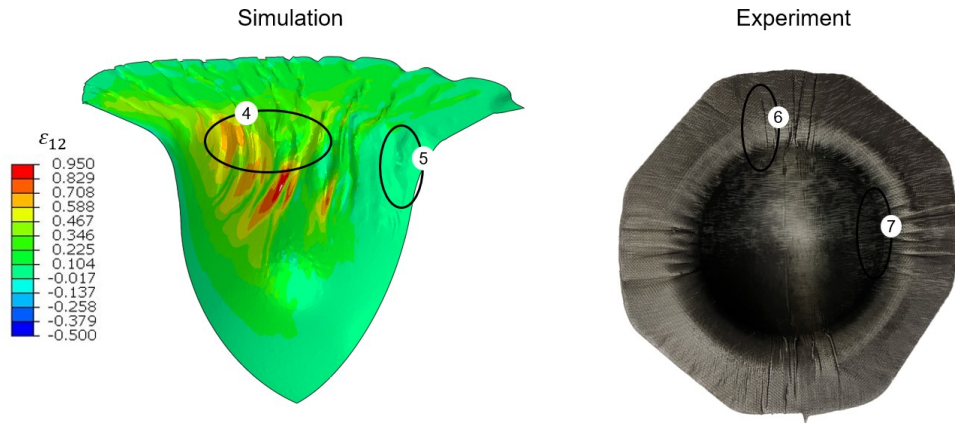
formed component (Figure 15). The differences in overall length, width and height were 3.48%, 9.91% and 1.62%, respectively. The distance from the dome apex to the highest outer wrinkle was 17.24 mm in the simulation and 17.39 mm in the experiment, a difference of 0.15 mm (0.86%).

The numerical model also reproduced the main spatial locations of wrinkling observed experimentally. On the outer surface, the principal wrinkle-prone region identified in the simulation (region ①) corresponded closely to the main wrinkle band observed on the formed component (region ②), and this location was consistent with the wrinkle position seen in the CT cross-section (region ③) (Figure 15a). On the inner surface, the two principal wrinkle regions identified numerically (regions ④ and ⑤) corresponded well to the experimentally observed regions ⑥ and ⑦, respectively (Figure 15b). Although the difference in overall width was larger than those in length and height, the model reproduced the global geometry and principal wrinkle locations of the 205 °C component.

Fibre splitting and delamination are not represented in the present constitutive model and were therefore assessed experimentally. The numerical–experimental comparison supports the capability of the model to capture the overall deformation and wrinkling response of the selected 205 °C forming condition, while its predictive scope remains limited to the deformation modes represented in the model.



(a) Outer-surface comparison



(b) Inner-surface comparison

Figure 15. Numerical–experimental comparison for the 205 °C forming condition: (a) outer-surface comparison showing the principal wrinkle-prone region identified in the simulation (①), the corresponding wrinkle band on the formed component (②), and the corresponding wrinkle position in the CT cross-section (③); and (b) inner-surface comparison showing the two principal wrinkle regions identified in the simulation (④, ⑤) and their corresponding experimentally observed regions (⑥, ⑦).

6 Discussion

The combined results show why the forming window must be assessed using both surface and internal quality. The following discussion considers the competing temperature-dependent mechanisms and the influence of blank shape and ply blocking on their local expression.

6.1 Solid-state forming window

The reduction in simulated wrinkling with increasing temperature does not imply a monotonic improvement in overall forming quality. The experiments indicate competing limitations: insufficient softening restricts deformation and promotes cracking at the lower-temperature end, whereas reduced fibre and ply support promotes waviness and inter-ply movement at the

higher-temperature end. Wrinkling alone therefore cannot define the useful forming window. This interpretation is consistent with the sensitivity of UD thermoplastic forming to temperature, lay-up and local deformation reported in recent studies [3,10,14].

Internal quality further distinguishes conditions with similar surface appearance. The more pronounced delamination in the examined CT sections of the 195 °C component, despite its cleaner surface, supports the selection of 205 °C when surface and internal quality are considered together.

This comparison applies to the Type B blank, three-ply-blocked laminate and rapid cold-tool route investigated here; it does not establish a universal optimum temperature for UD CF/PA6 forming.

6.2 Effects of blank shape and ply blocking

Blank shape controls the balance between material available for draw-in and flange area available for blank-holder restraint. The Type A and Type C results illustrate the limitations of excess flange material and excessive trimming, respectively. Type B provided the most balanced formed profile among the three geometries examined.

Ply blocking introduces a separate trade-off: the three-ply-blocked laminate maintained better surface integrity experimentally, while thicker blocks produced more persistent inter-ply wrinkling numerically. This behaviour is consistent with the coupled roles of bending, in-plane deformation and inter-ply sliding in multilayer wrinkling [17,36].

These comparisons support retaining the Type B blank and three-ply-blocked laminate as a fixed configuration for assessing temperature effects, rather than treating either choice as universally superior.

6.3 Process implications

Process selection should combine numerical predictions of deformation and wrinkling with surface inspection and internal-quality assessment. In particular, similar surface quality at neighbouring temperatures should not be taken as evidence of comparable internal integrity. Blank geometry and ply blocking should be held constant when comparing temperature effects because both influence the observed defect pattern.

For the present cold-tool route, the approximately 8 s transfer makes the laminate temperature immediately before forming more relevant than the furnace set point. Controlling this

temperature is particularly important near the useful forming range, where relatively small changes in thermal state can alter the balance between competing defect modes.

The temperature trends and numerical agreement reported here are specific to the tested UD CF/PA6 laminate, dome geometry and rapid cold-tool route. Extending the model to predict fibre splitting or delamination quantitatively would require explicit failure descriptions and further characterisation of the relevant bending and contact behaviour. The quarter-symmetry representation also excludes asymmetric wrinkle modes. Within this scope, numerical predictions of deformation and wrinkling should be considered together with experimental observations of surface and internal defects when selecting forming conditions.

7 Conclusions

This study combined finite-element analysis, dome-forming experiments and X-ray CT to assess solid-state stamp forming of cross-ply UD CF/PA6 using a rapid cold-tool route. The main conclusions are as follows:

- Blank shape primarily affects material draw-in and the area available for blank-holder control. Ply blocking introduces a trade-off: the three-ply-blocked laminate showed better surface integrity experimentally, whereas increasing ply-block thickness produced more persistent inter-ply wrinkling numerically.
- At 180 °C, insufficient softening resulted in high forming resistance, extensive surface cracking and severe local deformation. Among the temperatures tested, 195 and 205 °C produced the most favourable surface response, whereas at 215 °C and in the 260 °C melt-state reference, fibre waviness, inter-ply movement and shape instability became more pronounced as fibre and ply support decreased.
- X-ray CT revealed more pronounced internal delamination in the examined sections of the 195 °C component than in those of the 205 °C component, despite the cleaner surface appearance of the 195 °C part. These findings supported the selection of 205 °C based on combined surface and internal quality and showed that surface appearance alone is insufficient to identify favourable forming conditions.
- For the selected 205 °C condition, the numerical model reproduced the global component dimensions with differences of 1.62–9.91%, captured the principal outer- and inner-surface wrinkle regions, and placed the selected outer-wrinkle landmark within 0.15 mm of the experiment.

The useful forming window for the tested configuration reflects a balance between sufficient material mobility and retained fibre and ply support. Its assessment requires internal-quality evidence in addition to surface appearance and predicted wrinkling.

Appendix A

A.1. Optical microscopy of representative local defects

The Type A component from Trial 1 (target 205 °C; measured forming temperature 208 °C) was sectioned at three representative locations to characterise the local morphology associated with visible surface defects. As shown in Figure A.1, Section a-2 intersected a visible surface split and revealed local separation within the surface region, while Section c passed through a visible wrinkle and showed pronounced local ply distortion. No comparable large internal separations were evident in the other examined sections. Because this specimen used a different blank geometry from the Type B components in the main temperature series, the observations are presented as additional characterisation of representative local defect morphology rather than for direct comparison between forming temperatures.

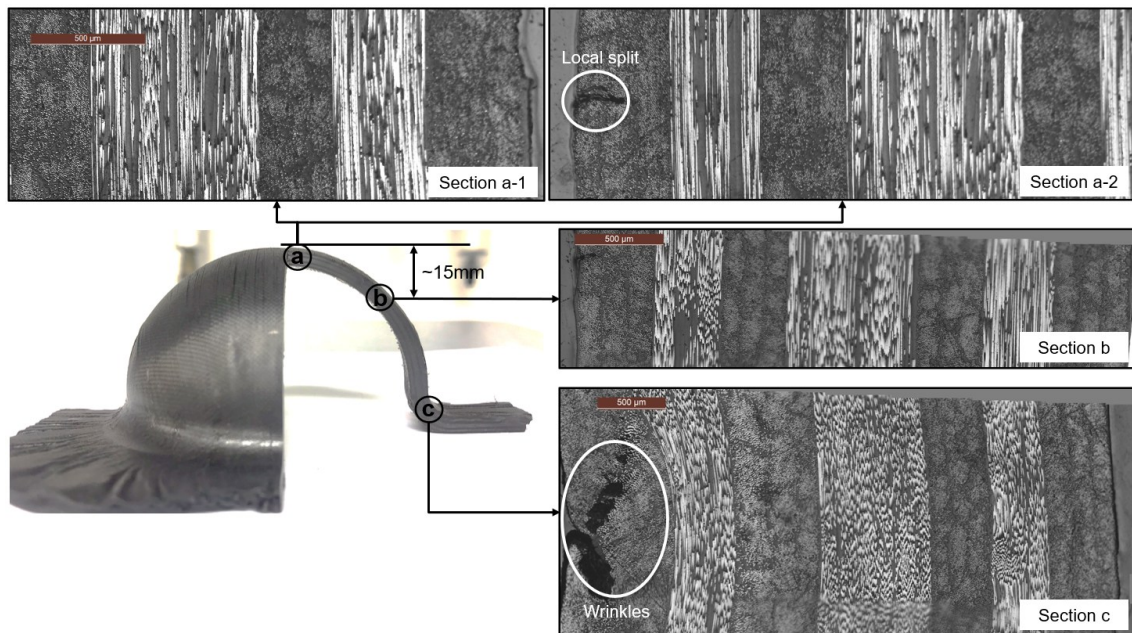


Figure A.1. Optical micrographs from selected sections of the Type A component from Trial 1. The section locations are indicated on the specimen image. Sections a-1 and a-2 correspond to the crown region, Section b to the side wall, and Section c to the flange region. A local surface split is visible in Section a-2, while local ply wrinkling and distortion are observed in Section c.

Data availability

The data supporting this study are available from the corresponding author upon reasonable request.

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CRedit authorship contribution statement

Hongyan Wang: Conceptualization; Methodology; Data curation; Formal analysis; Visualization; Writing – original draft. **Zerong Ding:** Methodology; Formal analysis; Writing – review & editing. **Zhutao Shao:** Formal analysis; Writing – review & editing. **Chunyi Gao:** Visualization; Writing – original draft; Writing – review & editing. **Haibao Liu:** Supervision; Methodology; Formal analysis; Writing – review & editing. **Nan Li:** Investigation; Supervision; Conceptualization; Methodology; Formal analysis; Writing – review & editing; Project administration; Funding acquisition.

References

- [1] R.A. Brooks et al., A review on stamp forming of continuous fibre-reinforced thermoplastics, *Int. J. Lightweight Mater. Manuf.* 5 (2022) 411–430. <https://doi.org/10.1016/j.jlmm.2022.05.001>.
- [2] L. Zhu, N. Li, P.R.N. Childs, Light-weighting in aerospace component and system design, *Propuls. Power Res.* 7 (2018) 103–119. <https://doi.org/10.1016/j.jprr.2018.04.001>.
- [3] E. Barocio et al., Validation of shape change predictions for stamp forming of carbon fiber thermoplastic composite laminates, *Compos. B Eng.* 275 (2024) 111325. <https://doi.org/10.1016/j.compositesb.2024.111325>.
- [4] R.B. Pipes, J. Hicks, E. Barocio, K. Chinwigham, S. Yamamoto, Shape compensation for carbon fiber thermoplastic composite stamp forming, *Compos. B Eng.* 282 (2024) 111577. <https://doi.org/10.1016/j.compositesb.2024.111577>.
- [5] T. Yoneyama, T. Teraoka, K. Masuzawa, Y. Nishihara, S. Nagashima, H. Yoshida, Press forming of carbon-fiber-reinforced thermoplastic sheets, *J. Jpn. Soc. Technol. Plast.* 53 (2012) 145–149. <https://doi.org/10.9773/sosei.53.145>.
- [6] S.P. Haanappel, R.H.W. ten Thije, U. Sachs, B. Rietman, R. Akkerman, Formability analyses of uni-directional and textile reinforced thermoplastics, *Compos. A Appl. Sci. Manuf.* 56 (2014) 80–92. <https://doi.org/10.1016/j.compositesa.2013.09.009>.
- [7] P. Boisse, J. Colmars, N. Hamila, N. Naouar, Q. Steer, Bending and wrinkling of composite fiber preforms and prepregs. A review and new developments in the draping simulations, *Compos. B Eng.* 141 (2018) 234–249. <https://doi.org/10.1016/j.compositesb.2017.12.061>.

- [8] Q. Chen, P. Boisse, C.H. Park, A. Saouab, J. Bréard, Intra/inter-ply shear behaviors of continuous fiber reinforced thermoplastic composites in thermoforming processes, *Compos. Struct.* 93 (2011) 1692–1703. <https://doi.org/10.1016/j.compstruct.2011.01.002>.
- [9] K. Potter, In-plane and out-of-plane deformation properties of unidirectional preimpregnated reinforcement, *Compos. A Appl. Sci. Manuf.* 33 (2002) 1469–1477. [https://doi.org/10.1016/s1359-835x\(02\)00138-0](https://doi.org/10.1016/s1359-835x(02)00138-0).
- [10] D. Brands, W.J.B. Grouve, S. Wijskamp, R. Akkerman, A press forming benchmark to isolate deformation mechanisms for simulation validation, *Int. J. Mater. Form.* 18 (2025) 27. <https://doi.org/10.1007/s12289-025-01891-x>.
- [11] P. Hallander, M. Akermo, C. Mattei, M. Petersson, T. Nyman, An experimental study of mechanisms behind wrinkle development during forming of composite laminates, *Compos. A Appl. Sci. Manuf.* 50 (2013) 54–64. <https://doi.org/10.1016/j.compositesa.2013.03.013>.
- [12] P. Hallander, J. Sjölander, M. Åkermo, Forming induced wrinkling of composite laminates with mixed ply material properties; an experimental study, *Compos. A Appl. Sci. Manuf.* 78 (2015) 234–245. <https://doi.org/10.1016/j.compositesa.2015.08.025>.
- [13] D. Brands, V. Vomáčko, W. Grouve, S. Wijskamp, R. Akkerman, Dataset with press forming results of unidirectional thermoplastic composite laminates including in-plane deformation data for validation of forming simulations, *Data Brief* 53 (2024) 110099. <https://doi.org/10.1016/j.dib.2024.110099>.
- [14] M.O. Voltz, O. Zöllner, P. Mitschang, Effects of thermoforming parameters and layup on unidirectional reinforced amorphous thermoplastic composite surfaces, *Compos. A Appl. Sci. Manuf.* 180 (2024) 108063. <https://doi.org/10.1016/j.compositesa.2024.108063>.
- [15] K. Chikamori, S. Minakuchi, In-situ deformation measurement of thermoplastic composite during stamp forming using embedded shape sensors, *Compos. A Appl. Sci. Manuf.* 206 (2026) 109761. <https://doi.org/10.1016/j.compositesa.2026.109761>.
- [16] S. Allaoui, C. Cellard, G. Hivet, Effect of inter-ply sliding on the quality of multilayer interlock dry fabric preforms, *Compos. A Appl. Sci. Manuf.* 68 (2015) 336–345. <https://doi.org/10.1016/j.compositesa.2014.10.017>.
- [17] W. Zhang, L. Wang, X. Peng, Ply-ply friction behavior between unidirectional thermoplastic prepreg plies during thermoforming: Characterization and modeling, *Mater. Des.* 247 (2024) 113426. <https://doi.org/10.1016/j.matdes.2024.113426>.
- [18] C. Gao, J. Tran, Z. Ding, B. Blackman, N. Li, Cohesive-friction transition in compressed unidirectional thermoplastic composite interfaces, *Compos. B Eng.* 328 (2027) 114187. <https://doi.org/10.1016/j.compositesb.2026.114187>.
- [19] C. Gao, B. Blackman, Z. Ding, N. Li, Isothermal and non-isothermal friction at thermoplastic composite interfaces, *Compos. B Eng.* 329 (2027) 114254. <https://doi.org/10.1016/j.compositesb.2026.114254>.
- [20] W. Zhang, H. Liao, L. Wang, X. Peng, A prepreg-tool slipping model for unidirectional CF/PPS prepreg during hot-stamping process, *Compos. A Appl. Sci. Manuf.* 199 (2025) 109239. <https://doi.org/10.1016/j.compositesa.2025.109239>.
- [21] R.D.R. Sitohang, W.J.B. Grouve, L.L. Warnet, R. Akkerman, Effect of in-plane fiber waviness defects on the compressive properties of quasi-isotropic thermoplastic composites, *Compos. Struct.* 272 (2021) 114166. <https://doi.org/10.1016/j.compstruct.2021.114166>.
- [22] A.F. Schug, Unidirectional fibre reinforced thermoplastic composites: A forming study, Ph.D. dissertation, Technical University of Munich, Munich, Germany, 2019. <https://mediatum.ub.tum.de/doc/1469957/685138.pdf>.
- [23] H. Lessard, G. Lebrun, A. Benkaddour, X.-T. Pham, Influence of process parameters on the thermostamping of a [0/90]₁₂ carbon/polyether ether ketone laminate, *Compos. A Appl. Sci. Manuf.* 70 (2015) 59–68. <https://doi.org/10.1016/j.compositesa.2014.12.009>.

- [24] S.P. Haanappel, R. Akkerman, Shear characterisation of uni-directional fibre reinforced thermoplastic melts by means of torsion, *Compos. A Appl. Sci. Manuf.* 56 (2014) 8–26. <https://doi.org/10.1016/j.compositesa.2013.09.007>.
- [25] D. Brands, S.P. Haanappel, W.J.B. Grouve, S. Wijskamp, R. Akkerman, Critical evaluation of torsion rheometry to characterize the anisotropic intraply shear resistance of unidirectional thermoplastic composites in melt, *Compos. A Appl. Sci. Manuf.* 190 (2025) 108661. <https://doi.org/10.1016/j.compositesa.2024.108661>.
- [26] H. Wang, Z. Ding, X. Chen, H. Liu, N. Li, Experimental characterisation and constitutive modelling of the intra-ply tensile and shear properties of unidirectional fibre reinforced thermoplastics (UD FRTPs) under solid-state stamp forming conditions, *Compos. A Appl. Sci. Manuf.* 179 (2024) 108034. <https://doi.org/10.1016/j.compositesa.2024.108034>.
- [27] H. Wang, H. Liu, Z. Ding, N. Li, Experimental and constitutive modelling studies of semicrystalline thermoplastics under solid-state stamp forming conditions, *Polymer* 228 (2021) 123939. <https://doi.org/10.1016/j.polymer.2021.123939>.
- [28] B. Zheng et al., Formability and failure mechanisms of woven CF/PEEK composite sheet in solid-state thermoforming, *Polymers* 11 (2019) 966. <https://doi.org/10.3390/polym11060966>.
- [29] T. Deng et al., A hybrid lamination model for simulation of woven fabric reinforced thermoplastic composites solid-state thermo-stamping, *Mater. Des.* 200 (2021) 109419. <https://doi.org/10.1016/j.matdes.2020.109419>.
- [30] U. Sachs, Friction and bending in thermoplastic composites forming processes, Ph.D. dissertation, University of Twente, Enschede, The Netherlands, 2014. <https://doi.org/10.3990/1.9789462594838>.
- [31] B. Chen, J. Colmars, N. Naouar, P. Boisse, A hypoelastic stress resultant shell approach for simulations of textile composite reinforcement forming, *Compos. A Appl. Sci. Manuf.* 149 (2021) 106558. <https://doi.org/10.1016/j.compositesa.2021.106558>.
- [32] D. Jauffrès, J.A. Sherwood, C.D. Morris, J. Chen, Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming, *Int. J. Mater. Form.* 3 (2010) 1205–1216. <https://doi.org/10.1007/s12289-009-0646-y>.
- [33] D. Dörr, F.J. Schirmaier, F. Henning, L. Kärger, A viscoelastic approach for modeling bending behavior in finite element forming simulation of continuously fiber reinforced composites, *Compos. A Appl. Sci. Manuf.* 94 (2017) 113–123. <https://doi.org/10.1016/j.compositesa.2016.11.027>.
- [34] Toray Advanced Composites, Toray Cetex® TC910, product data sheet. <https://www.toraytac.com/product-explorer/products/r2Vf/Toray-Cetex-TC910> (accessed 24 September 2026).
- [35] D. Dörr, Simulation of the Thermoforming Process of UD Fiber-Reinforced Thermoplastic Tape Laminates, *Karlsruher Schriftenreihe Fahrzeugsystemtechnik*, vol. 78, KIT Scientific Publishing, Karlsruhe, Germany, 2021. <https://doi.org/10.5445/KSP/1000099858>.
- [36] B. Lv, J. Zhang, J. Xiao, S. Wang, L. Wen, X. Hou, Analyses of wrinkling mechanisms during forming of multi-layer woven fabric reinforced thermoplastic prepregs, *Compos. A Appl. Sci. Manuf.* 184 (2024) 108240. <https://doi.org/10.1016/j.compositesa.2024.108240>.