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# Formability Experiments for Unidirectional Thermoplastic Composites

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**Abstract.** Reliable composite forming experiments are required to characterize composite formability, to aid material development, and to validate process simulations models. Due to practical reasons, however, typically a limited amount of forming configurations is studied. The objective of this study is, therefore, to develop a methodology for obtaining controlled forming results in a wide range of configurations.

Press forming experiments using a dome geometry were used to explore the formability of two commercial unidirectional thermoplastic composite materials. A variety of forming configurations was employed by changing the blank dimensions and layup. The observation of wrinkling defects was simplified by leaving an additional 3 mm tool gap. Blank width and layup had the most influence on the wrinkling severity, followed by blank thickness and length. Quasi-isotropic layups were found to produce wrinkles in nearly all cases, confirming a difficulty in general to form double curved parts. The size and number of wrinkles in these layups were found to change with the stacking sequence. Cross-ply layups showed better formability, but significant wrinkles were still observed depending on the orientation of the blank relative to the layup.

The formability experiments using a dome geometry provided a reliable methodology for controlled forming results in many configurations using a generic toolset. Additionally, a comprehensive comparison of formability for two commercial thermoplastic UD materials in a variety of scenarios was provided.

## Introduction

The occurrence of defects limits the applicability of press forming for unidirectional (UD) fiber reinforced thermoplastic composites. Currently, complex parts impose a high risk because of the uncertainty for defects, typically detected late in the product development process. Press formed parts can suffer from forming defects, consolidation defects and shape distortions. Wrinkles and waviness that arise during forming are particularly risky because solution routes are not generalized or require significant modifications to part and process design. Understanding the formability of the material and the occurrence of wrinkles is key to designing and manufacturing such complex parts.

The formability of unidirectional composite materials has been studied in the past and present. After the introduction of these materials there was an initial wave of applications whilst searching and developing new manufacturing methods, which is nicely illustrated in the work of Mallon et al. [1] for example. Initial research on process modelling also appears in the early 90's, examples of early work include [2–5], in which the underlying physical deformation mechanisms were identified and analyzed. The topic of composite forming has since received continuous attention and knowledge was bundled over time in various books [6–11]. Meanwhile, the research and development of parts and processes have shifted towards industry, which initially focused on fabric based composites for complex forming applications [12]. Hence, research efforts for process modelling focused predominantly on woven fabric composites, for example in the work of Lamers [13]. The use of unidirectional material has since slowly reemerged because of certain inherent advantages in structural properties and processing. Ease of automation, scalability and the ability to tailor product layup are amongst the important arguments for using thermoplastic UD tape.

Despite the industrialization of composite materials and forming processes, composites forming research is continued by focusing on optimization of parts and processes. Herein, researchers typically develop process models and simulations that can be used as design tools. Controlled forming studies on benchmark and validation geometries are important tools, as they provide the means to study the formability of (new) materials, as well as to assess the predictive capabilities of the developed process simulation models. Various researchers have published forming studies on UD materials in recent years, a non-extensive list is provided in Table 1. The list shows a variety of geometries being used, ranging from elementary shapes like angles and domes to application specific parts and generic complex geometries. Different materials are also investigated, typically associated with specific industries or applications.

Table 1: List of recent composites forming research on formability of unidirectional material.

| Researchers | Material | Geometry | Process |
|---|---|---|---|
| Dörr et al. [14,15] | UD/C/PA6 | Generic complex geometry | Press forming |
| Larberg, Hallander et al. [16,17] | UD/C/Epoxy | Spar | Hot drape forming |
| Johnson et al. [18] | UD/C/Epoxy | Spar | Double diaphragm forming |
| Haanappel et al. [19] | UD/C/PEEK | J-nose stiffener | Press forming |
| Haanappel [20] | UD/C/PEEK | Dome | Press forming |
| Sachs [21] | UD/C/PEEK | J-nose stiffener , L-shape | Press forming |
| Dangora et al. [22] | UD/UHMWPE/PU | Helmet | Press forming |
| Slange et al. [23] | UD/C/PEEK | Spar | Press forming |
| Lessard et al. [24] | UD/C/PEEK | Generic complex geometry | Press forming |
| Benkaddour et al. [25] | UD/C/PEEK | Generic complex geometry | Press forming |
| Harrison et al. [26] | UD/G/PP | Double dome | Press forming |
| Liu et al. [27] | UD/G/PP | Dome | Press forming |

The complexity of setting up a forming study for research, validation, or benchmarking is not a unambiguous task and can be prone to arbitrary design choices. Especially for validation of process simulation models, the use of a single part and process can lead to narrow conclusions of validity. Instead, one should respect the broad scope for which the models are developed and attempt to validate over a large range of geometries and processes to gain confidence in the results. This obviously poses a challenge since it is impossible to cover all forming applications. The objective of this study is to develop an experimental methodology to provide controlled forming results in a wide range of configurations.

A forming limit test for composites using a dome geometry was proposed by Wolthuizen et al. [28] to enable the classification of materials by their formability. Strips of varying width induce a varying degree of double curvature in order to find the width at which the material starts to wrinkle. The current study implements a similar experiment on a comparable dome geometry as a basis for the proposed methodology. The boundary conditions and process parameters were modified to achieve near-isothermal forming with minimum influence of the material handling. Effectively, it extends the study of Wolthuizen et al. by comparing two unidirectional materials for various layups in two different thicknesses. Comparing the formability of composite materials can also aid in the understanding and development of forming processes and materials.

**Method**

Laminates were prepared using two commercially available unidirectional thermoplastic composite tape materials. These materials were chosen for their current relevance and future potential in press forming applications in the aerospace industry. Solvay APC is a combination of AS4D carbon fiber and a PEKK-FC thermoplastic matrix [29] and Toray TC1225 has a T700 carbon fiber in a LMPAEK matrix [30]. The relevant material characteristics are collected in Table 2.

Table 2: Material characteristics, from [29,30].

| | Toray TC1225 | Solvay APC |
|---|---|---|
| Fiber | T700 | AS4D |
| Fiber areal weight [g/m2] | 145 | 145 |
| Fiber volume fraction [%] | 59 | 59 |
| Matrix | LM-PAEK | PEKK-FC |
| Resin content by weight [%] | 34 | 34 |
| Glass transition temperature [°C] | 147 | 159 |
| Melting temperature [°C] | 305 | 337 |
| Consolidated ply thickness [mm] | 0.14 | 0.14 |

Consolidation was performed in picture frame molds treated with Marbocoat 227CEE release agent. Multiple laminates were consolidated in a single mold by separating the laminates with stainless steel caul sheets, also treated with release agent. APC was press-consolidated at 375 °C for 15 minutes and TC1225 at 365 °C for 30 minutes, both at a pressure of 10 bar. The laminate thickness after consolidation is shown in Table 3. Rectangular blanks for forming were cut from the laminates using a water cooled diamond saw. The width of blanks was varied and the length of the blank was 295 mm and 380 mm for the 8-ply and 16-ply blanks, respectively.

Table 3: Thickness of consolidated laminates in millimeters incl. standard deviation.

| | Solvay APC | Toray TC1225 |
|---|---|---|
| 8-ply laminates | 1.140±0.032 | 1.127±0.016 |
| 16-ply laminates | 2.254±0.032 | 2.245±0.037 |

Prior to press forming, the blanks underwent a drying treatment at 120 °C overnight to reduce the effect of deconsolidation during subsequent processing, as suggested by Slange et al. [31]. Blanks were formed within 8 hours after the drying treatment.

Press forming experiments were conducted using the 200 ton press from Pinette Emidecau Industries installed at the TPRC. A steel hemispherical tool set, illustrated in Figure 1, was used where the convex (male) tool has a radius of 125 mm and a depth of 39.5 mm, centered on the 300 mm square tool body. The concave (female) tool has a constant offset of 1.1 mm in the case of the 8-ply blanks, while a different tool with a 2.2 mm offset was used for 16-ply blanks. Tooling was treated with release agent prior to heating them to a constant 220 °C tool temperature.

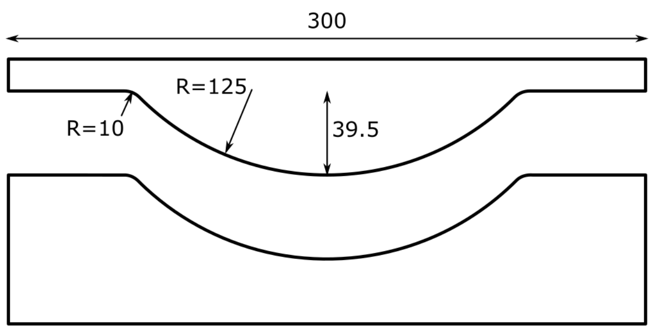
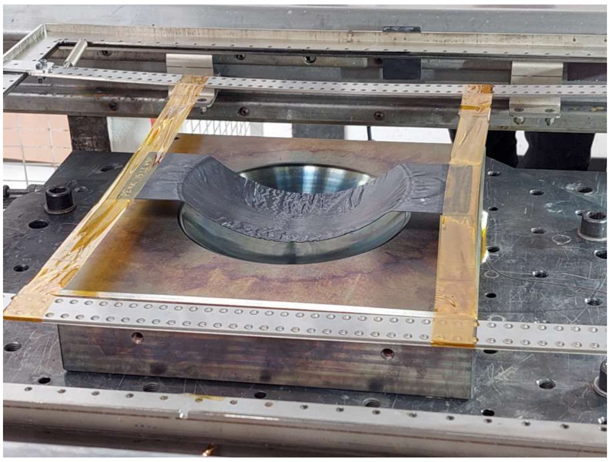
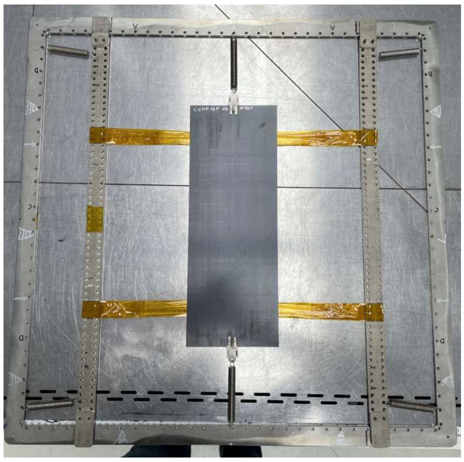



Figure 1: Tool cross-section including dimensions. The bottom tool is offset 1.1 mm from the top tool for 8-ply blanks, while a different tool with an offset of 2.2 mm was used for 16-ply blanks.

The blanks were suspended in a shuttle frame to enable automatic transport between the infra-red (IR) oven and the press. A suspension system was rigged inside the shuttle frame to handle the laminate during heating and forming. It consists of polyimide (PI) tape stretched between sliding metal bars, which are tensioned using springs as shown in Figure 2a. The ends of the 8-ply blanks were encapsulated between the PI-tape, which provided sufficient support during heating and transport. The suspension using PI tape allows the full blank to be molten, which was a requirement since the blanks were smaller than the tool. The heavier 16-ply blanks required additional support because the adhesive on the polyimide tape allowed too much sliding of the blank at elevated temperature. Therefore, a longer blank length was adopted for 16-ply blanks which extends out from the tooling when formed, thereby allowing the use of a hook and spring in the center of the laminate for tensioning as shown in Figure 2b. The blank was also supported in vertical direction by resting it on the non-sticky side of two PI tape strips. The metal hooks used to attach the spring to the blank create a local cold-spot by reflecting and absorbing part of the heat from the IR oven, enabling proper force introduction into the molten blank.



(a)



(b)

Figure 2: Laminate handling systems. (a) Setup for 8-ply blanks, after forming; Suspended in between PI-tape, strechted between metal bars. (b) Setup for 16-ply blanks, before forming; Laminate on top of PI-tape, springs attached in the center.

Blanks were heated in the IR oven to 365 °C and 375 °C for Toray TC1225 and Solvay APC, respectively. The 8-ply blanks required 1 minute and 30 seconds of heating time and the 16-ply blanks required 2 minutes and 45 seconds. Automatic transfer to the press over a length of 80 cm took 1.4 seconds, with an additional 0.3 seconds before the press started to close. The frame was approximately 3 cm above the fixed concave mold on the bottom, with the blank centered over the tool. The blank, at this point, has already deformed slightly due to gravity, but did not yet touch the tool. Then, the press closes to form the part. The initial gap between the tool surfaces was 110 mm, with the upper convex tool moving downward. The tool travels quickly for the first 100 mm of travel, taking about 1 second, whereafter the press switched to a velocity of 20 mm/s for the remainder of the tool travel. A gap between the tools of 3 mm on top of the laminate thickness was used to observe the out-of-plane deformation of the blank more clearly. Additionally, some experiments were repeated where 10 bar consolidation pressure was applied.

Table 4: Test matrix showing combinations of layup and width used in the experiments for Solvay APC. The same experiments have been performed on Toray TC1225, with the exception of the $[90/-45/0/45]_{2s}$ layup.

| Width [mm] | $[0/90]_{2s}$ | $[45/-45]_{2s}$ | $[0/45/90/-45]_{s}$ | $[90/-45/0/45]_{s}$ | $[0/90]_{4s}$ | $[45/-45]_{4s}$ | $[0/45/90/-45]_{2s}$ | $[90/-45/0/45]_{2s}$ |
|---|---|---|---|---|---|---|---|---|
| 140 | x | x | | | x | x | | |
| 105 | | | x | | | | | |
| 90 | | | x | | | | | |
| 75 | | | x | x | | | x | x |
| 65 | | | x | x | | | x | x |
| 55 | | | x | x | | | x | x |
| 45 | | | x | x | | | x | x |
| 35 | | | x | x | | | x | x |

The test matrix for the experiments described in this article is shown in Table 4. A variety of widths was used in combination with a variety of layups, both in 8-ply and 16-ply versions. The 0° direction is defined as the blank's length direction. The majority of configurations have been performed on both Solvay APC and Toray TC1225 materials, except for the $[90/-45/0/45]_{2s}$ layup which were only formed for Solvay APC. Some experiments were repeated several times to assess the repeatability of the forming behavior. Additionally, some experiments were performed both with a gap between the tools as well as closed tools and a 10 bar consolidation pressure to study the flattening of the wrinkles during the last stage of forming.

## Results

The various forming results are explained in separate sections, starting with the various 8-ply layups, followed by the 16-ply blanks. Repeatability and consolidation pressure are considered at the end.

**Quasi isotropic layup, 8 plies.** Figure 3a shows an overview of forming results with an 8-ply quasi-isotropic layup, $[0/45/90/-45]_s$, with the 0° direction on the outer plies. Out-of-plane wrinkling is clearly observed in all cases for Toray TC1225, with quite significant wrinkles for the larger width of 105 mm and a few wrinkles on the edges for a width of 35 mm. The Solvay APC material wrinkles similarly for this configuration but appears to have less wrinkles for samples with a smaller width. Nevertheless, some in-plane wrinkles were still observed along the edges for a width of 55 and 45 mm in APC. All samples show a ribbon (marked &) without wrinkles running over the middle of the dome geometry. The width of this wrinkle-free area seems to be unaffected by the blank width and is equally wide for both materials.

An increase in the number of wrinkles along the sides (marked #) is observed for wider blanks in Figure 3a, but the shape of each wrinkle itself seems to be affected minimally. Apparently, the shape of the wrinkle, at this particular tool gap, is a constant determined by the properties of the molten blank. An increase of width, leading to a higher degree of double curvature, gives more material over-length along the sides and therefore leads to a greater number of wrinkles.

Another type of wrinkling defect is observed in Figure 3a for blanks of 75 mm and wider. On the edges of the dome, right next to the small radius, an area of wrinkles is found that point radially outward from the dome (marked *). This wrinkling effect is not found for widths of 65 mm and smaller.

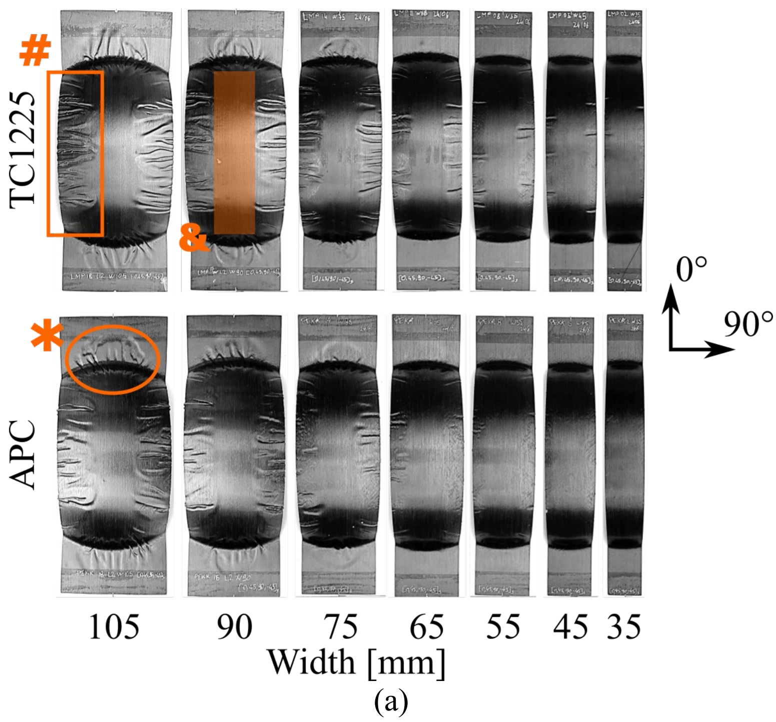



Figure 3: Formability experiments with 8-ply quasi-isotropic layup using Toray TC1225 and Solvay APC materials. Initial blank length was 295mm and the width as indicated in the figure. (a) $[0,45,90,-45]_s$ (b) $[90,-45,0,45]_s$.

**Quasi isotropic layup, rotated 90°.** Figure 3b shows the forming results for the quasi-isotropic layup, $[90,-45,0,45]_s$, with the 90° direction on the outer plies. Effectively this rotates the layup 90° with respect to the blank compared to Figure 3a. The wrinkling observed for Toray TC1225 on the long sides (marked #) of the parts has a smaller wavelength compared to the results in Figure 3a. Possibly, a blank with 0° fibers on the outside is more resistant to bending in this direction than with 90° surface plies, leading to a lower critical buckling length. Also, the wrinkle-free ribbon area (marked &) in the center of the parts is still present, but slightly narrower. The wrinkles near the edge of the dome (marked *) are still present for 75 mm wide blanks.

Wrinkling for the Solvay APC on the rotated layup is not as pronounced as for Toray TC1225, but out-of-plane wrinkles are still observed for all widths shown. The wrinkle-free ribbon is not clearly observed, but wrinkling near the dome edge is still present in the 75 mm wide blanks.

**Cross-ply layup, 8 plies.** Cross-ply layups are expected to show less wrinkling than the quasi-isotropic layups due to the presence of only two fiber directions. The forming results for the $[0/90]_{2s}$ and $[45/-45]_{2s}$ layups with 140 mm wide blanks are shown in Figure 4. The parts with a $[45/-45]_{2s}$ layup show little wrinkling for TC1225 and hardly any wrinkles for Solvay APC. However, the parts with a $[0/90]_{2s}$ layup shows significantly more wrinkling for both materials, with more pronounced and larger sized wrinkles for Toray TC1225. The wrinkle-free zone along the center of the dome (marked &) appears to be wider than those observed for the quasi-isotropic layups.

The top and bottom edges of the 8-ply parts in Figure 4 show a curved draw-in profile, as expected for these lay-ups, being concave for $[0/90]_{2s}$ and convex for $[45/-45]_{2s}$, indicating that some in-plane deformation has taken place during forming. On the contrary, all quasi-isotropic parts shown in Figure 3 do not have curved profiles but straight edges on top and bottom of the part, indicating that little to no in-plane deformation has taken place.

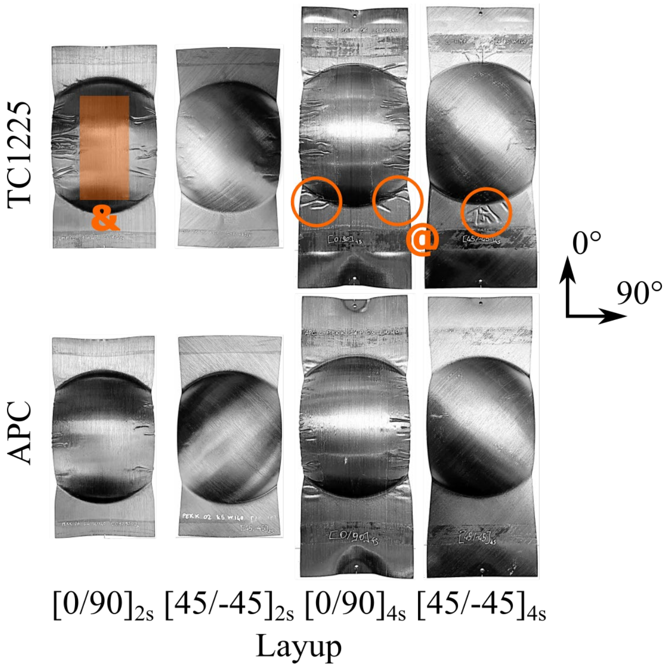



Figure 4: Formability experiments with cross-ply layups using Toray TC1225 and Solvay APC materials. Initial blank width was140 mm with a length of 295 mm and 380 mm for the 8-ply and 16-ply blanks, respectively.

**Blank thickness and length.** Figure 5 shows an overview of the forming results for 16-ply parts with a quasi-isotropic layup. Compared to the thinner and shorter 8-ply parts from Figure 3, the wrinkling has changed moderately. Toray TC1225 still shows wrinkles for the full range of widths used, but the number of wrinkles has decreased whilst the severity of individual wrinkles has increased. The wrinkling near the edge of the dome is less significant than in the 8-ply case. For Solvay APC, wrinkling is more significant at the smaller widths, with very comparable severity to the Toray TC1225 material. With 90° fibers on the outside the wrinkling has become more pronounced, but with the same pattern as the 8-ply variant.

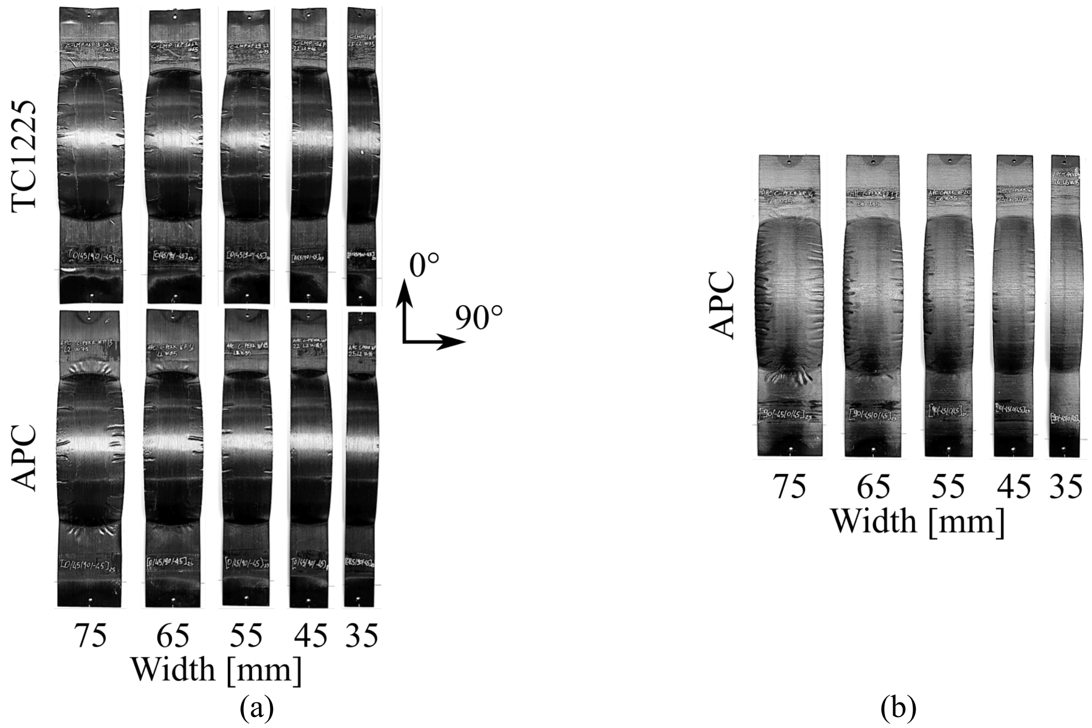



Figure 5: Formability experiments with quasi-isotropic layup using Toray TC1225 and Solvay APC materials. Specimen length was originally 295mm and the width as indicated in the figure. (a) $[0,45,90,-45]_{2s}$ (b) $[90,-45,0,45]_{2s}$.

The forming results for cross-ply parts with a 16-ply layup were included in Figure 4. More wrinkling is observed on the edge of the dome geometry (marked @), possibly related to the greater length of the blanks used that hinder the book-ending deformation (through thickness transverse shear). Solvay APC shows less wrinkles than the Toray TC1225 for all cross-ply parts formed in this research.

In the 16-ply forming experiments a notable difference is found between wrinkling on the top and bottom surface of the parts, which was not observed for the 8-ply parts. Figure 6 shows both sides of the same specimen for 8- and 16-ply parts, where the 16-ply parts have more pronounced wrinkling on the bottom surface when compared to the top surface. The wrinkles on the bottom of the 16-ply Toray TC1225 part contains wrinkles that are not perpendicular to the edge of the laminate (examples marked with an arrow), which is in contrast to the other wrinkles observed so far.

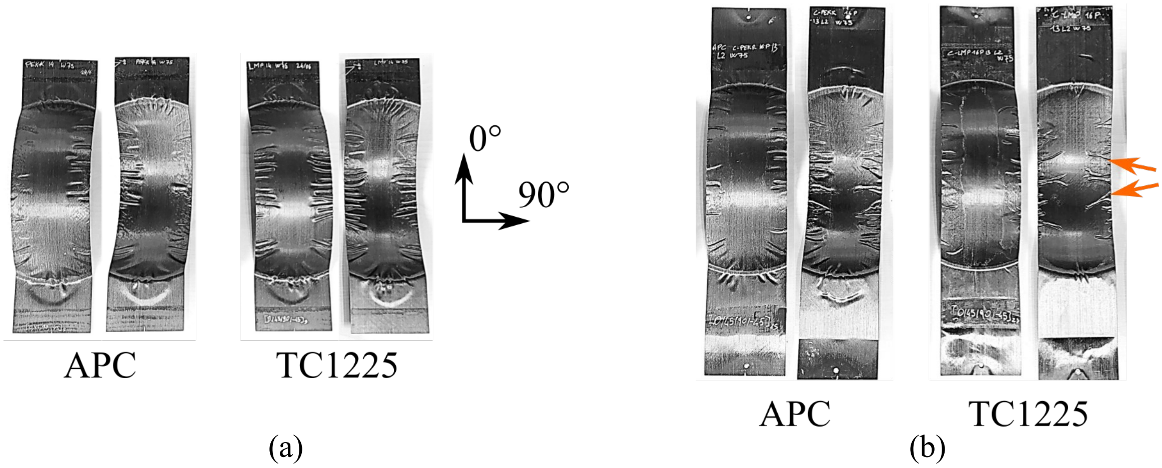



Figure 6: Forming results for 75 mm wide blanks with a quasi-isotropic layup. Pairs of pictures shows the top and bottom surface, respectively. Part was flipped over the long edge. (a) $[0/45/90/-45]_s$ (b) $[0/45/90/-45]_{2s}$.

**Repeatability.** The majority of the forming experiments were performed multiple times to assess the repeatability of the results. Figure 7 shows a side-by-side comparison of a selection of these repetitions to give insight into the variation. Figure 7a shows a range of different widths for a quasi-isotropic layup in APC, where wrinkling was found to increase for larger widths. Individual wrinkles on each part cannot be matched directly on the repetitions, however the overall picture of wrinkling severity and location is maintained. Differences between repetitions become more apparent in cases with few wrinkles, since the exact location of the wrinkle can vary along the perimeter of the dome.

Figure 7b shows four repetitions for a cross-ply sample. Again, the location and severity of the wrinkles is roughly preserved amongst the repetitions, but not all wrinkles are found in the same locations. However, the four significant outer wrinkles that point radially from the center (marked with arrows) are found in the same location each time.

The degree of variation observed in the experiments is sufficiently low to use the results for formability research. The buckling phenomena underlying the out-of-plane wrinkling are likely to be sensitive to local variations in the material and process, hence some degree of variation is to be expected in any such forming process.

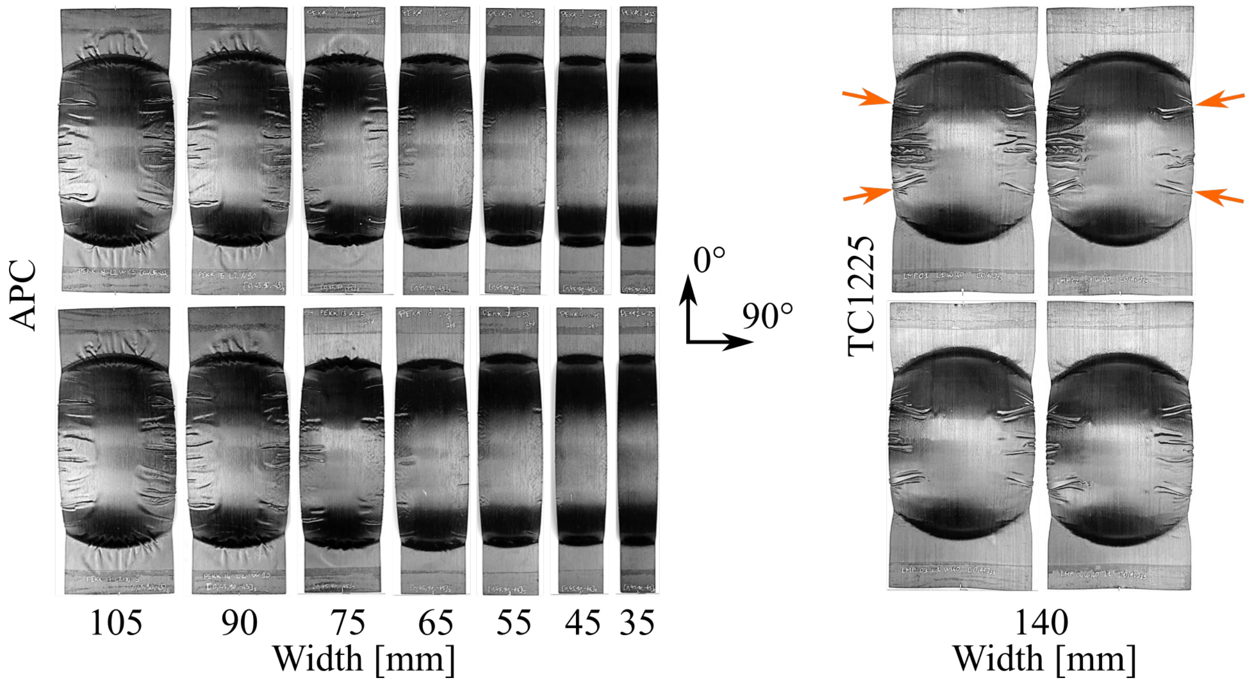



Figure 7: Repetitions amongst forming results to assess repeatability. (a) Solvay APC with $[0/45/90/-45]_s$ layup, two results for each width. (b) Toray TC1225 with $[0/90]_{2s}$ layup, four results.

**Consolidation pressure.** Figure 8 shows a comparison between samples formed with an additional 3 mm tool gap and parts that were consolidated at 10 bar. The out-of-plane wrinkling behavior that is clearly identifiable in parts with a tool gap seems to have been flattened and pressed into the surface of the part upon consolidation. Nevertheless, a complex combination of in-plane and out-of-plane wrinkling is observed on the consolidated parts that is similar in size and shape as the out-of-plane buckling observed with a tool gap. This suggests that defects recognized with a 3mm tool gap are still representative of the expected defect location and severity if a consolidation pressure would have been applied. The surface of the consolidated parts is smooth to the touch despite the local wrinkling that is present.

The out-of-plane wrinkling deformation on the edge of the dome geometry (marked *) at a width of 75 mm is clearly visible with a tool gap but difficult to see by visual inspection on the consolidated part. Perhaps the tool gap gives an exacerbated view of possible defects in this case, as this same area on the final part might not be regarded as a defective area.

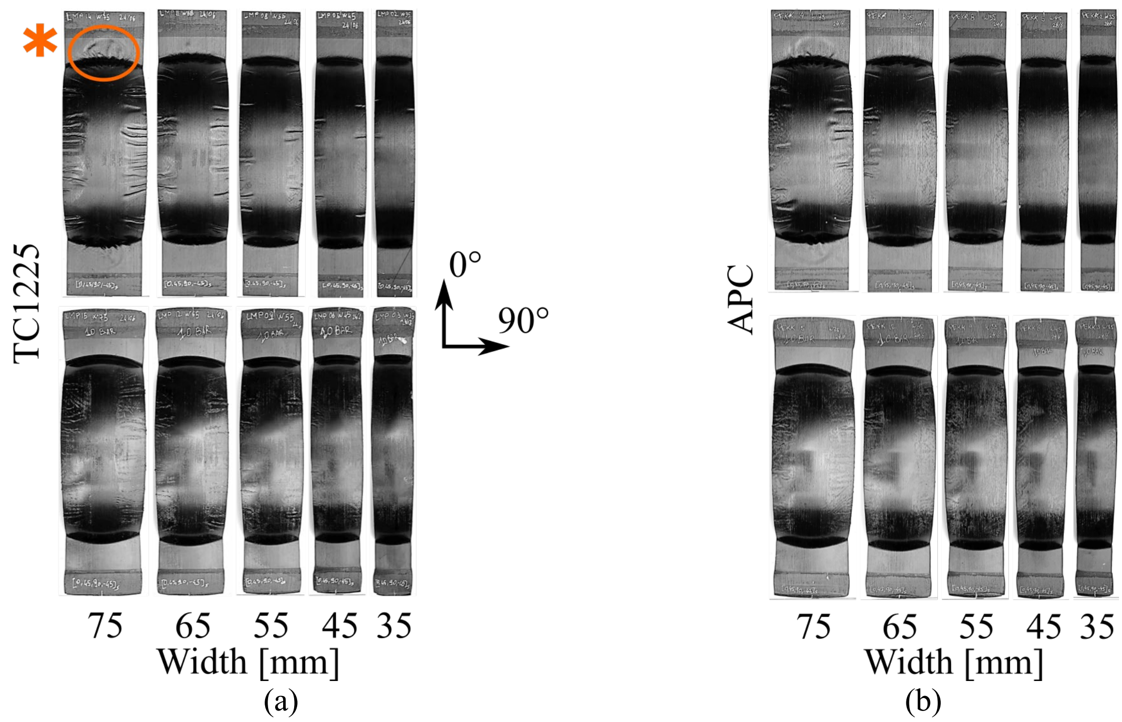



Figure 8: Parts with an additional tool gap of 3mm (top) compared to parts with 10 bar consolidation pressure applied (bottom). (a) Toray TC1225 $[0/45/90/-45]_s$ (b) Solvay APC $[0/45/90/-45]_s$.

**Discussion**

Consecutively, we will discuss the obtained forming results, the methodology and the use of current results for validation of process simulation models.

**Forming results.** Significant wrinkling was observed for most forming configurations in the results presented, indicating that the unidirectional materials used in this study have a limited formability in case of doubly curved shapes. Wrinkling started to appear when sample width exceeded 35 mm for TC1225 and 55 mm for APC. Wolthuizen et al. also observed the occurrence of wrinkling in their forming experiments already at a width of 20 mm for a UD-C/PEKK material with a $[0/90/45/-45]_{2s}$ layup on a similar dome geometry. In the same study an 8HS-G/PPS fabric material started to wrinkle at a sample width of 60 mm, indicating better formability compared to the UD materials. Haanappel et al. [19] also found significant wrinkles for a quasi-isotropic layup in UD-C/PEEK material and attributed this to a high combined rigidity of intra-ply shear and ply-ply friction compared to the apparent bending rigidity.

The forming results with a cross-ply layup demonstrated improved formability compared to the quasi-isotropic layup. Still, significant wrinkling was observed for [0/90] layups at a width of 140 mm, whereas the [45/-45] layups showed much less wrinkling at the same width. Forming results obtained by Lessard et al. [24] using UD-C/PEEK material in a $[0/90]_{12}$ layup on a complex generic geometry also show that the cross-ply layups can be formed, to some extent, into double curved shapes without wrinkles. A direct comparison of the results is difficult, but wrinkles in the their study seem less significant, possibly due to the use of a thicker layup and a higher laminate temperature of 425 °C. The improved formability of cross-ply laminates over quasi-isotropic ones is logically related to the reduced influence of ply-ply friction for in-plane shear deformation of the laminate.

A comparison of the forming results obtained in this research using TC1225 and APC does provide an overall impression of better formability for the APC material. However, the differences are not as clear in all configurations. Hence, no conclusive statement can be made for future applications and a better understanding is required on the origin of their formability differences.

**Methodology.** The handling system for the 8-ply blanks in this study was designed to be of minimal influence on the forming results and result a homogeneous temperature distribution.

However, the heavy 16-ply blanks were found to require more support and hence a different handling system. The combined modification of the blank length and thickness can thereby create difficulty in comparison of the forming results, since the book-ending effect is influenced by both parameters. Hence, the trend in wrinkling with blank thickness is obscured and, instead, one should observe the 8-ply and 16-ply results in isolation. Lessard et al. [24] and Haanappel et al. [19] used grippers that introduce cold spots to handle the laminate during the forming process which are prone to have a significant influence on the forming results also. For future forming studies it is recommended to give appropriate thought to the design of the handling systems.

The process parameters in this study were aimed at fast forming to achieve near-isothermal forming conditions. Hence, the laminate temperature, transfer time and press closing rate were optimized and kept constant for all parts formed. However, as a result, this approach only covers a part of the full processing range for these materials since the formability is known to be dependent on temperature and rate for all deformation mechanisms. To obtain a more complete picture of the formability of a material future studies could include the effects of temperature and rate.

**Validation cases for process simulation.** Possible uses for a forming study as presented here include the validation of process simulation models. This study was performed with this same goal in mind. However, forming is, both in reality and in a model, a complex collection of mechanisms that sum up to give a final deformation. Composite forming of thermoplastic UD material specifically is currently described in models using several de-coupled mechanisms with non-linear material behavior based on an advanced material characterization [14,19]. Ideally, one would like to validate over a range of geometries and processes to cover an extensive spectrum of the material behavior and trigger all deformation mechanisms. A benefit of the formability experiments presented here is the large variety of possible configurations, through the use of other layups, widths, lengths and thicknesses, thereby providing a multi-point reference for validation.

Verification of isolated deformation mechanisms would facilitate easier detection of underlying problems in the process models, which is possible to some extent with the proposed experiments. For example, a narrow blank formed over the dome geometry produces a nearly single-curved part where bending and ply-ply friction (book-ending) are the dominant deformation mechanisms. Altering the layup can change the bending (buckling) behavior as observed in the presented results, but will also change the friction interfaces at the same time. The balance between the mechanisms might be changed using the length and thickness of the blank. The narrow 35 mm wide blanks presented in the results still relied on some in-plane shear deformation due to a slight double curvature, perhaps a single curved center section of the dome could have eliminated this effect.

The in-plane shear deformation mechanism is best validated on parts with a cross-ply layup, due to a low in-plane shear resistance that makes this deformation dominant during forming. Quasi-isotropic laminates have a much higher in-plane shear resistance, due to additional fiber directions combined with ply-ply friction, which almost eliminates the in-plane shear deformation during forming and obstructs its validation. The layup can be used to modify the role of ply-ply friction on the in-plane shear resistance by changing the ply-orientations and interfaces. For example, the quasi-isotropic layup used here, [0/45/90/-45]s, might be changed into [0/90/45/-45]s to effectively make it into 3 stacks of cross-ply layups.

The previous section also mentioned the importance of a range of processing conditions, which also need to be varied to validate the full processing range in simulation models. A fast process with high blank- and tool temperatures could result in a near-isothermal process to eliminate the effects of temperature. On the other hand, slower processes will inherently suffer from more cooling, thereby introducing a possible coupling of the rate- and temperature dependence within a validation case.

Another challenge is to find and quantify the right criteria to compare model against reality. Defect prediction is arguably the most important aspect of a simulation model, therefore, this study has focused on the occurrence of wrinkling. However, the majority of the wrinkling was found on the edges of a part and was fairly severe in most cases. Engineered parts in industrial applications typically do not have most wrinkles on the edges and will avoid the most severe wrinkling cases, putting emphasis on the accurate prediction of the smaller and less severe types of wrinkles in simulation models. Moreover, the shape and size of wrinkles in the consolidated state would be of interest for the structural properties of a part, whereas the current study focused on out-of-plane wrinkling prior to tool closing. Nevertheless, it is believed that a proper prediction and classification of wrinkling prior to tool closing using simulations could be sufficient for the majority of engineering practice. Ensuring a good prediction on a wide variety of generic parts can also lead to confidence in models to predict deformations and defects for industrial applications.

## Conclusion

An experimental methodology was presented to obtain press forming results in a wide range of configurations using a dome geometry. The method was applied in a formability study on two commercial unidirectional thermoplastic composites tape materials. A variety of forming configurations provided a good insight into the formability of the materials and allowed for a comprehensive comparison. The laminate layup and blank width were found to have the most significant influence on the formation of wrinkles, followed by a combined influence of blank thickness and length. A change in stacking sequence for quasi-isotropic layups was also found to influence the size and number of wrinkles, which might be related to a different bending/buckling rigidity of the laminate. Cross-ply layups show better formability compared to quasi-isotropic blanks, but the wrinkling observed still suggests a high intra-ply shear rigidity compared to the bending rigidity of the laminate. Out-of-plane wrinkles clearly observed with a 3mm tool gap correlated well to the wrinkling severity when a consolidation pressure was applied.

The formability experiments presented cover only a sub-set of the possibilities with this set-up. For example, the effects of temperature and rate could be investigated in future experiments to span a larger part of the material's processing window. Alternatively, the sample may be designed such that specific forming mechanisms are emphasized. The formability experiments using a dome geometry can thus be used as a reliable methodology to provide controlled forming results in many configurations.

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