PROCESS-INDUCED SHAPE DISTORTIONS IN AEROSPACE THERMOPLASTIC
COMPOSITES

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Abstract

Thermoplastic composite materials are of great interest in aerospace structures due to their potential for shorter manufacturing cycle times, high production rates, and their ability to be re-heated and shaped multiple times. Thermoplastic resins offer many new possibilities in their ease of repair, recycling, and welding capabilities. Aerospace-grade thermoplastic composites such as carbon fibre-reinforced polyether-ether-ketone (PEEK) are processed well above their melting point at temperatures as high as 390°C to allow proper forming and consolidation of the material to take place. During subsequent cool-down from the process temperature, residual stresses develop due to effects of material anisotropy, part geometry, and tool-part interactions that eventually lead to undesired shape distortions in the final part geometry. As observed with thermoset composites, common distortions include spring-in of corner angles and warpage of flat sections. The tight dimensional tolerances required for aerospace parts demand that process-induced shape distortions be well understood in order to eliminate scrap parts and fitting problems during the assembly stage of the components.

In this project, L-shape flanges with a corner designed at 90° are manufactured from aerospace-grade AS4/PEEK thermoplastic composite in a hot press using a matched-die tooling configuration. A thermoforming technique is employed that involves heating previously-manufactured flat panels of the material to the processing temperature prior to transfer and consolidation within a relatively cold tool held at constant load and temperature. L-shape flanges consisting of a quasi-isotropic layup of unidirectional plies as well as short randomly-oriented strands of AS4/PEEK are thermoformed at 105°C, 215°C, and 290°C. Spring-in angles of the manufactured parts are quantified using a coordinate measuring machine and the results are compared with predictions from the Nelson-Cairns expression based on material thermal expansion anisotropy. The spring-in angles are also evaluated against measurements of change in part corner angle as a function of temperature due to thermo-elastic effects during heat-up from ambient temperature in a quasi-isotropic and ROS part. The parts are further assessed in terms of thickness measurements, surface quality observations, cross-section optical microscopy, and mechanical strength testing.
Preface
This research work was performed as part of the COMP 412 project for the Consortium for Research and Innovation in Aerospace in Québec (CRIAQ) entitled “Thermoplastic Composites Forming Technology for Complex and Integrated Aerospace Components” led by Professor Pascal Hubert from McGill University. The project involved financial and technical support from Bell Helicopter Textron Canada, Pratt & Whitney Canada Inc., Bombardier Aerospace, Delastek Aerospace Inc., Marquez Transtech Ltd., Avior Integrated Products Inc., CRIAQ, the National Research Council of Canada (NRC) and the Natural Sciences and Engineering Research Council of Canada (NSERC). The results of this work were presented in a paper at the 2015 Canadian – International Conference on Composites held in Edmonton, Alberta. All of the experiments and results detailed in Chapters 4 and 5 of this thesis are my work.
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<th>Description</th>
<th>Unit</th>
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<tr>
<td>$S$</td>
<td>Flange displacement</td>
<td>[m]</td>
</tr>
<tr>
<td>$R$</td>
<td>Distance along flange from corner</td>
<td>[m]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Part corner angle, angle of tool</td>
<td>[°]</td>
</tr>
<tr>
<td>$CTE_I$</td>
<td>In-plane coefficient of thermal expansion</td>
<td>[1/°C]</td>
</tr>
<tr>
<td>$CTE_T$</td>
<td>Through-thickness coefficient of thermal expansion</td>
<td>[1/°C]</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature change during cool-down</td>
<td>[°C]</td>
</tr>
<tr>
<td>$V_f$</td>
<td>Fibre volume fraction</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_I$</td>
<td>In-plane strain</td>
<td></td>
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<tr>
<td>$\varepsilon_T$</td>
<td>Through-thickness strain</td>
<td></td>
</tr>
<tr>
<td>$\phi_I$</td>
<td>In-plane crystallization shrinkage parameter</td>
<td></td>
</tr>
<tr>
<td>$\phi_T$</td>
<td>Through-thickness crystallization shrinkage parameter</td>
<td></td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>Spring-in angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$f$</td>
<td>Flange length</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>Part length</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Flange warpage deviation</td>
<td>[m]</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Glass-transition temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Melting temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Thermal diffusivity</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>$b$</td>
<td>Half-thickness of the laminate</td>
<td>[m]</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>[s]</td>
</tr>
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I dedicate this thesis to the cadets and staff of 828 Hurricane Squadron Royal Canadian Air Cadets.

“Knowledge Conquers Fear”
Chapter 1: Introduction

1.1 Composite materials
The maiden flight of the Boeing 787-8 on December 19, 2009 [1] marked a significant event in the history of aviation and the evolution of aerospace materials technology. With powered flight being just over a century old, materials in aircraft construction have evolved from wood and fabrics, to lightweight metals, and most recently to fibre-reinforced composite materials [2]. Approximately 80 percent by volume and 50 percent by weight of the Boeing 787’s airframe, including the wings and fuselage, are constructed from advanced composite materials [3]. The composite materials consist of high-strength and high-stiffness carbon fibres impregnated in a polymer matrix resin. The matrix surrounding the fibres plays the important role of holding the fibres in place and introducing external loads to the fibres, while the fibres provide the majority of the mechanical properties. Carbon fibre-reinforced composites are lightweight, stiff, and strong materials that provide weight savings and improved fuel efficiency in service. Their properties can be tailored as required for optimal load paths and they are unique in that complex shapes that are impossible with metals can be produced [4-5]. Other reinforcing materials besides carbon fibres are also popular in various other applications such as aramid fibres in safety clothing and equipment and glass fibres in recreational boats and water slides. However, this thesis focuses on composites reinforced with carbon fibres for use in the aerospace industry.

1.2 Thermoset and thermoplastic composites
The majority of composites in use today in aerospace are composed of a thermosetting polymer matrix that relies on permanent cross-linking chemical reactions as the material cures during manufacturing. Once a thermosetting polymer or thermoset is fully cured, the material remains solid permanently. The cross-linking reactions in a thermoset composite as the polymer matrix transitions from a liquid to a fully cured solid usually take place on the order of several hours in an autoclave under heat and pressure. Recently, a lot of attention is being drawn towards thermoplastic composite materials. Unlike thermosets, thermoplastics do not involve any permanent chemical reactions and are solely based on physical changes in the material. Thermoplastics are melt-processable and can be heated and melted multiple times over [6]. As
thermoplastics can be heated, melted, and cooled down on the order of minutes, the processing of thermoplastic composites becomes attractive for rapid processing of multiple parts. Aside from the processing times, thermoplastic composites offer several other advantages as well. During storage, thermoplastic composites do not need to be refrigerated due to the absence of cure reactions, and thermoplastic composites open new opportunities for recycling and repair capabilities [6-9]. In addition, thermoplastic composites can also be bonded together by welding processes, eliminating the need for adhesives and fasteners [10]. For example, the rudder and elevator of the Gulfstream G650 business jet were made from induction-welded polyphenylene sulphide (PPS) thermoplastic composites, resulting in 20% cost savings and 10% weight savings from previous designs [11].

Aside from PPS, another thermoplastic resin of interest is polyetheretherketone (PEEK). Both PPS and PEEK are semi-crystalline polymers, meaning that they consist of both amorphous and crystalline regions [8]. Upon cooling down from a liquid, ordered crystal regions are formed within the polymer network. The crystalline regions provide strength and stiffness to the material, and in the amorphous regions the chains can readily slide past each other, resulting in desirable toughness properties [6, 8]. The toughness of PEEK composites has been reported to be three times greater than traditional thermoset composites [12]. In general, advanced thermoplastic composites are better suited for energy absorption. PEEK also possesses excellent thermal stability as it has a relatively high glass-transition temperature of 143°C and a relatively high melting temperature of 343°C [7, 13]. However, the significantly high viscosity of advanced thermoplastics in the liquid phase requires that large external pressures must be applied during manufacturing of these materials [6-8, 14].

1.3 Manufacturing thermoplastic composites

Due to the high consolidation pressures and temperatures required for processing thermoplastic composites, parts are most commonly formed in a hot press, using either a compression moulding or thermoforming process [12, 15-17]. During compression moulding, individual sheets or pre-cut randomly-oriented strands of prepreg are placed within a mould cavity and pressed under high temperatures until complete consolidation of the part is achieved. During thermoforming, individual sheets or laminates of the material are pre-heated, typically in an infrared oven, and
transferred within a matched-die tool for final forming and consolidation [15]. A sketch of the thermoforming process for producing L-shapes from a flat laminate charge is shown in Figure 1.1.

In the thermoforming process, heated laminates can be formed and consolidated in a matter of seconds as they are rapidly cooled within a male and female tool held at a lower temperature [15]. In industry, matched-die tools are commonly made from tooling steel due to its durability against wear and tear during large production runs. Other variations of the thermoforming process include combinations of steel and rubber tool halves, such as in the ‘High Precision Rubber Pressing’ project lead by the Netherlands Agency for Aerospace programme [18]. In this case, the male tool is made from steel and the female tool is made from rubber to ensure uniform hydrostatic consolidation pressure on the part [18].

1.4 Discontinuous, randomly-oriented thermoplastic composite strands
There is growing interest in the aerospace industry in producing thermoplastic parts reinforced with discontinuous, randomly-oriented strands [12, 16, 17]. Each strand, typically measuring 1/8-inch to ½-inch wide by ½-inch to 1-inch long aims to facilitate forming parts with complex geometries while maintaining a reasonable balance of mechanical properties [12, 16]. There is the potential for parts made from these thermoplastic composite strands to fill the gap between short discontinuous fibres that lack the mechanical properties and continuous fibres that are limited to simple geometries [12]. As part of a project lead by the Consortium for Aerospace Research and
Innovation in Québec and supported by aerospace industries in Canada, there is significant interest in developing a thorough understanding in the processability and behaviour of these materials.

1.5 Process-induced shape distortions in composites

Processing of fibre-reinforced composite materials generally leads to the formation of residual stresses and process-induced shape distortions. During composites manufacturing, extrinsic sources including tool-part interactions and processing parameters can have an effect on the extent that shape distortions become apparent in the final part geometry. The anisotropic nature of composites also plays a significant role, especially when a part is subject to changes in temperature and the differential thermal expansion and contraction between the fibres and matrix leads to the development of residual stresses. A common shape distortion that affects composite materials with cornered geometries is spring-in, a decrease in the corner angle due to effects of anisotropy. As a curved part is cooled down, thermal contraction is significantly greater in the through-thickness direction than in the in-plane direction, and as a result spring-in occurs upon removal from a tool resulting in a final part corner angle that is typically 1 – 3 degrees less than the original design angle [18].

During processing of thermoplastic composites, very large changes in temperature are encountered as a part must be heated above its melting point and cooled down to ambient temperature within a forming tool, promoting the spring-in effect. Spring-in can generally be compensated for by modifying tooling geometries via a trial and error approach, however this can be costly and time consuming. To be able to properly predict the extent that spring-in will occur, it is imperative to properly understand the underlying physical mechanisms in the material as well as the manufacturing process. As our understanding of shape distortions during the manufacturing of thermoplastic composite parts is still quite limited compared to thermoset composites, further experimental testing must be performed on these materials. The information obtained from the manufacturing experiments becomes valuable input for the development and validation of processing models for thermoplastic composites. During manufacturing, not only is it critical to study the resulting shape distortions in parts, but to also evaluate the overall quality of the parts in
terms of surface finish, mechanical strength, thickness variations, consolidation quality, as well as any other observable features that become apparent.
Chapter 2: Background and Literature Review

2.1 Causes of spring-in

Early work from Nelson and Cairns [19], and Radford and Diefendorf [20] has clearly shown that spring-in is caused in angled composite laminates primarily due to material anisotropy arising from the differential thermal expansion coefficients between the fibres and the matrix. During volumetric shrinkage in the material when the part is cooling down, the shrinkage in the through-thickness or radial direction of the corner is significantly higher than in the in-plane or longitudinal direction. In the through-thickness direction, the matrix can freely contract however in the in-plane direction, contraction is limited by the much smaller thermal contraction of the fibres. In addition to differences in thermal expansion coefficients, chemical shrinkage of a thermoset resin during curing also contributes to spring-in.

The causes of spring-in have been thoroughly studied experimentally by Albert and Fernlund [21, 22], and Wijskamp [18]. In Figure 2.1 adapted from Albert [21], a corner angle sector is shown. Shrinkage in direction 2 (through-thickness) is much greater than in direction 1 (in-plane) and as the material cures and cools down, an increase in the arc sector angle from $\theta_1$ to $\theta_2$ occurs. In Figure 2.1, it can also be seen that the uncured (bolded) and cured arc lengths are the same due to negligible shrinkage occurring in the fibre direction in-plane. Albert has shown that the increase in corner arc sector angle causes a decrease in the enclosed angle of a laminate. The angles are defined in Figure 2.2 [21].
2.2 Prediction of spring-in

Equation 2.1 proposed by the early work of Nelson and Cairns [19] allows for the prediction of spring-in in angled composite laminates based on the difference between the processing and ambient temperatures, the thermal expansion coefficients of the material, and cure shrinkage parameters (for thermosets).
\[
\Delta \theta = \Delta \theta_{CTE} + \Delta \theta_{CS} = \theta \left( \frac{(CTE_l - CTE_t) \Delta T}{1 + CTE_t \Delta T} \right) + \theta \left( \frac{\phi_l - \phi_t}{1 + \phi_t} \right)
\]  

(2.1)

Where \(\Delta \theta\) is the spring-in angle, which has a thermal expansion anisotropy component, \(\Delta \theta_{CTE}\), and a cure shrinkage anisotropy component, \(\Delta \theta_{CS}\). The thermal expansion anisotropy component of the spring-angle is dependent on the angle of the tool at which the part is being formed, \(\theta\), the in-plane coefficient of thermal expansion in the part, \(CTE_l\), the through-thickness coefficient of thermal expansion in the part, \(CTE_t\), and the difference between the processing and ambient temperatures, \(\Delta T\). The cure shrinkage component is dependent on the in-plane and through-thickness cure shrinkage parameters, \(\phi_l\) and \(\phi_t\) respectively, and the angle of the tool. Equation 2.1 does not include any extrinsic effects such as tool-part interactions and does not consider the development of the modulus for the calculation of the cure shrinkage component. Overall, equation 2.1 provides reasonable estimates of spring-in in thermoset laminates at the corner region of parts [21, 22].

2.3 Spring-in and warpage

Albert [21, 22] has shown that aside from the material anisotropy in a curved geometry that causes spring-in, additional part-deformations can arise in flat sections of a part such as warpage, due to extrinsic effects. The extrinsic effects are largely due to processing variables and tool-part interactions. After manufacturing thermoset composite L-shapes on a convex tool, Albert observed that the flanges were warped, resulting in greater spring-in measured at the flange tip compared to the corner due the flanges being curved inwards, towards the corner. Equation 2.1 was not able to predict the deformations induced by flange warpage. The effects of warpage on composite parts have also been studied extensively by Johnston [23], Yoon and Kim [24], Fernlund and Poursartip [25], Radford and Rennick [26], Twigg [27], and Cann and Adams [28].

Wijskamp [18] suggests that warpage can occur in flat symmetric parts if there are through-thickness stress gradients induced by tool-part interactions. Stress gradients can be caused due to temperature differences within the part or due to mechanical interaction with the tooling. In addition, warpage can also arise due to inhomogeneity in the part from resin rich and resin poor
areas, either through-thickness or within the plane of the part. Wijskamp manufactured V-shape thermoplastic composite parts using rubber press-forming and was not able to properly predict the spring-in angles using simple thermoelasticity. During the rubber press-forming process, significant tool-part interactions between the rubber tool and the part had an effect on the spring-in angle.

Fernlund and Poursartip [25] showed that there are complex interactions between cure-cycle, tool surface condition, and spring-in of composite C-channels processed on an aluminum tool. Simple formulas such as equation 2.1 can be used in certain cases, but there are other important factors that have an effect as well.

2.4 Thermoforming thermoplastic composite parts

Han et al. [29, 30] thermoformed woven carbon fibre-reinforced PPS composite V-shapes in a hot press and studied the effect of tool temperature on part spring-in. They have found that there is increasing spring-in with increasing tool thermoforming temperature. They suggest that spring-in occurs in the part during cool down from the tool temperature to room temperature, and that parts formed at higher temperatures exhibit greater spring-in due to a larger cool-down.

Jain et al. [31] studied the spring-in behaviour during thermoforming of a carbon fibre-reinforced polyetherimide (PEI) aileron rib. They focused on the amount of spring-in that occurs as well as the void content at different thermoforming temperatures. They reported that spring-in increases with increasing tool forming temperature, and that the void content in the part increases with decreasing tool forming temperature.

Salomi et al. [32] have investigated the spring-in angle of thermoformed commingled glass and polypropylene L-shape laminates. They have formed L-shapes with different internal radii. They noted that for parts with a very small inside corner radius, the spring-in angle is greater due to defects that occur in the corner. There appears to be fewer defects in parts with a larger corner radius. Sources of defects include fibre waviness, thickness variations, and local resin-rich regions in the corner.
2.5 Crystallization shrinkage in thermoplastics

Lynam [33] suggests that unlike thermoset composites, thermoplastic composite materials are usually processed well above their glass transition temperature. He explains that crystallization shrinkage in thermoplastic materials occurs when the resin is highly viscous, and that any stresses that develop due to crystallization shrinkage will be relaxed almost immediately during processing.

In the case of PEEK thermoplastic composites, studies by Gordnian [34] have also shown that crystallization occurs rapidly during cool-down, when the modulus of the resin is significantly low.
Chapter 3: Research Objectives

As part of the CRIAQ COMP – 412 project for “Thermoplastic Composites Forming Technology for Complex and Integrated Aerospace Components”, the goals of this project are to manufacture aerospace-grade thermoplastic composite L-shape parts in a hot press and to primarily study the effect of the tool consolidation temperature on the resulting shape distortions (including spring-in and warpage) as well as other factors relating to part quality in a continuous and discontinuous fibre system. The manufactured parts are assessed by physical thickness measurements, optical microscopy of corner and flange cross-sections, and observations of the visual surface quality. Mechanical strength testing of the parts under four-point bending is also performed. An overview of the items studied in this project is presented in Figure 3.1.

![Diagram showing the items studied in the manufacturing of thermoplastic composite L-Shapes.](image)

Figure 3.1: Overview of the items studied in the manufacturing of thermoplastic composite L-Shapes.

The research in this thesis has been performed as part of a work-package for the CRIAQ COMP-412 project to help validate a residual stress and deformation model being developed within The Composites Research Network at UBC.
A critical portion of this project involved commissioning a newly acquired hot press and designing the required tool fixtures for manufacturing all parts. As a first attempt to manufacture thermoplastic composite parts within the new equipment in the composites group at UBC, a simple L-shape geometry has been chosen as the focus of this work.

It should be noted that the process for manufacturing the L-shape parts in Chapter 4 of this thesis involves modifications that are not part of the conventional thermoforming process applied in industry. The modifications were made in order to facilitate the manufacturing workflow with the equipment available. The modifications are documented and considered in the analysis of the results.

The research objectives of this study are as follows:

a) Commission a hot press in order to manufacture thermoplastic composite parts;
b) Design and implement tool fixtures for processing flat and L-shaped parts;
c) Manufacture flat panels made from unidirectional material as well as randomly-oriented strands;
d) Assess the influence of the tool consolidation temperature on the measured process outcomes (spring-in, flange warpage, mechanical strength, wrinkling and surface quality, flange termination profiles, thickness variations) of manufactured L-shape parts made from unidirectional material and randomly-oriented strands;
e) Assess the ability to predict spring-in using a simple thermo-elastic formulation based on material thermal contraction anisotropy;
f) Study the thermo-elastic spring-in behaviour of manufactured L-shape parts during a heating and cooling experiment inside a furnace;
g) Better understand the spring-in and warpage behaviour of thermoplastic composite L-shape laminates manufactured in a hot press.
The research presented throughout the remainder of this thesis is organized as follows:

**Chapter 4** - presents the experimental methods in this research, including all of the procedures for manufacturing parts and performing measurements;

**Chapter 5** - includes all of the results for the experiments performed in Chapter 4;

**Chapter 6** - provides discussions on the results that were obtained in Chapter 5;

**Chapter 7** - summarizes the main findings in this project and provides plans for future work;

**Appendices** - provide supporting material on the hot press, tool designs and detailed drawings, and the experimental methods and results. A case study is also presented in Appendix M where a part is formed below the melting temperature of the resin in order to assess low-temperature processing options.
Chapter 4: Experimental Methods

All of the parts in this study were manufactured in the Wabash hydraulic hot press with platens sized 90 cm x 90 cm (see Appendix A). The parts were made from Royal Tencate’s commercially-available TC1200 unidirectional AS4/PEEK tape ($V_f = 59\%$, tape thickness = 0.14 mm) in the form of a 12-inch wide roll (Figure 4.1) [35]. This material was used for all of the parts consisting of a quasi-isotropic layup. The ROS parts were made from pre-cut chips of TC1200 AS4/PEEK tape measuring 12.7 mm x 3.175 mm. The chips are also commercially available from Tencate as MC1200 bulk moulding compound [36]. The first step in the manufacturing process involved consolidating flat panels that would serve as the charge for the L-shape forming discussed further in this thesis.

Figure 4.1: Tencate TC1200 AS4/PEEK unidirectional roll.
4.1 Flat panel manufacturing

Flat laminates 20 cm x 20 cm (8” x 8”) were consolidated from AS4/PEEK tape in the picture frame tool assembly of Appendix B.1. The laminates made from the unidirectional TC1200 material were made by cutting the individual plies to size and carefully stacking them in the desired orientation within the tool assembly. The laminates consist of 16 plies in a quasi-isotropic layup: [0/+45/-45/90]$_{2S}$ resulting in a consolidated laminate thickness of 2.20 mm ± 0.05 mm. The laminates were processed within the tool assembly centred on the press platens. Details involved in the preparation and manufacturing of flat panels made from AS4/PEEK are included in the following sections.

4.1.1 Cutting the thermoplastic prepreg sheets

The prepreg sheets were cut to size using a pair of scissors and the sizing template (Figure 4.4.2). The sizing template ensured that the sheets were cut to the maximum size allowable in the picture frame tool. The scissors were most effective for cutting the sheets as they minimized splitting along the fibre direction. Splitting can easily occur in thermoplastic prepreg sheets as the resin is well below its glass transition temperature during cutting at room temperature. Unlike thermoset prepreg materials that are only partially cured during cutting in the lay-up room, thermoplastic sheets possess no tackiness and are comparatively much more likely to split or tear inconveniently. Prior to cutting the sheets with the scissors in the [0/90] or [±45] directions, the contour of the template was carefully traced with a very light cut from an X-Acto knife.

![Figure 4.4.2: Template for cutting [0/90] (left) and [±45] orientations from unidirectional AS4/PEEK.](image-url)
4.1.2 Preparing the surfaces of the picture frame tool

The entire surface of the picture frame tool in contact with the thermoplastic composite was thoroughly cleaned with isopropanol prior to applying release agent. The area to be cleaned included the entire inside walls of the outer frame, and the polished surfaces of the two flat plates.

On the clean tool surface, two coats of Frekote® 700-NC release agent were applied. The first two coats were allowed to dry for 15 minutes. A third coat was also applied and allowed to dry for a period of 24 hours before manufacturing.

4.1.3 Loading the material and tool into the press

With the outer frame piece lying flat, one of the steel plates was gently placed inside with the polished surface facing up. The plate was gently tapped into place with a rubber mallet as placement was challenging at times due to the very tight gap between the plate and frame. The bottom surface of the plate was seated flush with the bottom of the frame. The material was then ready to be loaded within the tool.

The cut sheets of AS4/PEEK were stacked one by one inside the frame until the desired lay-up was obtained. Finally, the second steel plate was placed inside the frame on top of the stack with the polished surface facing down towards the material. The upper plate that rested on top of the stacked sheets protruded higher than the rest of the frame once in place – this ensured that the press platens would apply consolidation pressure to the part lying between the plates, as opposed to the outer frame. An image of the tool ready for loading in the press is shown in Figure 4.3.
4.1.4 Hot press setup and panel manufacturing

With the platens in the fully open position, the platen surfaces were cleaned of any debris with the compressed air line located at the front of the press. The tool was then loaded and centred onto the lower platen with the upper plate facing upwards. If a thermocouple was not placed inside the tool and part, a stopper block was screwed in place to prevent any flow of resin from the thermocouple access port (Figure 4.3 and Figure 4.4). The thermocouple access port was simply a 1/16-inch hole drilled through the upper plate (Figure 4.5). The press was centred such that the stopper block on the upper steel plate was aligned with the middle t-slot of the upper platen. Once centred, the platens were slowly closed and a relatively low contact force of 1.5 tons was applied on the tool. This contact force was maintained throughout the entire heating segment. At the processing temperature of 385°C, a full consolidation force of 9 tons (21 bars) was applied. The full consolidation pressure was maintained during cool-down to room temperature where the tool was removed from the press. An image of the tool under consolidation in between the platens as viewed through the safety enclosure is shown in Figure 4.6. Careful observation of the figure reveals that the upper steel plate is sitting higher than the frame, and transferring all consolidation pressure to the underlying part.
Figure 4.4: Thermocouple entry location and hole stopper located on the top side of the upper flat steel plate.
Figure 4.5: Thermocouple access port as seen from the polished side of the upper flat steel plate.

Figure 4.6: Picture frame tool under consolidation within the press platens.
One set of trial laminates were produced with a thermocouple embedded mid-thickness (between plies 8 and 9) in the part (Figure 4.7). The thermocouple was carefully inserted through a small hole perforated in the first 8 plies, and taped securely in place at the desired location (Figure 4.8). In this case, the steel plate with the thermocouple access port of Figure 4.5 was inserted in the frame first, followed by the first 8 sheets of material (with the perforated centre), the thermocouple, the remaining 8 sheets of material, and lastly the second steel plate. Once the tool was ready and in place in the press, the thermocouple extending from the tool in Figure 4.7 was carefully aligned with the middle t-slot to prevent any damage from occurring when the platens would close.

Figure 4.7: Picture and schematic of the thermocouple location for mid-thickness thermal profile measurements.
Figure 4.8: Thermocouple placed at the mid-thickness of the AS4/PEEK laminate, prior to stacking the remaining sheets and closing the tool.

The temperature profile during pressing was recorded with a data acquisition unit at a frequency of 5 Hertz, shown in Figure 4.9. The total manufacturing time for each laminate was 2 hours and 45 minutes and can be summarized in the following steps:

a) Contact Pressure (1.5 tons) applied on the tool during heating from ambient to 385°C (duration: 1 hour and 15 minutes);

b) Full consolidation pressure of 21 bars (9 tons) applied at 385°C and start of the platens air cooling* from 385°C to 340°C (duration: 1 hour);

c) Start of platens water cooling from 340°C to room temperature and removal of tool from hot press (duration: 30 minutes)

*The built-in hot press safety limitations prevent rapid water cooling from taking place above 340°C.
Figure 4.9: Temperature and consolidation pressure profiles during the manufacturing of AS4/PEEK flat panels.

In order to obtain the results of Figure 4.9, one single laminate was processed with a thermocouple embedded mid-plane as described earlier, and with a second thermocouple located on the top surface of the laminate (beneath the upper steel plate). This was accomplished by inserting a thermocouple through the side of the frame, at the location where the bolt is shown at the reference corner marker of Figure 4.3. The bolt could be removed in order to provide access to a 1/16th inch hole, similar to the one machined through the top steel plate. However, only one laminate (thermal profile of Figure 4.9) was produced with the second thermocouple as it was easily damaged during the removal of the part from the tool. For that reason, the thermal profiles during L-shape consolidation of section 5.2 were generated from a laminate with a single thermocouple located at mid-thickness. During manufacturing of the laminates, the bolt remained in place in the frame as shown in Figure 4.3.

The picture frame tool was centred on the press platen with all edges aligned in the same direction during all tests. The specific reference corner on the picture frame tool of Figure 4.3 was useful in order to monitor and document the orientation of the panel as loaded within the tool and press. The
material was always stacked in the tool in the same manner. Once the laminates were removed from the tool, the location of the tool reference corner was labelled on the top surface (as viewed from the top during consolidation) of the corresponding corner on the laminate. The orientation of the laminates during consolidation becomes useful for the warpage measurements of section 4.1.8.

4.1.5 Flat panel manufacturing thermal simulation

The measured temperature profile of Figure 4.9 was compared with a one-dimensional thermal simulation run in RAVEN [37] in order to get a sense of the temperature variations through-thickness within the tool and part. The dimensions of the plates and the laminate for the simulation are shown in Figure 4.10. The set temperature was applied on the top and bottom surfaces of the upper and lower steel plates, respectively.

![Steel plates and laminate configuration for thermal simulation in RAVEN.](image)

The temperature profile includes the following steps:

1. Temperature ramp from 25°C to 385°C at 6°C/min
2. Temperature hold at 385°C for 5 minutes
3. Air cooling at 1°C/min from 385°C to 340°C
4. Water cooling at 10°C/min from 340°C to 25°C

The temperature ramps and holds were selected to reproduce the measured thermal profile during the manufacturing of a laminate in the picture frame tool. The results of the thermal simulation are shown in Figure 4.11.
Figure 4.11: Thermal simulation during manufacturing of an AS4/PEEK laminate.

The simulation results show no through-thickness variation in temperature from the outside of the steel plates to the mid-thickness of the laminate. No through-thickness temperature gradients are expected during the manufacturing process.

4.1.6 Disassembling and removing the part from the picture frame tool

Once the tool had cooled down to room temperature, the next step was to remove the part from the picture frame tool. Even with release agent applied on the inside surfaces, the flat plates and frame were all stuck as one piece upon removal from the press. A simple system for dislodging the plates and the composite panel was established with the use of the press, two 30 cm long aluminum shims, and one square aluminum plate measuring 18 cm x 18 cm x 2 cm. The following step-by-step description applies to the majority of the parts that did not have any thermocouples embedded inside.
With the platens in the fully open position, the steel tool was carefully positioned over two aluminum shims lying beneath the outer frame of the tool (Figure 4.12). The aluminum plate was then placed on top of the tool, centred directly over the upper steel plate (Figure 4.13). Ensuring that the aluminum plate was not resting over any portion of the frame was critical to prevent damage from occurring during closure of the platens.

Figure 4.12: Resting the outer frame on two aluminum shims.

Figure 4.13: Aluminum plate resting over the centre of the upper steel plate.
Once the tool, the aluminum shims and plate were all in place as illustrated in Figure 4.14, the press was slowly closed together until the upper platen just came into contact with the top of the aluminum plate. The press was closed further slowly and carefully in order to push the top aluminum plate as far in as possible while displacing the steel plates through the bottom of the frame. The press was closed until the lower steel plate was in contact with the lower platen. The platens were then opened and the tool was carefully removed with one hand supporting the frame and the other supporting the steel plates to prevent them from falling. A rubber mallet was used to tap out the plates from the frame. With the plates removed, the composite panel was then separated from the steel plates. At times, the rubber mallet was gently tapped on the plates to help loosen the part. While separating the part, some resin flashing was observed along the edges of the steel plates (Figure 4.15). This flashing had to be removed prior to cleaning and preparing the tool surfaces for a new part.
Figure 4.15: Flashing present on the edges of an AS4/PEEK laminate sandwiched in between the two steel plates.

For the sample that had an embedded thermocouple inside, the upper steel plate with the thermocouple access port had to be removed extremely carefully to prevent any damage. All the same steps were followed, except that the entire picture frame tool was placed in the press upside down, such that the upper steel plate (and thermocouple access port) was facing but not touching the lower platen as the frame was resting on the aluminum shims. The thermocouple access port was aligned with the platen t-slot throughout the process. The aluminum plate was placed on the bottom steel plate (now facing the upper platen), and both plates and tool were carefully dislodged as outlined in the previous steps. Additional caution was taken when separating the composite panel from the upper steel plate to ensure that no damage occurred to the thermocouple.

4.1.7 Post manufacturing and processing of ROS panels

The flashing present around the edges of the laminate was removed with a Nakanishi Inc. sonic cutter (Figure 4.16) and the edges of the laminates were trimmed to final dimensions of 19.6 cm x 19.6 cm (7.75” x 7.75”) in order to ensure proper sizing for the L-shape thermoforming stage. The laminates weighed 140.1 g prior to trimming (amount of sheet material loaded in tool) – this weight was used to determine the correct amount of MC1200 chips that would be required to produce an ROS laminate of equivalent thickness. The chips for the ROS parts were manually and randomly placed in the tool (Figure 4.17). The ROS panels were all processed in the same manner as
described above for the quasi-isotropic laminates. Sample flat panels made from a quasi-isotropic lay-up and ROS are shown in Figure 4.18. A total of nine quasi-isotropic and nine ROS panels were pressed for the forming process outlined in section 4.3. An example of an AS4/PEEK panel with an embedded thermocouple is shown in Figure 4.19.

Figure 4.16: Flashing present on the edges of the laminate as removed from the tool (left), and removal of flashing prior to trimming (right).

Figure 4.17: Placement of AS4/PEEK strands prior to closing the tool.
Figure 4.18: Manufactured flat panel charges made from A) $[0/+45/-45/90]_{2S}$ layup, and B) randomly-oriented strands.

Figure 4.19: Embedded thermocouple inside a manufactured AS4/PEEK panel.
4.1.8 Warpage measurements of ROS panels
The ROS panels were scanned in a Nikon coordinate measuring machine (CMM) and the part deviations were measured by reference to a plane of best fit generated by the scanning software. All of the ROS panels warped upon removal from the tool, and the amount and orientation of the warpage with respect to the orientation of the panel inside the picture frame tool varied randomly among the samples. The flat panels were all scanned with the marked reference corner labelled on the top surface from section 4.1.3 facing upwards and oriented in the same direction on the CMM table (Figure 4.20). No warpage was observed in the quasi-isotropic panels. A thin white coat of Ardrox® 9D1B developer was sprayed on the panel surface to ensure proper detection by the laser head during scanning.

![Figure 4.20: Scanning the surface of an ROS panel with the CMM.](image)

4.2 Preparation and installation of the tooling for manufacturing L-shape parts
The following sections outline the procedures for preparing and installing the L-shape forming tool within the hot press in order to successfully manufacture L-shape parts. Details on surface preparation and the clamping system that secured the tool halves to the press platens are provided. An experimental thermal characterization and simulation that was conducted on each tool half installed in the hot press is also presented.
4.2.1 Surface preparation of the tool halves
The proper surface preparation of the tool is an important step to ensure that the thermoplastic resin does not stick on the surface during the manufacturing process. Prior to applying any release agent, the polished steel surface was thoroughly cleaned with Zyvax® Mould Cleaner and Kimwipes™. This cleaner is specifically designed for removing any old layers of release agent and residue from a tool steel surface. The manufacturer’s recommended steps were followed for the application of all mould sealers and release agents [38].

Once all residue was removed from the tool, four coats of Zyvax® Mould Sealer GP [38] were applied to all surfaces that would be in contact with the thermoplastic, allowing 15 minutes for each coat to dry before applying the next. After the final coat of sealer was applied, a drying time of 30 minutes was required prior to coating the tool with release agent.

Three coats of Zyvax® release agent (Composite Shield) [38] were applied in the same manner. Following the final coat, the tool was set aside to dry for a period of 24 hours.

4.2.2 Loading and clamping the tool halves in the hot press
The following procedure was followed when loading the 90° tool halves in the hot press:

With the male and female halves separated on the workbench, the very first step was to insert the two alignment pins in the female tool at the locations shown in Figure B.5 in Appendix B. This allowed the female tool to be properly aligned onto the male tool. With both female and male halves assembled together, the entire tool was then positioned onto the lower platen surface. The male half of the tool was positioned on the bottom, lying directly on the lower platen. The male and female halves were then clamped securely on the lower and upper platens, respectively.

4.2.2.1 Clamping system and procedure
Both the male and female tool halves were secured at four locations with a unique clamping system that was integrated into the machined t-slots of the press platens (Figure 4.21).
The clamping system consists of the following five components:

1. Step clamp
2. Step block
3. T-slot nut
4. Flange nut
5. Stud bolt

For both tool halves, the same clamping system was incorporated to secure the four corners except that the step clamps were four inches long for the male tool and six inches long for the female tool. The tool was centred and aligned on the lower platen, and the edges of the male tool at the corners were clamped securely with the nearest t-slots (Figure 4.22). The edges of the male tool were clamped such that there was enough clearance for vertical displacement of the female tool. A sketch of the clamping system and the clearance gap between the female tool is shown in Figure 4.23.
Figure 4.22: Male and female tool assembly – male tool clamped in place prior to raising the lower platen.

Figure 4.23: Sketch of male tool edge clamped onto lower platen.

With the male tool clamped, the lower platen was then raised slowly until the top surface of the female tool came into contact with the upper platen (Figure 4.24). Prior to raising the platen, the maximum load in the program menu was set to “0” to ensure that no excessive force was applied on the tool. With the lower platen in the fully raised position, the female tool was clamped in the
same manner as the male tool, using the nearby t-slots. Once clamped into place as shown in Figure 4.25, the two halves remained aligned and displacement of the male tool was controlled by raising or lowering the hydraulically-controlled lower platen.

Figure 4.24: Male and female tool assembly – lower platen raised and female half in contact with upper platen.
With both halves clamped in place, the next step was to lower the male tool relative to the female tool and to increase the distance separating the tool halves as much as possible. At this point, the alignment pins in the female tool were removed. This was important to prevent any damage to the tool in the event that platen shifting occurred. It should also be noted that the gap between the male and female tool shear edge (~0.006 inches) was greater than the gap between the alignment pins and holes (~0.003 inches). The dowel pins were internally threaded as seen in the close-up image of Figure B.5 in Appendix B and were easily removed with a custom-made device provided by the Materials Engineering machine shop. An image of the device is presented in Figure 4.26, and a sketch of the cross-section of the hammer and screw are illustrated in Figure 4.27. In order to dislodge the pins from the female tool, the screw that rested inside the hammer was first threaded into the alignment pin. The hammer was then raised toward the alignment pin and abruptly lowered until striking the head of the screw and ultimately freeing the pin from the female tool.
Following removal of the pins, the tool surfaces were cleaned of any foreign debris with the compressed air line installed at the front of the press. The alignment of the tool halves was verified once again by carefully closing and re-opening the platens and ensuring that there was no contact between any surfaces. The entire tool assembly was now ready for manufacturing L-shape parts.
4.2.3 Set-up of hot press controls for L-shape manufacturing

The following specifications were implemented in the manual program of the hot press for manufacturing L-shape parts:

- Clamp force: 12 tons (40 bars pressure applied on the L-shape part)
- Clamp slow-down position: 5.0 inches
- Clamp position: 0 inches
- Pressing speed: 5 inches per minute
- Platen temperature: 105°C, 215°C, or 290°C

Example screenshots of the hot press specifications are shown in Figure 4.28. In order to ensure that the press is under load-limited control (as opposed to position-limited control), the ‘clamp position’ of 0 inches allows the lower platen to continue closing until the desired clamping force on the part is reached. The load was maintained throughout the entire consolidation process. The male and female tool halves would close together at the maximum allowable pressing speed of 5 inches per minute up to the target load. The clamp slow-down position is the point where the platens close automatically at the set pressing speed. In this project, the clamp slow-down position of 5.0 inches corresponded to the point where a 1 cm gap separated the male and female tool contact surfaces. The slow-down position must be defined before the point of contact between the tools and part. Prior to loading the material within the tool and closing the press, the press was open just beyond the slow-close position at the start of the manufacturing cycle. An image of the tool halves open just beyond the slow-close position is shown in Figure 4.29. A Solidworks® drawing at the same position has also been included in Figure 4.30 for better visual clarity. The clamp-slowdown position selected ensured that a part could easily be loaded within the tool cavity at the start of the cycle while minimizing the time required for complete closure and consolidation on the part. The positioning of the platens at the beginning of the cycle also took into consideration that no automated transfer device was in place for transporting and positioning the AS4/PEEK charge within the tool. A simple and repeatable method was chosen based on the equipment and resources available. Details on the placement method of the part on the tool are provided in section 4.3.4.
Figure 4.28: Hot press control screen – setup specifications.

Figure 4.29: Positioning of male and female tool at the start of the manufacturing cycle.
The press platens were allowed to heat up to the target temperature of 105°C, 215°C, or 290°C for a period of three hours prior to the start of a manufacturing cycle. Beyond this time, all surfaces of the male and female tool were within ± 3°C of the target temperature. This was verified by taking point measurements on the tool surface with a thermocouple and data acquisition unit. No changes in tool surface temperature were observed beyond the 3-hour mark from start of heating.

4.2.4 Thermal profiling the tool halves

The surface temperature at 15 different locations on both the male and female tool surfaces was measured during heat-up, a hold temperature, and cool-down within the hot press. The temperature at each location was measured with a K-type thermocouple and National Instruments data acquisition unit. The placement and numbering of the thermocouples on the male tool is shown in Figure 4.31. The thermocouples were placed in a similar manner on the female tool surface. Due to the number of thermocouples used in this test, the thermal profiles of the male and female tools were conducted at two different times. The thermocouples were placed directly on the tool surfaces with Kapton® tape. The best practice, especially when measuring the surface temperature of a tool being heated in an autoclave, is to shield the thermocouple from the hot circulating air to ensure that the temperature measurements are accurate. However, in this particular case the tool is heated from the press platens as opposed to surrounding air and therefore thermocouple shielding is not as critical.
The hot press was set to heat up both platens from room temperature to 340°C, followed by a cool-down to room temperature using water cooling. The heat-up ramp rate of the platens is controlled by the heating cartridges and cannot be changed by the user. Cool-down from 340°C was controlled by water cooling inside the platens. In order to avoid slow-cooling by air and to save time during the experiment, the maximum heat-up temperature of 340°C was chosen – the highest temperature where rapid cooling of the platens with water is permitted by the program in the press. For any temperature higher than 340°C, only air cooling is allowed. The purpose of the test was to measure variations in temperature at different locations on the tool subject to heating and rapid cooling conditions. The water cooling flow-rate was set by the manufacturer’s recommended specifications.
4.2.4.1 Thermal profiling results

The thermal profile of the male and female tool surfaces is shown in Figure 4.32 and Figure 4.33, and an overlap of the two profiles is shown in Figure 4.34. Due to the difference in duration of each thermal profile test, there is an off-set present in Figure 4.34. The average heating rate on both tools was 5°C/min, and the average cool-down rate was 9°C/min. On the male tool surface, a temperature difference of 6.6°C was measured during the hold at 9,000 seconds, and a difference as large as 42°C was measured during the cool-down at 11,000 seconds (Figure 4.32). On the female tool surface, a temperature difference of 6°C was measured during the hold at 10,000 seconds, and a difference as large as 45°C was measured during the cool-down at 12,000 seconds (Figure 4.33).

![Figure 4.32: Surface temperature profile of male tool.](image)
Figure 4.33: Surface temperature profile of female tool.
Due to the geometry of the tool, thermocouples 1, 3 and 8 on the male tool were reading higher during cool-down than all other thermocouples as they were located furthest away from the platens, on the highest point of the tool. Conversely, thermocouples 1, 3 and 8 on the female tool were positioned closest to the press platens on the lowest point of the tool and were reading lowest during cool-down. Where the male tool is thickest and the female tool is thinnest, such as along the corner region, the greatest difference in temperature will occur when the tools are subject to cooling by the platens. If a part were placed in the tool during cool-down, this would lead to significant temperature differences on either side of the part and temperature gradients through the thickness of the part. As the source of cooling for the tool halves is solely by the platen surfaces, temperature gradients at different locations are inevitable. A non-isothermal forming process where the tool temperature is changing with time has not been chosen for this project. Instead, an isothermal forming process with a fixed tool temperature is applied, as implemented by McCool [15] and Han [29, 30]. A non-isothermal forming process would require additional cooling.
channels within the tool design that are not incorporated in this project. Details on the manufacturing process are provided in section 4.3.

4.2.5 Thermal profiling of the tool halves in Raven

A one dimensional thermal analysis was performed on different cross-sections of the male and female tool when closed together on a 2 mm thick AS4/PEEK laminate. The approximate vertical distance from the platen surface to the tool surface was measured at various locations on the cross-section (Figure 4.35), and input into Raven as a tool thickness. Three regions were studied: (1) a region where the female tool is thick and the male tool is thin, (2) a region where the male and female tool are of similar thickness, and (3) a region where the male tool is thick and the female tool is thin.

It should be noted that the analysis was performed during the initial conceptual design of the tool, and the actual tool design is somewhat different than what is shown in Figure 4.35. However, the overall dimensions of the tool halves at the regions studied are approximately the same, and are sufficient for the analysis performed. In addition, the male tool is shown as being on top with the female tool on the bottom, however as the same heating boundary conditions are applied at the point of contact with the platens, this does not affect the simulation results. Different thicknesses of steel corresponding to different locations on the tool cross section from Figure 4.35 were compared when subject to a heat-up and cool-down. The H13 tool steel material was not present in the Raven software and the analysis was therefore performed on 1020 steel. The steel tool halves and composite stack were subject to a heating rate of 20°C/min, a 20 min hold at 380°C, and cooling rates of 1, 5, and 20°C/min.
When subject to a cooling rate of 20°C/min, the temperature difference between the male tool surface (dotted green line) and the female tool surface (solid turquoise line) is almost 50°C at the corner, region 3 (Figure 4.36). At a cooling rate of 5°C/min, the difference is approximately 15°C (Figure 4.37), and at a cooling rate of 1°C/min, the difference is negligible (Figure 4.38).
Figure 4.36: Thermal simulation of tools and part subject to cooling at 20°C/min at region 3.

Figure 4.37: Thermal simulation of tools and part subject to cooling at 5°C/min at region 3.
Figure 4.38: Thermal simulation of tools and part subject to cooling at 1°C/min at region 3.

During the experiment, the actual tool surfaces were cooled at 9°C/min resulting in a temperature difference of approximately 45°C between the peak of the male tool and the valley of the female tool. This result falls in between the simulated results at 5 and 20°C/min as expected, and further reinforce that significant temperature gradients can be obtained when the tool halves are being cooled by the platens. The remainder of the simulation runs for the other two regions of the tool are included in Appendix D.

4.3 Manufacturing L-shape parts

The L-shape flanges in this study were made by pre-heating the flat panels to the processing temperature of 390°C inside a box furnace located next to the hot press. The pre-heat times to ensure that the parts were at the processing temperature were determined by recording temperature data from a thermocouple embedded at mid-thickness – the same thermocouples that were embedded in select panels from section 4.1.4. Once the part was at temperature, it was transported as rapidly as possible to the forming tool, followed by rapid closing of the press platens to ensure proper consolidation. Throughout the manufacturing process, the matched-die tool was held constant at three test temperatures: 105°C, 215°C, and 290°C. At each temperature, three repeats
for each of the quasi-isotropic and ROS parts were formed. The manufacturing process was briefly conducted as follows:

a) Transport of the charge from the furnace to the thermoforming tool held open in the position indicated in Figure 4.29;
b) Closing the tool at a speed of 5 inches per minute and applying the consolidation pressure of 40 bars (12 tons);
c) Allowing the part to cool-down within the tool under consolidation pressure for 5 minutes;
d) Opening the tool, removing the L-shape flange, and allowing it to cool to ambient temperature by natural convection.

The following sections outline the step-by-step procedure for manufacturing L-Shape flanges from pre-consolidated panels of AS4/PEEK from the very beginning to the end of the process.

4.3.1 Step 1 – Clamping the flat panel to the aluminum fixture
In order to facilitate placement and centering of the AS4/PEEK charges inside the matched-die tool cavity, the panels were heated on an aluminum fixture that facilitated transport to the matched-die tooling configuration in the hot press (Figure 4.39 and Figure 4.40). During heating, the panels were pre-formed to a 90° angle by applying hand pressure against one of the flanges until it conformed to the shape of the aluminum fixture. The aluminum fixture had a thickness of 1.60 mm. The hand forming took place once the charge had reached the target temperature of 390°C inside the box furnace. With the charge now being angled as opposed to flat, it could easily be centred on the male tool half in a consistent manner prior to closure of the press and final consolidation. The initial alignment of the composite flat panel while clamped on the aluminum fixture was critical to ensure that the desired orientation was maintained in the final part.
Figure 4.39: AS4/PEEK panel clamped on the aluminum fixture prior to heating.
The first step involved applying three coats of Frekote® 700-NC release agent to the entire surface of the aluminum fixture in contact with the AS4/PEEK material throughout the heating and pre-forming stages.

The flat panels of AS4/PEEK were clamped during heating as shown in Figure 4.39 and Figure 4.40. All of the panels were oriented such that the reference corner from section 4.1.3 was clamped against the left-hand side of the aluminum fixture (Figure 4.39). As a result, one half of the panel is in contact with the aluminum, while the other half is extending freely past the aluminum surface. For future reference in this thesis, flange #1 of the composite part corresponds to the half that is initially clamped against the aluminum surface, as shown in Figure 4.39. Flange #2 corresponds to the half that is extending freely during initial clamping.

The left side of the panel (flange #1) was clamped into place with two binder clamps. Distances from the edges of the part to the edges of the fixture were carefully measured to ensure that it was...
properly centred and squared prior to heating. The aluminum fixture and panel were loaded inside the Thermo-Scientific Lindberg/Blue M™ Box Furnace as shown in the sketch of Figure 4.41.

![Figure 4.41: Sketch of aluminum fixture and AS4/PEEK panel loaded inside the box furnace.](image)

**4.3.2 Step 2 – Pre-heating the flat panel to the processing temperature of 390°C**

In order to determine the required heating time, a flat panel from section 4.1.4 with a thermocouple embedded at mid-thickness was placed inside the furnace pre-heated to 390°C. The internal temperature of the part as read by the thermocouple was monitored with a data acquisition unit. After 11 minutes, the internal temperature of the part had reached the target of 390°C. A total time of 15 minutes was used as the required soak time inside the furnace to safely ensure that the entire laminate would reach the desired processing temperature.

A simple thermal analysis was also performed in RAVEN software as a source for comparison of the pre-heating time in the box furnace. The simulation performed involved a 2.20 mm thick AS4/PEEK panel resting on a 1.60 mm-thick aluminum sheet. The composite and the aluminum could not be placed in air that was initially set to 390°C within the simulation, and therefore a maximum ramp rate of 100°C/min of the surrounding air up to 390°C was applied. The heat
The transfer coefficient of the air inside the furnace was set to 10 W/m²K [39]. The thermal analysis is shown in Figure 4.42. The blue line represents the temperature of the air inside the furnace, and the green and red lines represent the temperature of the panel and aluminum fixture.

The analysis clearly shows that the required heating time for the part to reach 390°C is slightly more than the time measured experimentally (for a conservative heat transfer coefficient of air value), but serves as a good confirmation that expected time is on the order of 15 minutes. It should be noted that in the actual heating setup, only half of the panel is in contact with the aluminum therefore slight differences in heating times from one region to another can be expected.

4.3.3 Step 3 – Pre-forming the flat panel to the shape of the aluminum fixture and final heating

Once the panel had reached the target temperature, the extended right-hand flange (flange #2) was carefully pressed down onto the aluminum surface by applying gentle hand pressure. The flange was pushed down as slowly and steadily as possible to ensure that the part did not shift from the clamped edges. Once the part was fully conforming to the angled aluminum, two additional binder
clamps were placed on flange #2 in order to hold it in place (Figure 4.43). An image of an ROS panel pre-formed on the aluminum fixture is shown in Figure 4.44, where deconsolidation of the strands is clearly observed by the roughened surface above the melting temperature of PEEK. This entire step took place inside the furnace over a period of ~20 seconds. Upon closing the furnace door, a heating of ~3 minutes was required to raise the temperature of the furnace back up to 390°C, at which point all four binder clamps were removed from the part (Figure 4.45). A final heating time of 15 minutes was applied to ensure that both the furnace and the part were at 390°C prior to transport to the hot press.

Figure 4.43: Pre-formed quasi-isotropic AS4/PEEK panel (clamps in place).
Figure 4.44: Pre-formed ROS AS4/PEEK panel (clamps in place).

Figure 4.45: Pre-formed quasi-isotropic AS4/PEEK panel ready for loading in the press (clamps removed).
4.3.4 Step 4 – Transport and placement of the charge inside the tool cavity
Following the soak time of 15 minutes, the heated charge was ready to be transported and placed onto the male tool half. At this point, the hot press platens and tooling were set to the correct position and temperature for loading of the charge. A complete description of the hot press parameters is outlined in section 4.2.3.

The AS4/PEEK charge was carefully removed from the aluminum fixture, carried by hand, and gently loaded onto the male tool surface from the front within the gap that separated both tool halves in the position described in section 4.2.3 (Figure 4.46). The pre-formed charge was easily aligned with the contour of the male tool. This was accomplished by centering the ridge on the charge with the ridge on the male tool. The total time elapsed from transporting the charge from the box furnace to the hot press was 3 seconds.

![Figure 4.46: Loading the pre-formed charge onto the male tool surface.](image)

4.3.5 Step 5 – Closure of the press and application of consolidation pressure
Once the charge was in place in the tool, the hot press safety interlock door was rapidly shut and the lower platen was closed at the maximum speed of 5 inches (12.7 cm) per minute. Closure of the press continued until the set consolidation pressure of 40 bars was applied on the charge (Figure
4.47 and Figure 4.48). A Solidworks® drawing is included to complement the dark photograph taken through the safety gate opening.

Figure 4.47: Drawing of tool halves closed and consolidation pressure applied on the part.

Figure 4.48: Tool halves closed and consolidation pressure applied on the part.
As the press is load-limit controlled, the positioning of the platens during closure on the part will automatically be adjusted in order to maintain the target consolidation load. The applied consolidation pressure on the part was determined by dividing the applied load of the press by the projected area of the angled charge, as viewed from above (Figure 4.49). An applied load of 12.4 tons corresponding to a consolidation press of 40 bars was set in the hot press program.

![Diagram](image)

Figure 4.49: Projected area of the L-shape part considered for calculation of the consolidation pressure within the tool (applied load divided by the projected area).

The amount of time elapsed from closing the hot press safety interlock door to reaching the target consolidation pressure was 4 seconds.

4.3.6 **Step 6 – Maintain consolidation pressure throughout a dwell time of 5 minutes**

Once the target consolidation pressure of 40 bars was reached, the timer on a stopwatch was set to 5 minutes. The same dwell time was applied to all of the manufactured quasi-isotropic and ROS parts in this project.
4.3.7 Step 7 – Opening the press, removal of the part from the tool cavity, and cool-down to room temperature

Following 5 minutes of consolidation, the pressure was removed and the tool halves were raised apart. Upon separating the tool halves, the part was resting on the male tool surface at the end of the cycle. The part was carefully lifted from the male tool surface and placed on the top surface of the workbench and left to cool down to room temperature.
4.4 Quality assessment of the L-Shape parts (visual)

The thickness profile of the manufactured L-Shape parts was measured along the flange and corner sections with digital calipers. To facilitate the caliper measurements, the parts sectioned for the mechanical testing conducted in section 4.9 were analyzed.

Samples taken from the corner and flange sections from each of the quasi-isotropic and ROS parts at each consolidation temperature were prepared for cross-section optical microscopy (Figure 4.50). The micrographs were analyzed for the presence of porosity, and changes in fibre orientation across the flange and corner sections. Microstructural features that are unique to the ROS parts are also identified.

Figure 4.50: Corner and flange sections prepared for optical microscopy from parts consolidated at 105°C (top), 215°C (middle), and 290°C (bottom).
4.5 Measuring spring-in

The L-shape flanges manufactured in the hot press were scanned in a Nikon CMM in order to produce a point cloud that would allow for the determination of the spring-in angle. The inside surface was scanned as shown in Figure 4.51 and the corner angles of each part were measured at three locations (top, middle, bottom) from the point cloud data generated in the Nikon Focus software. The L-shape scanning configuration on the CMM table is shown in Figure 4.52. The reference corner indicated is the same one that was marked on the panels prior to forming in section 4.1.3, and the cross-section lines for angle measurements were generated in the Focus software. An example image scan of an L-shape pressed at 215ºC is shown in Figure 4.53. The corner angles were measured by selecting two points on each flange within one inch from the corner region (Figure 4.54). The CMM scans for all manufactured parts are located in Appendix E. The angles of the parts were compared with the scanned angle measurements of the forming tool (90°) (Figure 4.55) and the resulting spring-in was computed. A schematic representation of the spring-in angle is shown in Figure 4.56.

Figure 4.51: Scanning the inside surface of the formed L-shapes with the CMM laser head.
Figure 4.52: CMM L-shape scanning configuration and location of cross-section lines for angle measurements.

Figure 4.53: Example CMM scan of the inside surface and location of angle measurements.
Figure 4.54: CMM scan angle measurements from two points selected on each flange within one inch from the corner region.

Figure 4.55: Scanning the thermoforming tool surface (both the male and female tool halves were scanned).
4.6 Measuring warpage along the L-shape flanges

Warpage of the L-shape flanges was measured along the mid-section of each part as a function of the distance from the corner, moving towards the flange tip. The warpage was quantified as the deviation height between the flange and a straight reference line extending from the corner to the flange tip. The first type of warpage observed is represented in the sketch of Figure 4.57, illustrating a part with flanges bowing outwards from the corner. The second type of warpage is represented in Figure 4.58, where the flanges are bowing inwards toward the corner. The deviations, $\delta$, were measured from the corner to the flange tip.
Figure 4.57: Schematic of the measurement of flange warpage $\delta$ from the corner to the flange tip. The schematic represents a part with the flanges bowing outwards.

Figure 4.58: Schematic of the measurement of flange warpage $\delta$ from the corner to the flange tip. The schematic represents a part with the flanges bowing inwards.
The deviation measurements were taken along the middle cross-section of the CMM surface scans that were generated in section 4.5 for the measurement of spring-in in the Nikon Focus software. The measurements were taken at 10 mm intervals from the corner at \( x = 0 \) mm to near the end of the flange at \( x = 80 \) mm. The middle cross-section and the measurement reference lines drawn at 10 mm intervals from the corner on the scanned surface of an L-shape are indicated in Figure 4.59 and Figure 4.60.

Figure 4.59: Scanned surface of an L-Shape part in the CMM Focus software. Flange warpage measurements were taken along the middle section, at 10 mm intervals from the corner to the tip indicated by the red parallel lines.
Within the Focus software, the flange was oriented such that the origin \((x = 0, y = 0, \text{ and } z = 0)\) was located at the first measurement reference line near the corner. Measurements of warpage deviation were measured in the \(z\)-direction, perpendicular to the surface of the flange at each 10 mm marker. The flange was also aligned to ensure that the \(z\)-coordinate values at both the origin and the marker at \(x = 80\) mm were set to zero, in order to produce the warpage profiles illustrated in Figure 4.57 and Figure 4.58. The measurements were not taken beyond \(x = 80\) mm as the scanned profiles appeared rough and uneven near the edge at the flange tip. A total of nine deviation measurements were taken from the origin at the corner towards the flange tip at \(x = 80\) mm for all flanges of the formed quasi-isotropic and ROS parts. The results of the flange warpage profiles as sketched in Figure 4.57 and Figure 4.58 are presented in section 5.8.
4.7 Thermo-mechanical analysis of the L-Shape parts

Samples measuring 1 cm × 1 cm were cut from the quasi-isotropic and ROS L-shape parts and thermo-mechanical analysis (TMA) was performed in order to obtain the in-plane and through-thickness thermal strain measurements (Figure 4.61). The samples were heated from room temperature to 290°C at 5°C/min followed by a cool-down to room temperature (5°C/min). The samples were not heated any higher in order to avoid deconsolidation of the plies throughout the test. Each test was performed multiple times, on different quasi-isotropic and ROS samples to ensure consistency in the results. The results of the thermo-mechanical analysis are incorporated in a simple formulation that predicts the spring-in angle.

Figure 4.61: Thermal-mechanical analysis of samples in the through-thickness direction (left) and the in-plane direction (right).

4.8 Measurement of spring-in angle as a function of temperature

Measurements of change in part corner angle during heating and cooling were performed on a quasi-isotropic and an ROS L-shape part clamped in place inside a box furnace. The part was secured such that one flange would freely deflect upwards due to a change in the corner angle – the flange deflections were measured with a digital dial gauge. A sketch and image of the test configuration is shown in Figure 4.62, Figure 4.63, and Figure 4.64. The dial gauge was safely
placed outside the furnace, and an invar extension rod threaded onto the dial gauge tip allowed for the measurement of flange displacement at elevated temperatures. Details on the invar rod extension are located in Appendix F. Measurements were taken at a specified distance of 76.2 mm (3.0 in.) from the corner, as shown in Figure 4.62 and Figure 4.65. The dial gauge was positioned at this location on the flange for easy positioning of the part within the box furnace. The measurements were taken at 10°C intervals during heat-up from 25°C to 305°C, and during cool-down back to ambient. The temperature throughout the experiment was monitored by placing three thermocouples at the corner section of the part on the inside surface, as shown in Figure 4.65. The flange displacements were converted to corner angle measurements using the arc-length and angle relationship.

Figure 4.62: Schematic representation of the experimental setup for measurement of change in corner angle as a function of temperature.
Figure 4.63: Side view of clamped part for measurement of change in corner angle as a function of temperature.

Figure 4.64: Digital dial gauge and invar extension rod setup for measuring changes in corner angle of a part inside the box furnace.
4.9 Mechanical strength testing of L-shapes

Three specimens from quasi-isotropic and ROS parts each formed at 105°C, 215°C, 290°C were cut to the size specifications defined in ASTM D6415 [40] for determining the curved beam strength of angled composite laminates (Figure 4.66). The parts were cut to the correct width using a high-speed diamond saw. All other formed part dimensions satisfied the test requirements.

The samples were loaded under four-point bending in an Instron® Dual-Column System. The ASTM test fixture configuration is shown in Figure 4.67 and Figure 4.68. During initial testing of the samples in the fixture, a considerable amount of deflection was observed prior to failure as the samples were relatively thin and compliant (Figure 4.69). A few of the samples did not break and the test had to be stopped prior to the upper and lower fulcrums of the fixture coming into contact. A modification of the test fixture was required in order to test the samples to failure. The solution
involved affixing 12.7 mm (0.5 in) thick half-shells on the bottom fulcrums in order to provide additional clearance during testing (raising the sample by 0.5 inches from the bottom and allowing for more deflection during the test as shown in Figure 4.70). All samples were tested in this modified fixture, and the alteration from the original ASTM test standard should be noted. The displacement rate of the Instron machine was set to 1.0 mm/min. The results of the tests are presented in section 7.11. It should be noted that the ASTM D6415 test is designed for continuous fibre composite parts, although the testing configuration is being applied to discontinuous ROS composites as well.

Figure 4.66: L-Shape specimen cut to dimensions for the ASTM D6415 test.
Figure 4.67: ASTM D6415 test fixture configuration (retrieved from ASTM standard D6415 [40]).

Figure 4.68: Specimen loaded inside ASTM D6415 test fixture.
Figure 4.69: Significant deflection of the specimens observed during the four-point bending tests.

Figure 4.70: Half-shells affixed on bottom fulcrums for providing additional clearance.
Chapter 5: Results

This chapter provides the results obtained from the experiments detailed in Chapter 4. Results on the warpage of the ROS panels are presented followed by the qualitative and quantitative analyses that were performed on the manufactured quasi-isotropic and ROS L-shape parts.

5.1 Warpage measurements of ROS panels

An example of the warpage deviations generated about a plane of best fit in the point cloud scan of an ROS panel is shown in Figure 5.1. The magnitude and direction of the part deviation from the plane of best fit are represented by magnified coloured lines. The warpage measurements for the ROS panels are summarized in Table 5.1 and include the maximum deviations from the plane of best fit in the positive and negative directions. The warpage deviation heights range from 1.40 mm to 2.57 mm in the positive direction, and from 1.75 mm to 4.34 mm in the negative direction. The total deviation column is simply the sum of both the absolute negative and positive warpage values.

The orientation and direction of the warpage deviations on the ROS panels relative to the reference corner marked on the panel upon removal from the picture frame tool in section 4.1.3 varied randomly. The orientation of the warpage is summarized in the sketches of Figure 5.2. The reference corner is indicated by the small white rectangle in the top left corner. The sketches illustrate the regions of positive and negative warpage, and within each region, the magnitude of the warpage increases towards the outside edges of the panel, as shown in Figure 5.1.
Figure 5.1: Warpage deviations about a plane of best fit (purple) generated through the scan data.

Table 5.1: Maximum positive and negative warpage deviation data.

<table>
<thead>
<tr>
<th>Flat Panel ID</th>
<th>Negative Warpage Deviation, Absolute Values (mm)</th>
<th>Positive Warpage Deviation (mm)</th>
<th>Total Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROS PANEL 1</td>
<td>1.859</td>
<td>1.404</td>
<td>3.263</td>
</tr>
<tr>
<td>ROS PANEL 2</td>
<td>2.176</td>
<td>2.114</td>
<td>4.290</td>
</tr>
<tr>
<td>ROS PANEL 3</td>
<td>1.750</td>
<td>1.844</td>
<td>3.594</td>
</tr>
<tr>
<td>ROS PANEL 4</td>
<td>1.813</td>
<td>1.645</td>
<td>3.458</td>
</tr>
<tr>
<td>ROS PANEL 5</td>
<td>4.342</td>
<td>2.566</td>
<td>6.908</td>
</tr>
<tr>
<td>ROS PANEL 6</td>
<td>2.775</td>
<td>2.542</td>
<td>5.317</td>
</tr>
<tr>
<td>ROS PANEL 7</td>
<td>1.922</td>
<td>1.777</td>
<td>3.699</td>
</tr>
<tr>
<td>ROS PANEL 8</td>
<td>2.501</td>
<td>2.213</td>
<td>4.714</td>
</tr>
</tbody>
</table>

All but one out of nine ROS panels could be measured for warpage as the one panel had already been previously formed into an L-shape in the press prior to conducting this analysis.
5.2 L-Shape manufacturing temperature profile

An example of a measured temperature profile for pressing L-shapes at 215°C is shown in Figure 5.3. The critical manufacturing events and temperatures related to the processing of PEEK thermoplastic composites are also labelled in the figure. The temperature profiles for consolidating at 105°C and 290°C are included in Appendix G of this thesis. The measured cooling rates at the three consolidation temperatures are: 2200°C/min at 105°C, 1400°C/min at 215°C, and 740°C/min at 290°C.
5.3 Initial observations of manufactured L-shapes

The geometry and dimensions of the formed L-shapes is shown in Figure 5.4. It should be noted that for all the quasi-isotropic parts, the 0° fibre direction was aligned parallel to the corner. The ROS parts were formed to the same geometry. Corner thinning and thickening was not apparent in any of the samples. Images of thermoformed quasi-isotropic and ROS L-shapes are shown in Figure 5.5, Figure 5.6, and Figure 5.7.

Overall, all of the quasi-isotropic samples had smooth surfaces, although some differences in the glossiness of the surface can be seen between parts pressed at 105°C and 290°C. The parts pressed at higher temperature have a shinier surface than the parts pressed at lower temperature. No significant differences were observed between parts pressed at 215°C and 290°C. For the ROS samples pressed at 290°C and 215°C, the surfaces were also very smooth with a glossy-like finish. A comparison of the surface glossiness between a part pressed at 290°C and 105°C is presented in Figure 5.8. The same lighting conditions were used in the image comparison.
Figure 5.4: L-shape geometry and 0º fibre direction for the quasi-isotropic [0/+45/-45/90]_2S layup.

Figure 5.5: Thermoformed L-shape parts manufactured from A) quasi-isotropic lay-up and B) randomly-oriented strands.
Figure 5.6: Thermoformed L-shape parts.
Figure 5.7: Thermoformed ROS L-shape part inside (left) and outside (right) view of the corner.

Figure 5.8: Surface glossiness comparison of a part pressed at 290°C (left) and 105°C (right).
5.4 Optical microscopy

Optical microscopy images of cross-section cuts for a quasi-isotropic and ROS L-Shape consolidated at 290°C are shown in Figure 5.9 and Figure 5.10. For each sample, images of the corner and flange sections are included. For the quasi-isotropic parts, no presence of porosity is observed in the flanges and corner sections. The plies all seem to remain straight and parallel in the flange section, and uniformly curved along the corner section. Overall, the fibre orientations are also well maintained. The black spots that appear on the images have been confirmed to be caused by surface contamination, and not by the presence of porosity.

The ROS micrographs indicate random and non-uniform fibre orientations within the flange and corner sections. In the ROS micrographs, localized regions that are rich in resin can also be observed. Due to the presence of discontinuous strands, small crevices and imperfections at the top and bottom surfaces of the sample can be seen.

The remaining micrographs for samples pressed at 105°C and 215°C can be found in Appendix H.
Figure 5.9: Corner (top), middle flange, and flange tip (bottom) section micrographs of a quasi-isotropic sample consolidated at 290°C, taken at 200X magnification.
5.5 Thickness measurements

Digital caliper measurements taken directly at and near the corner section of the quasi-isotropic and ROS parts revealed a thickness in the range of 2.20 ± 0.05 mm. No corner thinning or thickening was observed in any of the samples. The thickness measurements of the quasi-isotropic samples that were prepared for mechanical strength testing in section 4.9 are included in Table 5.2. The measurements were taken on three samples consolidated at 105°C, 215°C, and 290°C.
The thickness measurements of the samples that were cut from parts consolidated at 105°C were greater by approximately 0.04 – 0.05 mm. These measurements should be taken into consideration for the results of the mechanical strength tests in section 5.11.

### 5.6 Visual observation of spring-in

Spring-in was observed in all samples. Overall, the parts had greater spring-in with increasing tool consolidation temperature, with the parts at 290°C having the largest amount of spring-in. In addition, the ROS parts had greater spring-in than the quasi-isotropic parts at all tool temperatures. Visual observations of spring-in in the formed parts are shown in Figure 5.11 to Figure 5.13.
Figure 5.11: Spring-in at first glance of quasi-isotropic L-shapes consolidated at 105°C, 215°C, and 290°C.

Figure 5.12: Spring-in of quasi-isotropic and ROS L-shapes at 105°C, 215°C, and 290°C.
Figure 5.13: Spring-in at first glance, from greatest to least amount of spring-in: ROS at 290°C, QI at 290°C, ROS at 215 °C, QI at 215 °C, ROS at 105 °C, and QI at 105 °C.

5.7 Spring-in measurements

The results of the measured spring-in data for both quasi-isotropic and ROS L-shape parts thermoformed in the hot press are presented in Table 5.3 and Figure 5.14.

Table 5.3: Measured corner angles and spring-in for all manufactured quasi-isotropic and ROS parts.

<table>
<thead>
<tr>
<th>Tool Surface Temperature (°C)</th>
<th>Measured Corner Angle (°)</th>
<th>SPRING- IN RELATIVE TO 90° TOOL (°)</th>
<th>Average Spring-in (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[0/+45/-45/90]_25 ROS</td>
<td>[0/+45/-45/90]_25 ROS</td>
<td>[0/+45/-45/90]_25 ROS</td>
</tr>
<tr>
<td>105</td>
<td>89.56 88.68</td>
<td>0.44 1.32</td>
<td>0.58 1.23</td>
</tr>
<tr>
<td></td>
<td>89.39 88.66</td>
<td>0.61 1.34</td>
<td>0.61 1.34</td>
</tr>
<tr>
<td></td>
<td>89.30 88.97</td>
<td>0.70 1.03</td>
<td>0.70 1.03</td>
</tr>
<tr>
<td>215</td>
<td>87.79 87.76</td>
<td>2.21 2.24</td>
<td>2.21 2.43</td>
</tr>
<tr>
<td></td>
<td>87.79 86.95</td>
<td>2.21 3.05</td>
<td>2.21 3.05</td>
</tr>
<tr>
<td></td>
<td>87.99 87.31</td>
<td>2.01 2.69</td>
<td>2.01 2.69</td>
</tr>
<tr>
<td>290</td>
<td>86.71 86.71</td>
<td>3.29 3.29</td>
<td>3.29 3.29</td>
</tr>
<tr>
<td></td>
<td>86.64 86.80</td>
<td>3.36 3.20</td>
<td>3.36 3.20</td>
</tr>
<tr>
<td></td>
<td>86.82 86.30</td>
<td>3.18 3.70</td>
<td>3.18 3.70</td>
</tr>
</tbody>
</table>
Figure 5.14: Spring-in data of manufactured L-shapes measured in the CMM.
5.8 L-shape flange warpage measurements

Examples of measured flange warpage profiles for quasi-isotropic and ROS samples formed at 105°C, 215°C, and 290°C measured in the Nikon Focus software are shown in Figure 5.16 to 5.21. The warpage profiles for the remaining samples are located in Appendix I. The warpage profiles are shown for both flanges of each part, according to the scanning configuration of Figure 4.52. For almost all quasi-isotropic parts, the flanges bowed outwards, as illustrated in the sketch of Figure 4.57. Such profiles are represented by positive deviation heights on the vertical axis. For the ROS, the majority of the parts had either flanges bowing inwards or a combination of inwards and outwards bowing. Inwards bowing of the flanges as shown in Figure 4.58 is represented by negative deviation heights. The maximum values from the flange warpage deviation profiles for quasi-isotropic parts are presented in Figure 5.22, and the mean and range of these maximum values is shown in Figure 5.23. The maximum values from the flange warpage deviation profiles in ROS parts are shown in Figure 5.24. There is a clear trend of decreasing flange warpage with
increasing tool consolidation temperature for the quasi-isotropic parts. In the ROS parts, the trend is not as clear as the warpage largely consists of both negative and positive deviations (flanges bowing inwards and outwards), resulting in a larger range of values at each forming temperature.

Figure 5.16: Measured flange warpage profiles for a quasi-isotropic L-shape consolidated at 105°C.
Figure 5.17: Measured flange warpage profiles for a quasi-isotropic L-shape consolidated at 215°C.
Figure 5.18: Measured flange warpage profiles for a quasi-isotropic L-shape consolidated at 290°C.
Figure 5.19: Measured flange warpage profiles for an ROS L-shape consolidated at 105°C.
Figure 5.20: Measured flange warpage profiles for an ROS L-shape consolidated at 215°C.
Figure 5.21: Measured flange warpage profiles for an ROS L-shape consolidated at 290°C.
Figure 5.22: Maximum flange warpage deviations for all quasi-isotropic parts at 105°C, 215°C, and 290°C.

Figure 5.23: Average values of maximum flange warpage deviations for all quasi-isotropic parts at 105°C, 215°C, and 290°C.
Figure 5.24: Maximum flange warpage deviations for all ROS parts consolidated at 105°C, 215°C, and 290°C.
5.9 Spring-in predictions

Equation 2.1 proposed by Nelson and Cairns [19] in Chapter 2 will be implemented in order to predict the spring-in based on the anisotropy of the material’s thermal contraction during processing. As a first approximation for now, we will only consider the first term of Equation 2.1 related to the anisotropy in the thermal contraction of the material. Equation 2.1 can be simplified as follows:

\[
\Delta \theta = \theta \left( \frac{\varepsilon_l - \varepsilon_t}{1 + \varepsilon_t} \right) \tag{5.1}
\]

Where \( \varepsilon_l \) and \( \varepsilon_t \) are the in-plane and through-thickness thermal strains of the part respectively. The thermal strains were measured during heat-up and cool-down from 105°C, 215°C, and 290°C in the through-thickness and in-plane directions. TMA measurements of change in sample dimension in the in-plane and through-thickness directions for a quasi-isotropic sample are shown in Figure 5.25. The measured values were divided by the initial sample dimensions at the start of the test to obtain the thermal strains. The strains from the cooling portion of the curves in the TMA experiments have been chosen. The thermal strains from 290°C to 25°C at 10°C increments have been plotted in Figure 5.26 and Figure 5.27. The data was plotted this way in order to generate an approximate curve for the coefficients of thermal expansion that are also included in the figures. As the complete thermal strain curve from the TMA is not smooth over very small temperature increments, calculating the coefficients of thermal expansion as the derivative of this curve is a bit of a challenge without further manipulation of the data. In Figure 5.26, \( CTE_l \) increases from approximately \( 50 \times 10^{-6}/^\circ C \) below \( T_g \) to a range of \( 110 - 220 \times 10^{-6}/^\circ C \) from \( T_g \) to 290°C. In Figure 5.27, \( CTE_l \) increases from approximately \( 2 - 10 \times 10^{-6}/^\circ C \) from 25°C to 290°C with no visible elbow at \( T_g \). The TMA data for an ROS sample is included in Appendix J.

The complete thermal strain results at 105, 215, and 290°C are presented in Table 5.4. The measured thermal strains have been incorporated in Equation 5.1 for predicting the spring-in values. The strains are reported as negative due to thermal contraction when the part is cooling from the tool consolidation temperature down to room temperature. A comparison of the complete
experimental and predicted spring-in results obtained from the Nelson-Cairns prediction is shown in Figure 5.28.

Figure 5.25: TMA measurements of change in dimension in the through-thickness (top) and in-plane directions (bottom) of a quasi-isotropic sample.
Figure 5.26: Through-thickness strains and coefficient of thermal expansion as a function of temperature for a quasi-isotropic sample.
Figure 5.27: In-plane strains and coefficient of thermal expansion as a function of temperature for a quasi-isotropic sample.

Table 5.4: Through-thickness and in-plane strains for a quasi-isotropic and ROS sample.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>[0/+45/-45/90]_{2s}</th>
<th>ROS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Through-thickness strain</td>
<td>In-plane strain</td>
</tr>
<tr>
<td>105</td>
<td>$-3.71 \times 10^{-3}$</td>
<td>$-3.35 \times 10^{-4}$</td>
</tr>
<tr>
<td>215</td>
<td>$-1.60 \times 10^{-2}$</td>
<td>$-1.07 \times 10^{-3}$</td>
</tr>
<tr>
<td>290</td>
<td>$-3.04 \times 10^{-2}$</td>
<td>$-1.75 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Figure 5.28: Comparison of the measured spring-in data from figure 5.15 with the predictions from the Nelson-Cairns expression at 105°C, 215°C, 290°C.

5.10 Measurement of spring-in angle as a function of temperature

The dial gauge measurements of flange displacement during heating and cooling of a quasi-isotropic L-Shape taken at 76.2 mm (3.0 in) from the corner are shown in Figure 5.29. It can be seen that the heating and cooling curves follow the same path, and that the slope of the curve increases at approximately the glass-transition temperature of PEEK ($T_g = 143°C$). The associated change in corner angle $\theta$ was computed as follows:

$$\theta = \frac{S}{R}$$  \hspace{1cm} (5.2)

Where $S$ is the measured flange displacement, and $R$ is the distance of the dial gauge tip from the corner angle. For measurements taken at a distance of 76.2 mm from the corner, the corresponding angles as a function of temperature are shown in Figure 5.30, and the values obtained at the three
tool consolidation temperatures are indicated. The displacement values during the heating portion of the test were used for the angle calculations (both heating and cooling results were nearly identical). The values indicated represent the change in corner angle that occurs due to thermoelastic effects in the part. During thermoforming of the L-shapes, as the part is initially 90° at the forming temperature, the thermo-elastic effects cause the part to spring-in upon removal from the tool and during cooling from the forming temperature to room temperature. The changes in angle that are measured in this experiment are studied in order to get a better sense of the thermo-elastic contributions during processing of parts.

The thermal expansion of the invar rod was considered during the flange deflection measurements. The 30 cm long invar rod, with an approximate coefficient of thermal expansion of $1.2 \times 10^{-6}/\degree C$ [41] would lengthen by 0.029 mm at 105°C, 0.068 mm at 215°C, and 0.095 mm at 290°C. The measured flange deflections at 105°C, 215°C, and 290°C were 0.576 mm, 2.54 mm, and 4.64 mm respectively. The expansion of the invar rod would introduce a displacement error of 5% at 105°C, 3% at 215°C, and 2% at 290°C. The errors introduced by the invar rod are small enough to be ignored in this study.

The flange displacements and changes in corner angle for an ROS part have also been obtained in the same manner. The heating and cooling displacement curves are not quite as identical as in the quasi-isotropic part measurements, and the displacement values during the heating portion of the curve were once again selected for the angle calculations. The flange displacements and the associated changes in corner angle for an ROS part can be found in Appendix K.

The results of the change in corner angle from the dial gauge experiments are compared with the previous results in Figure 5.31. The changes in corner angle at 105°C, 215°C, and 290°C show a much better correlation with the measured part spring-in angles. Overall, the results are very close to the quasi-isotropic data at all temperatures. However, they are significantly less than the ROS spring-in measurements at 105°C and 215°C. The results also show that the temperature-induced change in corner angle of the ROS parts is slightly greater than in the quasi-isotropic parts, but not to the same extent that was measured in the formed parts at room temperature.
As the dial gauge measurements were taken at 3 inches from the corner, spring-in measurements taken with the coordinate measuring machine at 3 inches from the corner for all quasi-isotropic and ROS L-shapes are also included in Figure 5.31. The spring-in measurements taken at 3 inches from the corner lie slightly below the previous corner measurements at 215°C and 290°C due to the small presence of warpage on the flanges. At 105°C, the spring-in results taken at 3 inches from the corner are negative (corresponding to an angle greater than 90°) also due to the warpage present on the flanges.

![Measurement of Flange Displacement During Heating and Cooling of a Quasi-isotropic L-Shape](image)

Figure 5.29: Measurement of flange displacement during heating and cooling of a quasi-isotropic L-shape (dial gauge measurements taken at 76.2 mm from corner).
Figure 5.30: Change in corner angle during heating of a quasi-isotropic L-shape, measured at 76.2 mm from corner.
5.11 Mechanical strength testing of L-shapes

The load-displacement curves for the four-point bending of all quasi-isotropic samples are shown in Figure 5.32. The red, orange, and yellow curves represent the samples consolidated at 105°C, the green curves are the samples consolidated at 215°C, and the blue curves are for the samples consolidated at 290°C. The curves are also included in separate plots by consolidation temperature in Figure 5.33 to Figure 5.35. Overall, the samples consolidated at 105°C had much lower failure strengths than the remainder of the samples consolidated at 215°C and 290°C. The samples consolidated at 215°C and 290°C have similar failure strengths, with a couple of the samples consolidated at 290°C being slightly higher. A noticeable difference in the steepness of the load-displacement curves for the samples consolidated at 105°C is also observed. A close-up view of the curves at a displacement of 10 mm for all quasi-isotropic samples is presented in Figure 5.36.
The figure clearly shows that the curves from samples consolidated at 105°C lie higher than the curves at 215°C and 290°C. There is not a large difference in the steepness of the curves between samples consolidated at 215°C and 290°C. Apart from the green curve labelled as “215°C Sample 3”, the blue curves for the 290°C samples lie slightly below the green curves for samples consolidated at 215°C. On the right of Figure 5.32, it is also clear that the blue (290°C) curves lie slightly below the green (215°C) curves. In general, it appears as if the stiffness of the samples decreases with increasing tool consolidation temperature, with the greatest difference observed between the samples consolidated at 105°C and the other two higher consolidation temperatures. However, it is likely that the thickness results from Table 5.2 are the reason for the greater bending stiffness observed in the samples at 105°C in this particular case.

Figure 5.32: ASTM D6415 four-point bending load-displacement curves for quasi-isotropic samples consolidated at 105°C, 215°C, and 290°C.
Figure 5.33: ASTM D6415 load-displacement curves for quasi-isotropic samples consolidated at 105°C.
Figure 5.34: ASTM D6415 load-displacement curves for quasi-isotropic samples consolidated at 215°C.
Figure 5.35: ASTM D6415 load-displacement curves for quasi-isotropic samples consolidated at 290°C.
Figure 5.36: Close-up view of four-point bending load-displacement curves for quasi-isotropic samples consolidated at 105°C, 215°C, and 290°C.

The load-displacement curves for the ROS samples are shown in Figure 5.37. Unlike the results for the quasi-isotropic samples, the ROS curves cannot be as clearly distinguished into three different groups in terms of stiffness and strength. There is significantly more scatter in the displacement-to-failure for the ROS samples. With the exception of “ROS 105C Sample 3” and “ROS 215C Sample 1”, the curves for samples consolidated at 105°C and 215°C follow a very similar path. It can also be observed that the blue curves for samples consolidated at 290°C all follow a very similar path and are shifted below the 105°C and 215°C curves.
The mean and range of the failure loads for the quasi-isotropic and ROS samples is presented in Figure 5.38. For the quasi-isotropic samples, there is a clear trend of increasing failure load with increasing tool consolidation temperature. The mean failure load increases significantly from 900 N at 105°C consolidation to 2950 N at 215°C consolidation. The samples consolidated at 290°C had the highest mean failure load at 3380 N. The difference in failure load between the 215°C and 290°C samples is not as significant. For the ROS samples, there is no clear increase in failure load with increasing tool consolidation temperature. The ROS samples have a mean failure load of 640 N, 420 N, and 630 N at 105°C, 215°C, and 290°C respectively. At the consolidation temperature of 105°C, the mean failure load of the quasi-isotropic samples is much closer to the mean failure load of the ROS samples (900 N and 640 N respectively).
Figure 5.38: Average failure load values for quasi-isotropic and ROS samples consolidated at 105°C, 215°C, and 290°C.

The mean and range of the displacement-to-failure results for the samples are presented in Figure 5.39.
A summary of the resulting failure modes in the quasi-isotropic samples at each consolidation temperature are presented in Table 5.5 to Table 5.7, and failure of the ROS samples are presented in Table 5.8 to Table 5.10. In each table, images along with details on the location and type of failure are included. For the location of the failure within specific plies in the quasi-isotropic samples, the ply numbering convention shown in Figure 5.40 was applied. The plies are numbered from 1 to 16 starting from the inside corner. The samples were analyzed by optical microscopy in order to determine to exact location of the failure propagation. Example micrographs of the resulting failure in the quasi-isotropic and ROS samples are shown in Figure 5.41 to Figure 5.47. In all of the images, the flanges numbers (flange 1 and flange 2) are also labelled as per the L-shape manufacturing details described in section 4.3. The micrographs that follow the tables are meant to provide different examples of failure propagation observed at each temperature. For example, in the samples consolidated at 105°C, all three samples included multiple interlaminar cracks, and therefore one micrograph image is presented. For the samples consolidated at 215°C,
two of the samples have one interlaminar crack, and the other has multiple cracks, and therefore one image of each is included. Table 5.5 to Table 5.10 include the complete summary of the failure observations.

Figure 5.40: Ply numbering and orientations as seen in a quasi-isotropic sample with a [0/±45/-45/90]_{2S} lay-up.
Table 5.5: Failure of quasi-isotropic samples consolidated at 105°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure*</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Quasi 105°C - Sample 1 | ![Image 1](image1.png) | - Multiple interlaminar cracks located at the corner section  
- Interlaminar cracks located between plies (4 and 5), (5 and 6), (6 and 7), (12 and 13), and (13 and 14) | - Sample failed at 857.4 N |
| Quasi 105°C - Sample 2 | ![Image 2](image2.png) | - Multiple interlaminar cracks located at the corner section  
- Interlaminar cracks located between plies (4 and 5), (5 and 6), (6 and 7), (7 and 8), (9 and 10), and (10 and 11). | - Sample failed at 921.9 N |
| Quasi 105°C - Sample 3 | ![Image 3](image3.png) | - Multiple interlaminar cracks located at the corner section  
- Interlaminar cracks located between plies (4 and 5), (5 and 6), (6 and 7), (7 and 8), and (12 and 13). | - Sample failed at 919.0 N |
Table 5.6: Failure of quasi-isotropic samples consolidated at 215°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi 215°C - Sample 1</td>
<td></td>
<td>- One primary interlaminar</td>
<td>- Sample failed at 2655.7 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>crack located at the corner</td>
<td>- Crack length extends further along flanges than in the parts consolidated at 105°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>section</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Interlaminar crack located</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>between plies (12 and 13)</td>
<td></td>
</tr>
<tr>
<td>Quasi 215°C - Sample 2</td>
<td></td>
<td>- One primary interlaminar</td>
<td>- Sample failed at 2917.4 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>crack located at the corner</td>
<td>- Crack length extends further along flanges than in the parts consolidated at 105°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>section</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Interlaminar crack located</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>between plies (12 and 13)</td>
<td></td>
</tr>
<tr>
<td>Quasi 215°C - Sample 3</td>
<td></td>
<td>- Multiple interlaminar cracks</td>
<td>- Sample failed at 3287.4 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>located at the corner section</td>
<td>- Crack lengths extend further along flanges than in the parts consolidated at 105°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Interlaminar cracks located</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>between plies (2 and 3), (3 and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4), (4 and 5), (5 and 6), (6 and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7), (7 and 8), (11 and 12), and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(12 and 13)</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.7: Failure of quasi-isotropic samples consolidated at 290°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi 290°C -</td>
<td>Flange 1</td>
<td>- One primary interlaminar crack located at the corner section</td>
<td>- Sample failed at 3516.9 N</td>
</tr>
<tr>
<td>Sample 1</td>
<td>Flange 2</td>
<td>- Interlaminar crack located between plies (12 and 13), and one smaller crack located between plies (13 and 14)</td>
<td>- Crack length extends further along flanges than in the parts consolidated at 105°C (but similar to the parts consolidated at 215°C)</td>
</tr>
<tr>
<td>Quasi 290°C -</td>
<td>Flange 1</td>
<td>- One primary interlaminar crack located at the corner section</td>
<td>- Sample failed at 2942.9 N</td>
</tr>
<tr>
<td>Sample 2</td>
<td>Flange 2</td>
<td>- Interlaminar crack located between plies (12 and 13), and one smaller crack located between plies (13 and 14)</td>
<td>- Crack length extends further along flanges than in the parts consolidated at 105°C (but similar to the parts consolidated at 215°C)</td>
</tr>
<tr>
<td>Quasi 290°C -</td>
<td>Flange 1</td>
<td>- Multiple interlaminar cracks located at the corner section</td>
<td>- Sample failed at 3678.1 N</td>
</tr>
<tr>
<td>Sample 3</td>
<td>Flange 2</td>
<td>- Large interlaminar cracks located between plies (6 and 7), and (7 and 8)</td>
<td>- Delaminations and separation of plies are greatest in this sample</td>
</tr>
</tbody>
</table>
Table 5.8: Failure of ROS samples consolidated at 105°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROS 105°C - Sample 1</td>
<td>Flange 1 Flange 2</td>
<td>- Failure propagation did not occur in the corner region (occurred on flange 2, at the location highlighted). - Consists of separation occurring between the randomly-oriented strands</td>
<td>- Sample failed at 582.37 N - Highly localized failure in comparison to the quasi-isotropic samples</td>
</tr>
<tr>
<td>ROS 105°C - Sample 2</td>
<td>Flange 1 Flange 2</td>
<td>- Failure propagated within the corner region - Consists of interlaminar separation between the short strands</td>
<td>- Sample failed at 548.1 N - Highly localized failure in comparison to the quasi-isotropic samples</td>
</tr>
<tr>
<td>ROS 105°C - Sample 3</td>
<td>Flange 2 Flange 1</td>
<td>- Failure propagation did not occur at the corner (occurred on flange 1) - Consists of separation occurring between the randomly-oriented strands</td>
<td>- Sample failed at 782.31 N - Highly localized failure in comparison to the quasi-isotropic samples</td>
</tr>
</tbody>
</table>
Table 5.9: Failure of ROS samples consolidated at 215°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROS 215°C - Sample 1</td>
<td></td>
<td>- Failure propagation did not occur at the corner (occurred on flange 2)</td>
<td>- Sample failed at 532.0 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Consists of interlaminar separation between the short strands</td>
<td></td>
</tr>
<tr>
<td>ROS 215°C - Sample 2</td>
<td></td>
<td>- Failure propagation did not occur at the corner (occurred on flange 1)</td>
<td>- Sample failed at 438.2 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Consists of interlaminar separation between the short strands</td>
<td></td>
</tr>
<tr>
<td>ROS 215°C - Sample 3</td>
<td></td>
<td>- Failure propagated within the corner region</td>
<td>- Sample failed at 304.1 N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Consists of interlaminar separation between the short strands</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.10: Failure of ROS samples consolidated at 290°C.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Failure Image</th>
<th>Type and Location of Failure</th>
<th>Comments</th>
</tr>
</thead>
</table>
| ROS 290°C - Sample 1 | ![Image](flange1.png)                         | - Failure propagated within the corner region  
- Consists of interlaminar separation between the short strands                         | - Sample failed 404.17 N                                  |
| ROS 290°C - Sample 2 | ![Image](flange2.png)                         | - Failure propagation did not occur at the corner (occurred on flange 2)  
- Consists of interlaminar separation between the short strands                         | - Sample failed 701.18 N                                  |
| ROS 290°C - Sample 3 | ![Image](flange3.png)                         | - Failure propagation did not occur at the corner (occurred on flange 2)  
- Consists of interlaminar separation between the short strands                         | - Sample failed 794.07 N                                  |
Figure 5.41: Optical microscopy image showing the location of the interlaminar cracks in Quasi Sample 1 consolidated at 105°C, taken at 100X magnification.

Figure 5.42: Optical microscopy image showing the location of the interlaminar cracks in Quasi Sample 1 consolidated at 215°C, taken at 100X magnification.
Figure 5.43: Optical microscopy image showing the location of the interlaminar cracks in Quasi Sample 2 consolidated at 215°C, taken at 100X magnification.

Figure 5.44: Optical microscopy image showing the location of the interlaminar cracks in Quasi Sample 1 consolidated at 290°C, taken at 100X magnification.
Figure 5.45: Optical microscopy image showing the location of the interlaminar cracks in Sample 3 consolidated at 290°C, taken at 100X magnification.

Figure 5.46: Optical microscopy image showing the location of the interlaminar cracks in ROS Sample 1 consolidated at 290°C, taken at 100X magnification.
Figure 5.47: Optical microscopy image showing the location of the interlaminar cracks in ROS Sample 3 consolidated at 290°C, taken at 100X magnification.
5.12 Summary of spring-in, flange warpage, and failure strength of manufactured quasi-isotropic L-shape parts

The observed trends in corner spring-in, flange warpage, and the failure loads in four-point bending for the quasi-isotropic parts are summarized in Figure 5.48.

![Figure 5.48: Summary of the effect of tool temperature on the failure load, spring-in angle, and flange warpage of quasi-isotropic L-shapes. Average values are shown.](image)

5.13 Termination profiles examination

While sectioning the samples for the ASTM bending tests, the terminal profiles for flanges 1 and 2 were closely observed. In every quasi-isotropic sample, the profile of flange 1 had a much more angled appearance, and generally consisted of steps between the plies. On the other hand, the termination profiles of flange 2 had a much more rounded or irregular shape. Cross-section images of the termination profiles for both flanges are shown in Figure 5.49 to Figure 5.52. Alternate views of the profiles are included in Figure 5.53 and Figure 5.54. Example optical microscopy
images of the termination profiles for the quasi-isotropic parts consolidated at 105°C, 215°C, and 290°C are included in Figure 5.55 to Figure 5.60. All ROS samples had square edges after forming and consolidation, as shown in the microscopy images in Figure 5.61 and Figure 5.62. The naming of flange 1 and flange 2 is consistent with the convention described in section 4.3.1 where flange 1 refers to the left side of the panel that is initially in contact with the aluminium, and flange 2 is the right side of the panel that is pressed down by hand.

Figure 5.49: Termination profile of flange #1 from a sample consolidated at 105°C.

Figure 5.50: Termination profile of flange #2 from a sample consolidated at 105°C.
Figure 5.51: Termination profile of flange #1 from a sample consolidated at 290°C.

Figure 5.52: Termination profile of flange #2 from a sample consolidated at 290°C.
Figure 5.53: Alternate view of the flange #1 termination profile from a sample consolidated at 290°C.

Figure 5.54: Alternate view of the flange #2 termination profile from a sample consolidated at 290°C.
Figure 5.55: Termination profile of flange #1 from a quasi-isotropic sample consolidated at 105°C (Quasi 105°C – Sample 3), taken at 100X magnification.

Figure 5.56: Termination profile of flange #2 from a quasi-isotropic sample consolidated at 105°C (Quasi 105°C – Sample 3), taken at 100X magnification.
Figure 5.57: Termination profile of flange #1 from a quasi-isotropic sample consolidated at 215°C (Quasi 215°C – Sample 1), taken at 100X magnification.

Figure 5.58: Termination profile of flange #2 from a quasi-isotropic sample consolidated at 215°C (Quasi 215°C – Sample 1), taken at 100X magnification.
Figure 5.59: Termination profile of \textit{flange} #1 from a quasi-isotropic sample consolidated at 290°C (Quasi 290°C – Sample 2), taken at 100X magnification.

Figure 5.60: Termination profile of \textit{flange} #2 from a quasi-isotropic sample consolidated at 290°C (Quasi 290°C – Sample 2), taken at 100X magnification.
Figure 5.61: Termination profile of flange #1 from an ROS sample consolidated at 290°C, taken at 100X magnification.

Figure 5.62: Termination profile of flange #2 from an ROS sample consolidated at 290°C, taken at 100X magnification.
5.14 Wrinkles parallel to the corner

In all quasi-isotropic L-shape samples, wrinkles lying parallel and 1 – 2 cm away from the corner axis on the inside surface were present. Example wrinkles on quasi-isotropic parts consolidated at 105°C, 215°C, and 290°C are presented in Figure 5.63 to Figure 5.66. The wrinkles were only present on flange #2 – the flange that was manually pressed down onto the aluminum fixture inside the pre-heat furnace. The wrinkles present on flange #2 are likely related to the rounded termination profiles of flange #2 discussed in section 5.13.

Figure 5.63: Wrinkles lying parallel to the corner on flange #2 of a quasi-isotropic part consolidated at 105°C.
Figure 5.64: Close-up view of wrinkles lying parallel to the corner on flange #2 of a quasi-isotropic part consolidated at 105°C.

Figure 5.65: Wrinkles lying parallel to the corner on flange #2 of a quasi-isotropic part consolidated at 215°C.
Figure 5.66: Wrinkles lying parallel to the corner of a quasi-isotropic part consolidated at 290°C on flange #2.
Chapter 6: Discussion

6.1 Spring-in measurements performed in the CMM
For the quasi-isotropic L-shape parts, there is a clear trend of increasing spring-in angle with increasing tool consolidation temperature. This observed trend is in agreement with previous work by Han et al. [29, 30]. It is also interesting that the spring-in angle versus consolidation temperature is quite linear. The spring-in measurements are greater at higher tool consolidation temperatures because as the temperature of the tool increases for forming and consolidating the part, the amount of thermo-elastic cool-down within the part from the tool temperature back down to ambient temperature also increases. In order to minimize the amount of cool-down in order to reduce spring-in during a thermoforming process, it would make sense for parts to be consolidated within a tool maintained at a lower temperature.

For the ROS parts, there is also a trend of increasing spring-in angle with increasing tool temperature, however there is significantly greater scatter, and many of the results lie significantly higher than those from the quasi-isotropic parts. The greater scatter in the spring-in of the ROS can be attributed to the randomness of the short strands and inhomogeneities that may be present in both through-thickness and in different locations in the part. In section 4.1, it was clearly shown that even manufacturing perfectly flat panels made from ROS is near impossible – due to the nature of the material, there is bound to be some warpage. The greater spring-in observed in the ROS parts may be attributed to the differences in tool-part interactions between the surface of a quasi-isotropic and an ROS part. It is possible that the frictional forces between the steel tool and the surface of the ROS are greater, due to fibre discontinuities at the surface, and that this induces greater through-thickness stress gradients that contribute to spring-in. It should be noted that when the heated charge is first placed on the male tool, the female tool closes in against the top surface of the part, likely shearing the top layer of the L-shape outwards towards the flange tips. The combination of relative tool motion and the surface texture of the part may play a role.
6.2 L-shape flange warpage measurements

The flange warpage profiles of the quasi-isotropic L-shapes were generally all in the same direction. The flanges were curved or bowed towards the outside, or in the opposite direction of spring-in. This curvature of the flanges is likely caused by the interaction of the female tool in contact with the surface of the part during closure. This curvature of the flanges is also likely unique to the clamping configuration with the male tool on the lower platen and the female tool on the upper platen. As the tool halves are closed against the part, shear stresses are imposed on the top and bottom surfaces of the laminate by the female and male tools respectively as illustrated in Figure 6.1. Once the stresses are locked into the part during cool-down, removal of the part from the tool will allow the stresses to relax and warpage to occur in the expected manner that was observed in all the quasi-isotropic parts.

![Figure 6.1: Shear stresses imposed on the top and bottom surfaces of an L-shape part during closure of the tool halves.](image)

With increasing tool temperature, the flange warpage decreases, as measured by the height of the profiles. The reason for this is that when the part is placed within a hotter tool, the stresses induced by the tool during initial contact with the part have a greater chance to be relaxed at elevated temperature. When the stresses are imposed on a part pressed within a colder tool, there is a greater chance for the stresses to be stresses to be completely locked in, leading to more warpage. The temperature gradients that develop through-thickness within the part in a hot tool will also not be as large as when a part is placed on a relatively cold tool. The parts consolidated at 290°C had straighter flanges than the parts consolidated at 105°C.
The flange warpage profiles of the ROS parts varied, however a large number of the flanges were curved towards the inside of the part (opposite to the quasi-isotropic parts), or in the same direction as spring-in. Some of the ROS samples had each of their flanges bowed in the opposite direction. The variability of the flange warpage direction is again attributed to the randomness of the discontinuous strands. In addition, with increasing tool temperature, the amount of warpage in the ROS flanges tends to increase, in either direction. The cause of this is not clear.

6.2.1 Through-thickness temperature gradients in the part
The temperature gradients of the laminate initially at 390°C developing over time when the surfaces were suddenly lowered to a temperature of 105°C, 215°C, and 290°C were determined graphically from the solution provided by Carslaw and Jaeger [42]. The temperature profiles were for unsteady-state heat conduction in a slab of finite thickness $2b$. The initial temperature of the slab was $T_0$, and $T_1$ was the temperature imposed at the slab surfaces for time $t > 0$ (see Figure 6.2) [42].

Figure 6.2: Sketch of the laminate with half-thickness $b = 1.1$ mm at the initial temperature $T_0$ subject to an instantaneous temperature $T_1$ at the surface, at $x/b = 1.0$. 
The temperature profiles for an AS4/PEEK laminate were created by solving the following two equations:

\[
\frac{\tau_1 - \tau}{\tau_1 - \tau_0} = 1.0, 0.8, 0.6, 0.4, 0.2, \text{ and } 0 \tag{6.1}
\]

\[
\frac{\alpha t}{b^2} \text{ for values of } 0.04, 0.1, 0.2, 0.4, 0.6, \text{ and } 1.0 \tag{6.2}
\]

Equation 6.1 was solved for the y-axis values of the profiles given that \( T_1 \) is the surface temperature of 105°C, 215°C, and 290°C, and \( T_0 \) is the initial temperature of the laminate (390°C). Equation 6.2 was solved for calculating the time elapsed from \( t = 0 \) for each profile curve. The values set by equations 6.1 and 6.2 were simply obtained from the graphical solution by Carslaw et al. [42]. The value of \( b \) was set at 0.0011 m, and the thermal diffusivity \( \alpha \) for an AS4/PEEK laminate in the through-thickness direction was set to \( 4.43 \times 10^{-7} \text{ m}^2/\text{s} \) [43].

The through-thickness temperature profiles over time for a slab surface temperature change to 290°C, 215°C, and 105°C are presented in Figures 6.3, 6.4, and 6.5.
Figure 6.3: Through-thickness temperature gradients for a laminate subject to a surface temperature of 290°C.

Figure 6.4: Through-thickness temperature gradients for a laminate subject to a surface temperature of 215°C.
The plots assume that both surfaces of the part are suddenly lowered to the tool temperature at \( t = 0 \) seconds. For a sudden surface temperature change to 290°C, the plot shows that it takes just over 2.73 seconds for the middle of the laminate to be at the same temperature. In addition, it takes just over a second for the middle of the laminate to reach the melting point of the resin (343°C). When the surface of the part is instantly lowered to 215°C and 105°C, the temperature gradients over time are even larger. At very short time intervals, the temperature difference between the middle and surface of the laminate is also quite large. Evidently, there are large temperature gradients that can be expected within the laminate upon being placed on the tool. During the experiments, the part was first placed on the male tool followed by closure of the press, which took a few seconds. Within that time, the bottom surface of the laminate would have started cooling first prior to consolidation. The effects of through-thickness temperature gradients could be a source of residual stress in the parts.

Figure 6.5: Through-thickness temperature gradients for a laminate subject to a surface temperature of 105°C.
6.3 Spring-in predictions using thermal mechanical analysis data

In section 5.9, the thermal strains from a sample of a quasi-isotropic and ROS part were measured in the TMA and incorporated into the Nelson-Cairns formula to predict spring-in. The samples for each part were obtained from the flange portion of the L, because the curvature of a sample in the corner region could not be placed in the TMA accurately. By measuring the in-plane and through-thickness thermal strains in the flat samples, it was assumed that there would be no difference in those strains in the corner section of the L-shapes. The thermal contraction strains were measured from 105°C, 215°C, and 290°C to room-temperature in both directions because the same strains would have been present in the part during cool-down to room temperature from each of the tool temperatures. However, the spring-in predictions using these strains fall significantly lower than the measured spring-in values in the CMM and the dial gauge measurements. In assuming that both the CMM and the dial gauge measurements are true, the cause for the difference in spring-in values obtained by thermal mechanical analysis and the use of the Nelson-Cairns equation will be discussed.

First of all, the values obtained during the TMA tests may not be representative of the corner and could be due to the following:

- TMA Measurement error (perhaps due to temperature calibration during the tests)
- Sample size: as the samples were only 1 cm × 1 cm, bulging of the samples may have been present
- Differences in morphology between the corner and flange sections (only the flange sections were analyzed in the TMA)

It is also possible that the Nelson-Cairns equation does not well represent the corner due to non-uniformity within the parts, wrinkling near the corner, warpage along the flanges, and the presence of residual stress within the manufactured parts. Variations in individual ply thicknesses throughout the thickness of the part in both the corner and flange regions should be analyzed carefully in future studies. The effect of wrinkles lying close to the corner should also be investigated further.
6.4 Measurement of spring-in as a function of temperature

The measurements of change in corner angle as a function of temperature for a quasi-isotropic part clearly show that the changes in corner angle correlate very well with the measured spring-in data in the CMM (see Figure 5.31). The deflection of the flanges in the quasi-isotropic part during cool-down and heating also follow a nearly identical path, as shown in Figure 5.29. This implies that the changes in corner angle during heating and cooling are caused by thermo-elastic effects during this experiment. In Figure 5.31, the angle changes from the dial gauge experiment (data represented as squares) lie very close to the spring-in measurements (represented as circles), implying that the corner spring-in in the L-shape parts was largely caused by thermo-elastic effects during cool-down from the tool temperature to room temperature. The cool-down occurred when the parts were removed from the tool and allowed to cool by natural convection. In addition, the data lying along the curve from the dial gauge experiment allows for the approximate determination of the spring-in angle at various temperatures. The dial gauge experiment has provided a well-populated data-set of spring-in as a function of temperature.

For the ROS parts, the changes in corner angle as a function of temperature lie very close to the quasi-isotropic data. They are slightly higher than those angle changes measured in the quasi parts, however they do not correlate as well with the measured spring-in data from the CMM. The reasons for this are not so clear. The large variability associated with the processing of ROS parts can certainly play a role.

During the dial gauge measurements, the effects of flange warpage may have affected the results, as the corner angles were measured at three inches from the corner. Measurements of change in flange warpage as a function of temperature during heating and cooling were attempted, however no results were obtained in this project. It is not certain if the warpage of the flanges is also thermos-elastic and if it should be expected to change throughout a heating and cooling experiment.
6.5 Mechanical strength testing of L-shapes

The ASTM D6415 four-point bending results from section 5.11 show that the strength of quasi-isotropic L-shape samples increases with increasing tool consolidation temperature. In addition, the parts consolidated at 105°C had a large drop in failure strength. Examination of images of the failure surface from Tables 5.5, 5.6, and 5.7 show that in all samples, interlaminar failure occurs at the interface of the plies. The interlaminar strength is developed during the pressing stage. The higher the temperature during this stage, the lower the resin viscosity and the greater the ability to form high interlaminar strength. Time under pressure will also play a role but in the current case time and pressing speed are fixed.

In the ROS parts, we do not see any trend of increasing strength with increasing tool temperature. The failure images in Tables 5.8, 5.9, and 5.10 show that the failure propagates between the strands within the matrix. The discontinuity of the fibres seems to be the source of failure in these samples, as failure can easily propagate from in between one strand to another. In the ROS parts, the failure seems to be dominated by the strength of the matrix, as opposed to the continuous fibre quasi-isotropic parts where failure is directly related to the interfacial strength between the fibres and the matrix that is dependent on the tool consolidation temperature.

A few of the ROS samples had failure propagation occur just outside the corner region (unlike in the quasi-isotropic parts that all failed within the corner region). The reason may be that the additional warpage in the ROS parts likely made it more difficult for the parts to be perfectly aligned in the test fixture. Although failure did occur within the two upper fulcrums, it is possible that the randomness of the strands and inhomogeneities that may be present in the part due to localized variations in fibre orientation and fibre volume fraction may have also contributed to failure occurring just outside the corner region.

Gao et al. [44] studied the effect of the forming temperature and cooling rate on the interfacial shear strength (IFSS) of carbon fibre/PEEK composites. They have reported that parts consolidated at higher temperatures and for longer periods of time had higher IFSS values. They found that at higher consolidation temperatures, the matrix was given more time to diffuse and adsorb into
adjacent layers [44]. The results of Gao et al. are in agreement with this study. They have investigated the effect of cooling-rate on crystallinity and interface adhesion in carbon fibre/PEEK composites. They have reported that differences in crystallinity can affect the interlaminar strength. However, DSC measurements from samples taken from a part processed at 105°C (fastest cooling rate in this project) revealed that full crystallization had been reached (and no difference between parts processed at 215°C or 290°C) [34].

6.6 Termination profiles

Farnand [45] discussed flange termination profiles as they relate to allowable slip and shear with resulting ply buckling. In the case of ideal shear, we would expect a perfect book-end angle of 32.5° at the flange tip [45]. In the case of the observed profiles from flange 1 of the quasi-isotropic parts, it appears that the profiles best resemble a combination of partial shear and partial slip, and no shear and ideal slip occurring within the plies of the laminate. Both configurations lead to partial or full buckling of the plies within the flange. As wrinkles were not observed on flange 1, it is possible that fibre waviness may have been present, but this was not specifically detected in this research.

The termination profiles for flange 2 are much more irregular in shape. The terminations of flange 2 are much rounder, and is some cases almost square. In agreement with Farnand, wrinkles were also present parallel to the corner of the part on flange 2. The observed wrinkles are likely the cause for the difference in shape in the termination profiles between flange 1 and flange 2.

Example angle measurements of the flange termination profiles are included in Appendix L. The angles were measured on flange 1 of a quasi-isotropic sample consolidated at 105°C, 215°C, and 290°C with reference to the fibre orientations in the image lying parallel to the page, or running from left to right. Farnand has shown that the relative position of these inextensible 0° fibres at the flange tips can provide important information on the amount of shearing and slipping that takes place when a part is being formed. The termination angles obtained in the parts are: 44° for a part consolidated at 290°C, 52° for a part consolidated at 215°C, and 54° for a part consolidated at 105°C. The angles are greater than the ideal shear angle of 32.5° reported by Farnand, further
confirming a state of only partial shear and slip within the part. At a lower tool temperature, the viscosity of the resin during consolidation is greater and there is greater resistance to inter-ply slip. As the resistance to inter-ply slip increases, the flange termination angle will be greater as observed by the measurements in Appendix L.

6.7 Wrinkles parallel to the corner on flange 2
As the wrinkles were only present on flange 2, these were most likely caused during the hand pre-forming stage when conforming the heated panel to the angled aluminum fixture in the box furnace. As flange 1 was clamped against the aluminum surface, all deformations from pressing down flange 2 would have caused the wrinkling.

6.8 Overall observations from optical microscopy, thickness measurements, and visual surface quality
For all samples, the thickness profiles were quite uniform and in the range of 2.20 ± 0.05 mm. No significant variations in thickness were observed for the parts formed at different temperatures, for both the quasi-isotropic and ROS parts. Thickness measurements of samples from each consolidation temperature in Table 5.2 revealed that the parts consolidated at 105°C were slightly thicker by 0.04 to 0.05 mm.

Differences were observed in the surface glossiness between parts consolidated at 105°C and 290°C. It is possible that at the higher tool temperature, a greater amount of resin is located on the exterior of the parts formed at higher temperatures. It could be that due to the higher tool temperature, there was more time for the resin to evenly distribute itself throughout the sample. As this is not made entirely clear in the cross-section micrographs, further investigation is recommended.
Chapter 7: Conclusions and Future Work

7.1 Summary and conclusions

The objective of this study was to manufacture carbon fibre-reinforced PEEK composite L-shape parts in a hot press and to primarily study the effect of the tool consolidation temperature on the resulting shape distortions (including spring-in and warpage) as well as other factors relating to part quality in a continuous and discontinuous fibre system. The spring-in and warpage of the manufactured parts was quantified in the CMM, and assessments from physical thickness measurements, optical microscopy of corner and flange cross-sections, and observations of the visual surface quality were made. Mechanical strength testing of the parts under four-point bending was also performed. The main findings from this project are as follows:

- The spring-in of the parts with a quasi-isotropic layup increases with increasing tool consolidation temperature. The spring-in of the ROS parts also increases with increasing tool temperature, and is generally greater than the spring-in measured in the quasi-isotropic parts. The spring-in angle of the ROS parts have larger variability at all tool temperatures.

- The measurement of change in corner angle as a function of temperature for a quasi-isotropic part appears to be thermo-elastic, and correlates well with the measured spring-in data for the parts pressed at all tool temperatures. The same measurements do not correlate as well with the ROS spring-in data.

- The spring-in calculations based on through-thickness and in-plane thermal contraction of a small sample taken from the flange of a part under predicts the measured spring-in. It could be that the TMA values obtained are not representative of the corner due to measurement error (temperature calibration), the size of the samples, and differences in corner and flange morphology. It could also be that the Nelson-Cairns equation fails to represent the corner due to non-uniformity, wrinkling, residual stress, and warpage present in the manufactured parts.
Almost all of the parts with a quasi-isotropic layup had flanges warped in the same direction at all tool temperatures. The flanges were bowed outwards (in the opposite direction of spring-in) and the amount of warpage decreased with increasing tool consolidation temperature. In the ROS parts, flanges were warped in either direction.

Wrinkles lying parallel to the corner were observed on flange 2 of the quasi-isotropic parts due to the pre-forming process during heating. No wrinkles were observed in the ROS parts. In addition to the wrinkles, the termination profiles of flange 2 were more irregular in shape compared to a condition of partial shear and slip observed on flange 1.

The failure strength of L-shape samples with a quasi-isotropic lay-up in four-point bending increases with increasing tool consolidation temperature, with a significant increase occurring between a tool temperature of 105°C and 215°C. Interlaminar failure determined by the strength of the matrix and fibre interface is observed in the quasi-isotropic samples. In the ROS samples, no increase in failure strength is observed with increasing tool temperature, and failure occurs between the randomly-oriented strands and is dominated by the strength of the matrix.

Based on the results of this study, the following recommendations are proposed for processing AS4/PEEK thermoplastic composite parts:

1. Thermoforming parts from continuous fibres at a lower tool temperature gives rapid processing times and reduced spring-in, at the expense of greater flange warpage, lower mechanical strength, and a decreased surface finish.

2. Thermoforming parts from continuous fibres at a higher tool temperature gives higher mechanical strength, less flange warpage, and improves the surface finish, at the expense of greater spring-in.
3. As the trends for flange warpage and mechanical strength of parts made from randomly-oriented strands are not as clear at different temperatures, a lower tool temperature during thermoforming in order to minimize spring-in is recommended.

### 7.2 Future work

The following recommendations for the future are proposed:

- Implementation of a proper transport frame for carrying the heated charge from the heating station to the thermoforming tool. The charge should be held within the frame until final closure of the press. The transfer system should also accommodate any safety measures in place on the hot press (i.e. how to transfer the charge on the tool as fast as possible without having to open and close a safety gate).

- Investigating the effect of tool-part interactions on spring-in and warpage by inverting the position of the male and female tools in the press. By clamping the male tool on the upper platen and the female tool on the lower platen, differences in flange warpage direction may be observed. Tool-part interactions could also be studied by varying the release-agents on the tool, as well as the tool material.

- Manufacturing parts with varying thicknesses, alternate lay-ups, and corner radii to investigate additional effects on spring-in. For ROS parts, it would be interesting to investigate the effects of strand length on spring-in and warpage of L-shape laminates.

- To devise a method to measure the flange warpage from a manufactured part as a function of temperature, and to determine if the warpage varies thermo-elasticity or not.

- Performing detailed analyses on the fibre waviness and wrinkling within the laminates at various cross-sections of the manufactured parts.
Investigating the effects of viscoelastic behaviour during the thermoforming of thermoplastic composite L-shape parts above and below the glass-transition temperature of the resin.
Bibliography


[34] Gordnian, K. “Private Conversation”. 2015


Appendices

Appendix A  Hot press commissioning and overview

This appendix provides an overview of the hydraulic hot press that was installed and commissioned as part of a major task in this project for manufacturing thermoplastic composite parts. Details on the operation specifications, start-up procedures, and safety requirements are provided. A thorough understanding of the press and its limitations is required for the proper integration of tooling and processing steps described in Appendix B and Chapter 4 of this thesis.

A.1 Overview of the hot press

The hot press is manufactured by Wabash MPI and consists of a fixed upper platen and a moveable lower platen. The temperature of each platen can be adjusted from room temperature to 426°C – the temperature is controlled by a series of electric heating cartridges that are placed beneath the platen surfaces. The pressing load exerted by the platens can be adjusted from 0 tons to a maximum of 150 tons and is controlled by a hydraulic motor. The elevated temperature and load setting capabilities on the press are convenient features for manufacturing aerospace-grade thermoplastic composite parts that are typically processed at relatively high temperatures and pressures.

The press consists of an exterior safety gate in order to prevent any body parts from inadvertently coming into contact with the platen surfaces. The platens can only be accessed by the front sliding door (Figure A.1) – a safety interlock is incorporated in the door and does not allow one to open or close the platens when the door is raised (Figure A.2). The platen surfaces shall not be accessed at any other location such as temporarily removing the safety enclosure located at the rear of the press.
Figure A.1: Hot press safety gate and front access door.

Figure A.2: Access door safety interlock.
The platens can be cooled at varying rates depending on the type of cooling that is selected in the program. There are built-in program limitations as follows: above 340°C, only air cooling can be selected; between 170 and 340°C, a mixture of water and air cooling is recommended; and below 170°C, water only should be used for optimal cool-down. Water cooling cannot be used above the 340°C temperature limit. The flow of air and water are governed by solenoid valves that will open and close as deemed acceptable by the program. The water and air feed lines to the press are shown in Figure A.3. The flow-rate of water entering the press has been set according to the recommended manufacturer specifications that are detailed in the operating manual. The pressure of the air entering the press from the feed line shown in Figure A.4 must lie between 50 and 60 PSI. The air pressure can be read from the gauge that is connected to the feed line (Figure A.5).
Figure A.4: Air line connection to the press (red hose).

Figure A.5: Air feed line pressure gauge.
The exhaust line (Figure A.6) allows for the drainage of the hot air and water that exits the platens during a cooling process. The exhaust line directs the hot water and steam mixture to the drainage trench in the floor of the AMPEL high-head facility. The exhaust line can be very hot and should remain clear of any direct contact with people and any foreign objects lying on the floor. The drain end of the line is connected to a steam condenser and noise suppressor. This feature was designed and incorporated in this project in order to minimize steam and high-frequency noises that arose upon discharge of the hot water and steam. The steam condenser receives an intake of cold water that is controlled by the valve shown in Figure A.7. This valve must be opened whenever the platens are being cooled with water – failure to do so will result in a large amount of steam and noise being generated in the floor drain.

Figure A.6: Hot press exhaust line (red and black pipe elbow).
Figure A.7: Water valve for steam condenser (red hose).

Figure A.8: Intake water line valve (along high-head wall behind hot press).
Figure A.9: Intake water line valve (at side of hot press).

Figure A.10: Hot press main control panel.
A.2 Start-up and shut-down procedures

When starting the press, the following steps will be taken:

1. Ensure that both water intake valves - one located along the high-head wall (Figure A.8), and the second located on the side of the press (Figure A.9) - are open;
2. Verify the air pressure in the feed line is between 50 and 60 PSI;
3. Turn on the press by pressing the green power button on the front panel (an overview of the press control panel buttons is shown in Figure A.10).

Once the press is powered on, a touchscreen will be lit (bottom screen in Figure A.11) and will allow the user to enter the required parameters for safely controlling and operating the press. Turning on the electrical power to the press does not power the hydraulic motor for movement of the platens. A separate green button labeled ‘hydraulic pump’ must be pressed separately when it is necessary to control the position of the lower platen. Only the lower platen can be displaced.
Unless an experiment is running and a load must be applied on a tool, or movement of the lower platen is required, the hydraulic pump should be turned off to minimize unnecessary wear and energy consumption.

When the front safety gate is open, the safety interlock prevents the user from taking control of the platens, however the hydraulic pump is still able to run. For the purpose of safety, whenever parts and tools are placed or removed from the platen surface and whenever any sort of manual handling is required in the space located between the platens, the hydraulic pump must be turned off. Once the task is complete, the interlock gate should be closed followed by the hydraulic pump power button pressed on.

The ‘Heat On’ and ‘Heat Off’ buttons allow the user to control the electrical power to the heat cartridges located within the upper and lower platens. If a temperature has been set in the program (located within the touchscreen menu) and the ‘Heat On’ button is pressed and lit, the temperature recipe in the program will immediately take effect and this will begin heating the platens to the set-point. The safety interlock on the front door does not disconnect power to the heating cartridges. The only way to prevent heating of the platens is to ensure that the ‘Heat Off’ button is pressed and that the green heating light is turned off. The user must always be aware of the current temperature of the platens, and make sure the appropriate personal protection equipment is worn when working near the press.

In order to close the lower platen and raise it towards the fixed upper platen, the user must press both left and right black knobs labeled as ‘close’ together. Only one person should press both knobs at any given time, and the lower platen can only be closed (raised) if the hydraulic pump is on and the front gate is closed. To open the platen (lower), the yellow ‘open’ button must be pressed and held. The yellow button can be pressed at any time during the process as long as the front gate is closed.

The white ‘clamp sealed’ light indicates that the lower platen has reached a sealed position. Beyond this point during the closing stage, the ‘close’ knobs do not need to be pressed, and the platen will
continue to close slowly at 5 inches (12.7 cm) per minute until it reaches the final closed position or load that is specified in the touchscreen menu. Both the clamp sealed and final closed positions are specified by the user.

Pressing the red emergency-stop button will cut off all power to the press, including the hydraulic pump. The emergency-stop should only be used in the event of an emergency.

When turning off the press, the following steps will be taken:

1. Turn off the power to the hydraulic pump if it is running (Figure A.10);
2. Turn off the press by pressing the green power button on the front panel (Figure A.10);
3. Ensure that both water intake valves (one located along the high-head wall, and the second located on the side of the press) are closed (Figure A.8 and Figure A.9);
4. Shut off the water line for the steam condenser if it is open (Figure A.7).

For proper ongoing maintenance of the hot press, the appropriate supervisor for this equipment must be consulted.

**A.3 Box furnace and compressed air line**

As part of the hot press manufacturing station, a Thermo-Scientific Lindberg/Blue M™ 1700°C Box Furnace was commissioned and located on the left side of the hot press, shown in Figure A.12. The box furnace is used in section 4.3.2 for pre-heating panel charges prior to transfer and consolidation within the press. The distance between the furnace and the press was minimized to allow for shorter transfer times. All transfers occurred manually as no automated transfer systems have been set up in place for this project. A compressed air line and gun has also been installed at the front of the press for cleaning the platens as required.
Figure A.12: Pre-heat furnace and hot press workstation.
Appendix B Tooling for manufacturing thermoplastic composite parts

One of the very first tasks in this project was to design two different tooling fixtures that would allow for the manufacturing of both flat and L-shaped thermoplastic composite parts. The tools were designed so that they were compatible with the hot press and that they were durable and robust for long-term use.

B.1 Picture frame tool design

Detailed dimensions of all components in the picture frame tool are located in Appendix C. All components were machined and assembled in the Materials Engineering machine shop. A Solidworks® sketch along with a picture of the tool are shown in Figure B.1 and Figure B.2. The tool assembly consists of two short and two long bars fastened together forming a frame, and two individual plates of identical size that fit closely inside the frame. All components are made from H13 tool steel for resistance to wear and tear and for the long-term production of parts [46]. The concept allows the user to consolidate thermoplastic composite materials within the cavity that lies inside the frame and in between the two plates. The four bars that form the outer frame are to remain assembled at all times.

The frame is 0.9 inches (2.29 cm) thick and the inside of the frame has dimensions 7-7/8 x 7-15/16 inches (20 x 20.16 cm). The tool was designed this way to distinguish one edge length of the tool from the other. The steel plates are 0.45 inches (1.14 cm) thick and have the required dimensions to just fit inside the frame with a gap tolerance of 0.002 inches on all four sides. All of the components had a machined surface upon completion in the shop.

To prevent the part from adhering to the surfaces of the flat plates during the manufacturing process detailed in section 4.1, one side of each plate was manually polished to a final roughness of 600 grit. This surface roughness was chosen based on recent thermoplastic tool designs at McGill University for the COMP 412 project [46]. Each polished surface would be in direct contact with the thermoplastic composite material studied in this project. Details on the correct use of the tool in manufacturing flat panels from AS4/PEEK are included in section 4.1.
Figure B.1: Tool assembly for manufacturing flat panel charges.

Figure B.2: Picture frame tool assembly consisting of the upper steel plate (top left), lower steel plate (bottom left), and outer frame (right).
B.2 Tool for manufacturing L-shape parts

The tool assembly consists of matching male and female halves designed to consolidate a 90° flange from a laminate consisting of 16 plies of AS4/PEEK. Both tool halves are made from H13 tool steel, as commonly seen in industry for producing large quantities of parts [46]. The tool halves were machined and finished by Innovative Tool and Die Inc. in Delta, B.C.

Solidworks® drawings of the male and female halves of the tool are shown in Figure B.3. A few dimensions are shown on the drawings in order to get a sense of the overall size of the tool assembly. The maximum part length, $L$, and flange length, $f$, that can be formed within the tool cavity is also shown on the male tool drawing. All charges of AS4/PEEK had to satisfy these dimensions prior to loading in the tool. The corner radius of the male tool is 6.35 mm (0.25 inches), corresponding to the inside radius of a formed L-shape. The corner radius was chosen in order to satisfy the test specifications of ASTM D6415 for determining the curved beam strength of angled laminates [40] described in section 4.9 of this thesis. An image of the tool halves is shown in Figure B.4. The detailed dimensions of the tool halves are included in Appendix C. The male and female half were clamped in place on the lower and upper platens, respectively. Details on the clamping configuration are provided in section 4.2.2.

![Figure B.3: Solidworks® drawing of male tool (left) and female tool (right) with basic dimensions.](image)
Both tool halves are aligned with two 3/8-inch dowel pins seated in the corners of the female tool (Figure B.5). The dowel pins are placed in both corners of the female tool during the initial alignment and clamping of the tool halves as described in section 4.2.2. The inside surface of both halves in contact with thermoplastic resin has been polished to a roughness of 600 grit.
The fixture has been designed with support handles located on the sides of the female tool to facilitate transport from the nearby workbench to the hot press (Figure B.7). The support handles can be removed once the tool is in place in the press. Removable end plates that can be affixed on the ends of the female tool are also shown in Figure B.7. The dimensions of the end plates are included in Appendix C. The plates were considered during the initial stages of the project as a concept for completely enclosing the tool halves during forming of ROS parts from unconsolidated chips of AS4/PEEK manually inserted in the female cavity prior to closure. This forming process involves the combined application of heat and pressure to melt the chips and allow them to flow within the cavity volume until the desired part thickness is obtained. This forming technique has been studied at McGill University as part of the CRIAQ COMP 412 project [16, 17]. In this case, the end plates would prevent any of the material from being squeezed outside the cavity during the application of heat and pressure. In this project, ROS L-shapes are only made from pre-consolidated panels, and the end-plates are not required during the forming and consolidation process. The vertical shear edges between the male and female halves (labelled in Figure B.3) were also incorporated in the event of a process that would result in flow of the material beyond the tool cavity. The shear edges and tool surfaces were designed with reference to a manual for tool design in thermoplastics processing that has also served as an important guide for similar tool designs at
McGill University [46, 47]. The final configuration of the male and female tool set up in the press for manufacturing L-shape parts is shown in Figure B.8.

Figure B.7: Support handle and additional end plates shown on the female tool.
Figure B.8: L-shape thermoforming matched-die tooling configuration.
Appendix C Detailed Solidworks® drawings

This section provides the complete drawings for the flat panel picture-frame and L-shape forming tool fixtures. The drawings were submitted to the Materials Engineering machine shop and to Industrial Tool and Die Inc. for machining and finishing.
C.1 Picture-frame tool: flat plate
C.2 Picture-frame tool: long frame bar
C.3 Picture-frame tool: short frame bar
C.4 Picture-frame tool: exploded view
C.5 Male tool: dowel holes
C.6 Male tool: geometry dimensions
C.7 Female tool: tapped holes
C.8 Female tool: dowel pin holes
C.9 Female tool: geometry and dimensions
C.10 End plate: screw holes and dimensions

QTY: 2
C.11 End plate: dowel holes
Appendix D  L-shape part and tool thermal simulations

This section provides the remainder of the RAVEN thermal simulation runs for region 1 and region 2 of the L-shape part and tool cross-section from Figure 4.35 in section 4.2.5. The simulations include cooling rates of 20°C/min, 5°C/min, and 1°C/min.

Figure D.1: Thermal simulation of tools and part subject to cooling at 20°C/min at region 1.
Figure D.2: Thermal simulation of tools and part subject to cooling at 5°C/min at region 1.

Figure D.3: Thermal simulation of tools and part subject to cooling at 1°C/min at region 1.
Figure D.4: Thermal simulation of tools and part subject to cooling at 20°C/min at region 2.

Figure D.5: Thermal simulation of tools and part subject to cooling at 5°C/min at region 2.
Figure D.6: Thermal simulation of tools and part subject to cooling at 1°C/min at region 2.
Appendix E  CMM L-shape surface scans and corner angle measurements
This section includes all of the CMM surface scans and corner angle measurements for the manufactured quasi-isotropic and ROS L-shapes at all consolidation temperatures.

Figure E.1: Surface scan of a quasi-isotropic part consolidated at 105°C (part ID: 21.01.15.4).
Figure E.2: Surface scan of a quasi-isotropic part consolidated at 105°C (part ID: 16.03.15.1).

Figure E.3: Surface scan of a quasi-isotropic part consolidated at 105°C (part ID: 16.03.15.2).
Figure E.4: Surface scan of a quasi-isotropic part consolidated at 215°C (part ID: 02.04.15.1).

Figure E.5: Surface scan of a quasi-isotropic part consolidated at 215°C (part ID: 17.03.15.3).
Figure E.6: Surface scan of a quasi-isotropic part consolidated at 215°C (part ID: 17.03.15.4).

Figure E.7: Surface scan of a quasi-isotropic part consolidated at 290°C (part ID: 18.03.15.5).
Figure E.8: Surface scan of a quasi-isotropic part consolidated at 290°C (part ID: 18.03.15.6).

Figure E.9: Surface scan of a quasi-isotropic part consolidated at 290°C (part ID: 21.01.15.5).
Figure E.10: Surface scan of an ROS part consolidated at 105°C (part ID: 23.03.15.1).

Figure E.11: Surface scan of an ROS part consolidated at 105°C (part ID: 23.03.15.2).
Figure E.12: Surface scan of an ROS part consolidated at 105°C (part ID: 23.03.15.3).

Figure E.13: Surface scan of an ROS part consolidated at 215°C (part ID: 24.03.15.4).
Figure E.14: Surface scan of an ROS part consolidated at 215°C (part ID: 24.03.15.5).

Figure E.15: Surface scan of an ROS part consolidated at 215°C (part ID: 20.01.15.2).
Figure E.16: Surface scan of an ROS part consolidated at 290°C (part ID: 24.03.15.6).

Figure E.17: Surface scan of an ROS part consolidated at 290°C (part ID: 24.03.15.7).
Figure E.18: Surface scan of an ROS part consolidated at 290°C (part ID: 24.03.15.8).
Appendix F  Dial gauge invar extension rod configuration

This section includes images of the dial gauge and invar rod connection used for the L-shape corner angle measurements during heating in the box furnace in section 4.8.

Figure F.1: (A) – standard dial gauge probe with removable tip, (B) – threaded invar extension rod for connection onto the dial gauge probe, (C) – dial gauge probe and invar rod attached, (D) – rounded invar rod tip for proper resting on the L-shape flange.
Appendix G  L-shape manufacturing temperature profiles at 105°C and 290°C

This section includes the mid-thickness temperature profile measurements for manufacturing L-shape parts in the hot press at 105°C and 290°C.

Figure G.1: Measured mid-thickness thermal profile during the L-shape consolidation cycle at 105°C.
Figure G.2: Measured mid-thickness thermal profile during the L-shape consolidation cycle at 290°C.
Appendix H  Optical microscopy images of samples consolidated at 105°C and 215°C

Figure H.1: Corner (top), middle flange, and flange tip (bottom) section micrographs of a quasi-isotropic sample consolidated at 105°C, taken at 200X magnification.
Figure H.2: Corner (top), middle flange, and flange tip (bottom) section micrographs of an ROS sample consolidated at 105°C, taken at 200X magnification.
Figure H.3: Corner (top), middle flange, and flange tip (bottom) section micrographs of a quasi-isotropic sample consolidated at 215°C, taken at 200X magnification.
Figure H.4: Corner (top), middle flange, and flange tip (bottom) section micrographs of an ROS sample consolidated at 215°C, taken at 200X magnification.
Appendix I Flange warpage measurements

This section includes the remaining flange warpage profiles from section 5.8.

Figure I.1: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 16.03.15.2) consolidated at 105°C.
Figure I.2: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 21.01.15.4) consolidated at 105°C.
Figure I.3: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 17.03.15.4) consolidated at 215°C.
Figure I.4: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 02.04.15.1) consolidated at 215°C.
Figure I.5: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 18.03.15.5) consolidated at 290°C.
Figure I.6: Measured flange warpage profiles for a quasi-isotropic L-shape (ID: 21.01.15.5) consolidated at 290°C.
Figure I.7: Measured flange warpage profiles for an ROS L-shape (ID: 23.03.15.2) consolidated at 105°C.
Figure I.8: Measured flange warpage profiles for an ROS L-shape (ID: 23.03.15.3) consolidated at 105°C.
Figure I.9: Measured flange warpage profiles for an ROS L-shape (ID: 24.03.15.5) consolidated at 215°C.
Figure I.10: Measured flange warpage profiles for an ROS L-shape (ID: 20.01.15.2) consolidated at 215°C.
Figure I.11: Measured flange warpage profiles for an ROS L-shape (ID: 24.03.15.6) consolidated at 290°C.
Figure I.12: Measured flange warpage profiles for an ROS L-shape (ID: 24.03.15.8) consolidated at 290°C.
Appendix J  Thermal-mechanical data for an ROS sample

This section provides the thermal-mechanical data for an ROS sample. As the ROS samples were heated to 250°C instead of 290°C as detailed in section 4.7, the dimension change and strain values at 290°C presented in Table 5.4 were obtained by extrapolation of the data within the TA Instruments Universal Analysis software. The ROS samples were only heated to 250°C at the time that the tests were run to avoid deconsolidation of the short strands.

Figure J.1: TMA measurements of change in dimension in the through-thickness (top) and in-plane directions (bottom) of an ROS sample.
Figure J.2: Through-thickness strains and coefficient of thermal expansion as a function of temperature for an ROS sample.
Figure J.3: In-plane strains and coefficient of thermal expansion as a function of temperature for an ROS sample.
Appendix K  Dial gauge measurements of flange displacement and change in corner angle for an ROS L-Shape as a function of temperature

This section provides the dial gauge measurements of flange displacement and corresponding change in corner angle as a function of temperature for an ROS L-shape part. The heating and cooling flange displacement data at 3.0 inches (76.2 mm) from the corner is presented in Figure K.1. The heating portion of the flange displacement data was selected to calculate the changes in corner angles, presented in Figure K.2. The changes in corner angle measurements between a quasi-isotropic and ROS part are also compared in Figure K.2.

Figure K.1: Measurement of flange displacement during heating and cooling of an ROS L-shape (dial gauge measurements taken at 76.2 mm from corner).
Figure K.2: Change in corner angle during heating for a quasi-isotropic and ROS L-shape, measured at 76.2 mm from corner.
Appendix L  Flange termination profile angles

Figure L.1: Termination profile angle of a quasi-isotropic part consolidated at 290°C.

Figure L.2: Termination profile angle of a quasi-isotropic part consolidated at 215°C.
Figure L.3: Termination profile angle of a quasi-isotropic part consolidated at 105°C.
Appendix M  Case study: pre-heating an AS4/PEEK flat charge above $T_g$ and below $T_m$ prior to forming to an L-shape

A case-study was performed by attempting to form a flat AS4/PEEK panel charge above the glass-transition temperature and below the melting temperature of PEEK in order to assess low-temperature forming possibilities. The panel was heated to 250°C and placed within the male and female tool cavity held at the steady temperature of 215°C. As the panel was not heated above the melting temperature of PEEK resin, the panel could not be pre-formed and properly centred on the male tool cavity as per the manufacturing steps in section 4.3. During this case study, the female tool was clamped on the lower platen, and the male tool was clamped on the upper platen. This was the only way to place the flat charge onto the tool. However, it should be noted that closing of the platens would not guarantee that the part was properly centred within the tool assembly. The charge was placed as best as possible on the tool prior to closing the platens.

While pressing the part, it was evident that forming below the melting temperature of the resin was not feasible. As the platens were closing, cracking sounds could be heard and the part was clearly being damaged during forming. Upon re-opening the platens, the part simply sprung out a considerable amount as shown in Figure M.1. In addition, large wrinkles were present in the centre of the part as shown in Figure M.2.

![Figure M.1](image_url)

Figure M.1: Resulting part shape from pre-heating a quasi-isotropic charge at 250°C and forming at 215°C.
Figure M.2: Wrinkles resulting from pre-heating a quasi-isotropic charge at 250°C and forming at 215°C.