DIMENSIONAL STABILITY IN COMPRESSION MOULDED DISCONTINUOUS LONG FIBRE CARBON/PEEK COMPOSITES

Collins, C[1], Hubert, P[1]*
[1] Department of Mechanical Engineering, McGill University, Montreal, Canada
* Corresponding author (pascal.hubert@mcgill.ca)

Keywords: *Randomly-oriented strand composites, thermoplastic composites, compression moulding*

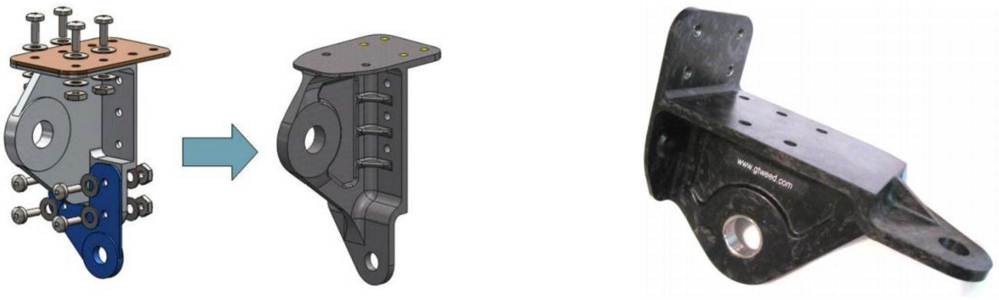
ABSTRACT

There is growing interest within the aerospace industry regarding the use of Discontinuous Long Fibre (DLF) composites with thermoplastic matrices. Composed of randomly oriented strands of chopped unidirectional pre-impregnated tape, these materials have been used successfully to produce intricate net-shape parts with complex features while maintaining high stiffness. As such, they present a viable means to replace metallic bracket and fitting assemblies with single lightweight parts.

The randomly-oriented chopped strands in these composites contribute to their many advantages - their excellent formability, their relatively isotropic properties, and their potential for short processing times. However, this heterogeneous meso-structure also creates challenges, particularly for predicting final part shape and producing consistent parts. In this paper, the characterization of the dimensional stability of compression moulded DLF carbon fibre/poly-ether-ether-ketone (PEEK) composites will be presented. Maintaining consistent processing conditions, flat panels of varying thickness were manufactured using two different sizes of DLF chopped strands. These panels were assessed for variation in surface finish, thickness, and warpage to gain a better understanding of the relationship between panel thickness and dimensional stability as well as between DLF strand size and dimensional stability. While variation was found in all panels for all three parameters, surface finish was found to be consistently better than 0.8 μm R_a, indicating that smooth DLF composite parts can be made. Variation in thickness and warpage were more dependent on panel thickness, showing that 1 mm thick panels were unstable and unpredictable in their level of variation. Magnitude of warpage was more significant, varying with both panel thickness and DLF strand size.

1 INTRODUCTION

With an ever-growing demand for weight reduction in the aerospace industry, carbon-fibre reinforced polymer (CFRP) composites have been the material of choice for many years. However, CFRPs are predominantly used to replace primary structures like fuselages and upper wing surfaces, leaving many small components with complicated geometries – like brackets and hinges – metallic. The Airbus A350 has introduced the use of thermo-formed thermoplastic composite “clips” to replace some components with complex geometries [1]. This process creates significant waste from the offcuts of preformed sheets and the trimming of the parts to final shape. Compression-moulded discontinuous long fibre (DLF) composites present an opportunity to replace metallic components that have complicated geometries with a single, lightweight, near net-shape moulded component, as has been demonstrated by a variety of authors such as van Wijngaarden [2], Howell [3], and Eguémann [4]. As such, demand for compression moulded DLF composites is growing in the aerospace industry and manufacturers like TenCate [5] and Greene, Tweed [6, 7] have demonstrated the potential for commercial usage of DLF composite parts. One such example is the Xycomp® bracket presented by Greene in [6] as a 43% lighter, single-piece replacement for a three-part aluminum assembly [6]. The DLF bracket is pictured alongside the original assembly in Figure 1.



(a) (b)

Figure 1. Industry example of DLF part replacing metallic assembly showing (a) concept and (b) final part [6]

DLF composite parts act as a compromise between high strength, but difficult-to-form continuous fibre composites and weak, but easily formable short strand composites [6, 8]. By using chopped strands of unidirectional pre-impregnated tape, a high fibre volume fraction is preserved, so parts maintain a relatively high stiffness [8]. The reduced fibre length provides sufficient formability for the creation of intricate net-shape parts with complex features like thickness variations, tight radii, holes, and ribs [6, 8], as seen in the example pictured in Figure 1 above. As well, the incorporation of a thermoplastic matrix has added benefits over a thermoset matrix in its production efficiency and performance. In terms of production, when using manufacturing techniques like compression moulding, parts are produced with relatively short processing times and create minimal waste [3, 7]. Regarding performance, thermoplastic parts typically have superior impact, moisture, and corrosion resistance [3, 7] when compared to parts with thermoset matrices. As well, they can withstand relatively high operating temperatures and are more easily recycled [7].

DLF compression moulded composite parts have shown their value and are beginning to be recognized in the aerospace industry. However, the use of DLF material is still novel, leaving room for further research and assessment.

2 SCOPE AND OBJECTIVES

The randomization of the chopped strands creates variation in mechanical properties [9, 10], and variation in the final part shape [9] and surface quality. Focussing on the final part shape and surface quality, the surface finish, thickness, and warpage of DLF composite parts will be discussed in the following sections.

2.1 Surface Finish

Little is known about the surface quality of DLF composite parts. Landry *et al.* [8] determined the correct processing conditions to minimize surface voids and matrix tearing in compression moulded DLF parts. When moulded with insufficient pressure, DLF composites have rough, white surfaces where the matrix tears away from the mould platen as it cools, as shown in Figure 2(a). Using the processing conditions prescribed by Landry *et al*. moulded parts are free of surface voids and appear black and smooth as shown in Figure 2(b) [8]. However, the final surface roughness of the produced parts was unknown. For determining potential use of DLF composites in applications with specific surface finish requirements, like for a flow path or seal surface, it is of interest to see if the randomly-oriented surface strands in DLF parts affect the final surface finish, or if there is a consistent surface finish between parts.

(a) (b)

Figure 2. Panel moulded at (a) insufficient processing pressure of 10 bar, showing white patches of rough, torn matrix and (b) processing pressure of 70 bar, showing smooth, black surface [8]

2.2 *Thickness Variability*

Part thickness varies because of the heterogeneous meso-structure of a DLF composite. The random dispersion of chopped strands of prepreg can lead to varying numbers of strands overlapping between different sections of the panel, creating resin rich regions and strand waviness – strands that are angled or curved out of plane – as shown in Figure 3. Since the matrix has a significantly higher coefficient of thermal expansion (CTE) than the fibres, it shrinks, predominantly radial to the fibres, as the part cools. By having variation between adjacent stacks of prepreg chips – and effectively variation in local properties – the local shrinkage varies and may create inconsistencies in part thickness. The magnitude of thickness inconsistencies created by the heterogeneity of the part require further understanding.

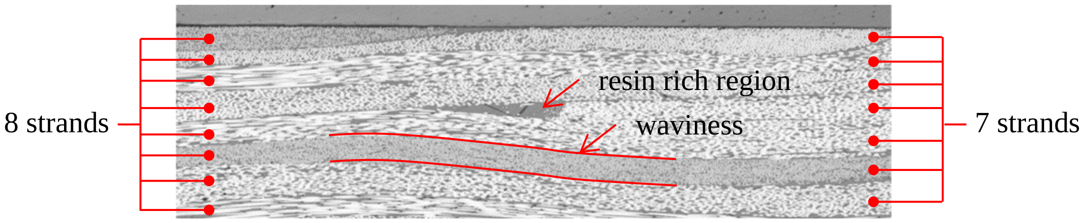


Figure 3. Cross-section of DLF composite plate, highlighting inconsistencies in fibre placement (micrograph taken from [8])

2.3 *Warpage*

As noted by [9], the final part shape of DLF composites is inconsistent. Flat plates warp from residual stresses within the plates. Residual stress generation occurs in all fibre-reinforced polymer matrix composites, but they are more apparent in thermoplastic composites due to their high processing temperatures and semi-crystalline nature [11]. The discrepancy in shrinkage from differences in CTE between the reinforcing fibres and matrix generates residual stress within the part. The high processing temperatures of thermoplastic matrices, and the additional matrix shrinkage seen during crystallization in semi-crystalline thermoplastics like PEEK, further exacerbate these residual stresses [11]. For traditional continuous fibre laminates, this creates stress on three levels. First, there is residual stress generated on the micro-mechanical level, between the individual fibre tows and the matrix, because the matrix undergoes relatively significant thermal and crystallization shrinkage as it cools, but is held in tension by the fibres that have minimal dimensional change as depicted in Figure 4(a) [11]. Then, there are the macro-mechanical residual stresses generated between each ply where the matrix shrinkage is constrained by its interaction with the fibre direction of adjacent plies, as depicted in Figure 4(b) [11]. Finally, there are global residual stresses that come from the gradient in cooling rate. Uneven cooling in a tool leads to regions of the part cooling - and stiffening - before others. These interactions have been studied at length for continuous fibre composites. Authors such as Fernlund *et al.*[12] include tool-part interactions as causes of residual stress. Fernlund *et al.* asserts that while all levels of residual stress are created in continuous fibre composite parts, dimensional instability in the form of warpage of flat plates is predominantly caused by tool-part interactions [12]. DLF composite parts are different from continuous fibre composites in that each individual strand acts as its own lamina, creating complex macro-mechanical stress interactions and discontinuities in stress at the edge of each strand. So, there is a lot unknown about the dimensional stability of DLF composites.

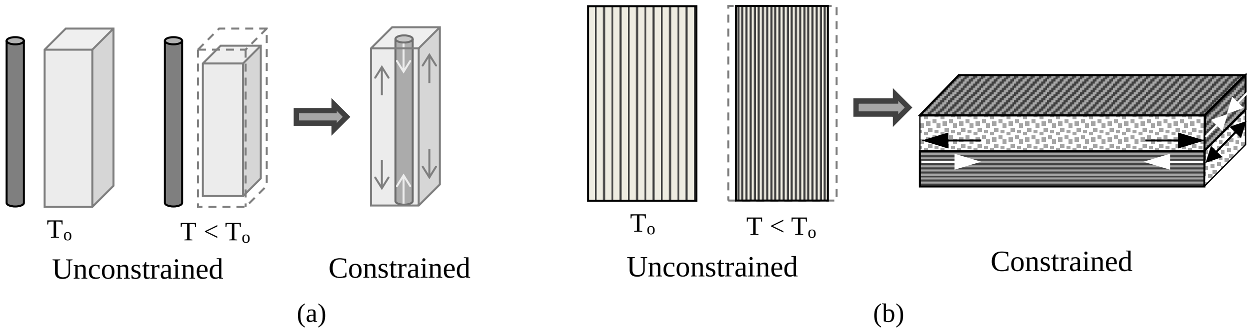


Figure 4. Visual representation of (a) micro-mechanical and (b) macro-mechanical residual stresses

In light of the above, the objective of this paper is to experimentally assess the magnitude of dimensional inconsistencies in DLF compression moulded parts. Understanding the range of dimensional instability and surface quality in DLF parts will help to better understand the potential applications for DLF compression moulding and to identify any limiting areas of this manufacturing process that can be further improved.

3 EXPERIMENTAL PROCEDURE

Surface finish, thickness, and warpage were assessed on compression moulded DLF flat plates measuring 101.6 mm x 101.6 mm. All flat plates were moulded at consistent processing conditions to enable direct comparison of these parameters. Thickness and material strand sizes were varied to observe trends between these parameters and the resulting dimensional stability.

3.1 Material and Test Matrix

Chopped strands of pre-impregnated, unidirectional AS4 carbon fibre/PEEK tape were used. Two different sizes of strands were assessed – 6.35 x 3.18 mm strands of TenCate Cetex® MC1200 bulk moulding compound and 12.70 x 12.70 mm strands of TenCate APC-2/AS4 tape. Both strand sizes have a fibre volume fraction of approximately 59%, a consolidated ply thickness of 0.132 mm, a melting point of 343°C, and a glass transition temperature of 143°C. Panels were moulded following the test matrix presented in Table 1.

Strand Size	**Quantity Moulded at Plate Thickness**				
	1 mm	2 mm	2.3 mm	3 mm	3.8mm
6.35 x 3.18 mm	2	2	-	2	2
12.70 x 12.70 mm	2	2	3	-	-

Table 1. Test matrix

3.2 Equipment

The panels were manufactured in a 250 kN MTS load frame, retrofitted with a small instrumented hot press as pictured in Figure 5. The press was heated using four 500 W FIREROD® heating cartridges by Watlow in each the top and bottom platen. The heating was controlled using an SD Series proportional-integrative-derivative (PID) controller from Watlow. The top platen’s and bottom platen’s heating cartridges were controlled separately. Platen surfaces had a high-quality surface finish as they were ground when initially manufactured. A picture frame mould was fitted around the bottom platen, creating a mould cavity for 101.6 x 101.6 mm flat plates. Cooling was implemented through forced air. A compressed air hose was fitted to both top and bottom platens during cooling to force air through three cooling channels in each platen. The rate of cooling was controlled by setting a fixed cooling rate on the PID control for the heating cartridges.

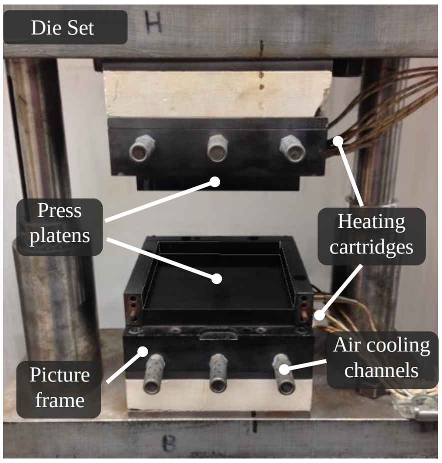
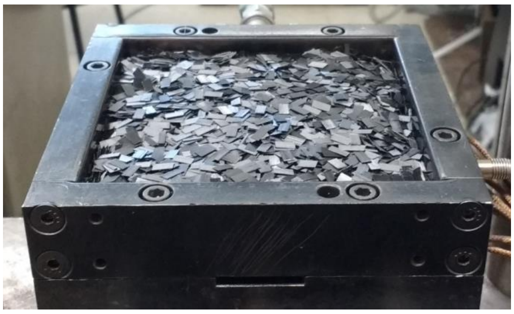


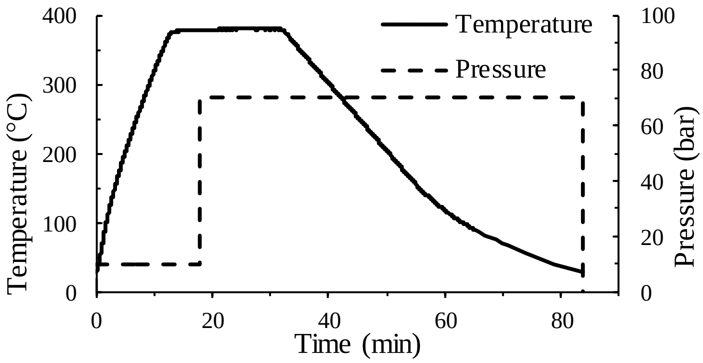
Figure 5. Instrumented hot press used to mould 101.6 x 101.6 mm DLF panels

3.3 Processing Conditions

All panels were moulded using consistent processing conditions, as determined to make "defect-free" panels by Landry *et al.* in [8]. Target part thickness was set based on the volume of the mould cavity and the density of the DLF material. The weight of material used for each panel was controlled. Material was manually distributed in the mould cavity coated with Frekote® NC-700 release agent. Following the example of panels moulded by Landry *et al.* [8] and Selezneva *et al*. [9], a low-flow moulding strategy was employed. This means that the cavity was filled completely, as pictured in Figure 6(a), to limit material flow and make the most mechanically consistent parts. Strands were added in small batches, gently shuffling the strands to reduce out-of-plane orientation, until all material was utilised and visually determined to be uniformly distributed. The process cycle is depicted in Figure 6(b).



(a)



(b)

Figure 6. (a) DLF material distribution and (b) processing cycle used to mould 101.6 x 101.6 mm DLF panels

After placing the material in the mould cavity, the platens were closed and approximately 10 bar of pressure was applied during the heating cycle to pack the strands together. Once the part reached target temperature (380°C), 70 bar of pressure was applied. This high processing pressure is necessary because, as explained in [8], as the part cools, it shrinks – both from effects of thermal expansion and from the crystallization of the matrix. As the mould temperature is not perfectly uniform, the part shrinks most in the sections that cool first. In [8], Landry *et al.* determined that 70 bar of pressure was sufficient to maintain contact between the part and mould platens until the full part had cooled below crystallization temperature, preventing surface defects in the final part. So, 70 bar pressure was maintained during the part cooling.

Cooling was performed at approximately 10°C/min. For semi-crystalline thermoplastics, like PEEK, it is known that cooling rate affects the degree of crystallinity as well as the crystallization temperature. For fast cooling rates, the matrix does not have time to crystallize and remains amorphous [13]. At extremely slow cooling rates, the level of crystallinity is at its maximum [13]. However, for the cooling rates possible in the instrumented hot press used – between approximately 5°C/min and 20°C/min – the degree of crystallization and crystallization temperature of PEEK remain relatively constant at approximately 33% and 343°C, respectively [8].

3.4 Panel Quality Measurements

Following manufacture, each panel's surface finish was measured with a Mitutoyo Surftest SJ-410 profilometer as an arithmetic mean of the surface profile amplitude in μm R_a, as this is one of the most common measures of surface roughness [14]. This measure of surface roughness indicates the average of the absolute variation of the surface profile (*Z(x)*) from a best-fit line across the scan length (*L*) of the measurement. It is calculated using Equation 1. Following a procedure similar to Palardy *et al.* in [14], each panel was measured in six locations, as pictured in Figure 7. Starting at the centre-line of the panel, the profilometer scanned 22.4 mm along the top, centre, and bottom of each side of the panel with a scan speed of 0.50 mm/s.

$$R_a = \frac{1}{L}\int_0^L |Z(x)|dx \tag{1}$$

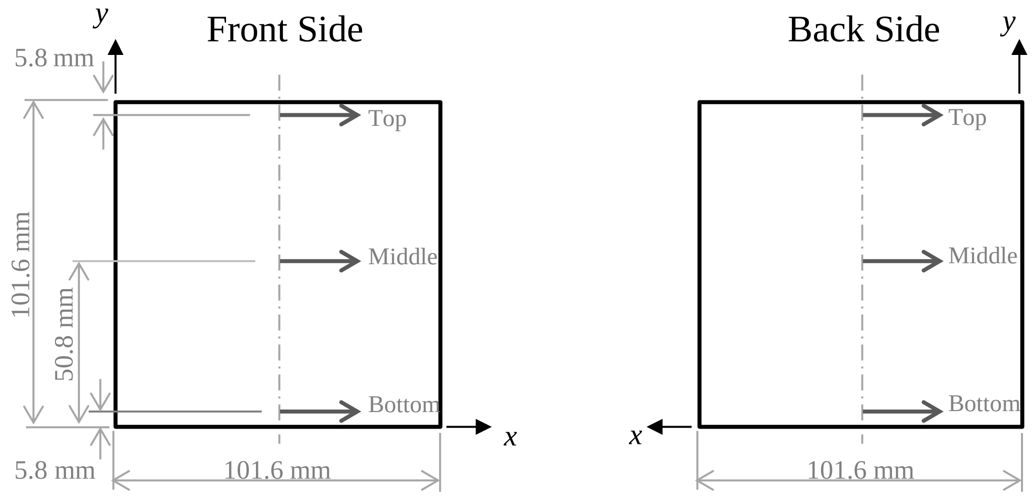


Figure 7. Surface finish measurement locations on moulded DLF panels

The panels were then scanned using a FARO® ScanArm to generate unique point clouds for each part. Using InnovMetric's PolyWorks® inspection software, the virtual panels were assessed for thickness and warpage. The panel scans were aligned with 3D models of perfectly flat panels using a best-fit approximation. The maximum total deviation of the panel surfaces, from lowest to highest point as pictured in Figure 8, was recorded as the warpage measurement. Thirty virtual calliper measurements were taken on each panel to determine panel thickness as well.

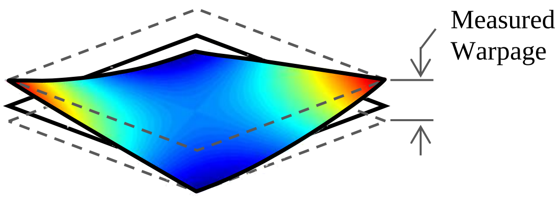


Figure 8. Depiction of warpage measurement for DLF panels

4 RESULTS

4.1 Surface Finish

All plates were successfully manufactured without visibly apparent surface defects. Variation was found in surface finish measurements, both within the same panel and between panels at the same location. However, there was no apparent trend between surface finish and panel thickness, strand size, or measurement location. All surfaces were smooth, with all readings falling between 0.28 μm R_a and 0.56 μm R_a. For comparison, a metallic surface typically has a finish of $\leq$ 0.8 μm R_a when turned or ground in a controlled manner. So, all panels had good quality surfaces. The average surface finishes for both front and back surfaces of the panels are depicted in Figure 9(a) for the 6.35 x 3.18 mm strand panels and Figure 9(b) for the 12.70 x 12.70 mm strand panels. The average surface finish of all panels moulded with 6.35 x 3.18 mm strands was 0.41 and 0.42 μm R_a for the front and back surfaces, respectively. Similarly, for the panels moulded with 12.70 x 12.70 mm strands, the average surface finishes were 0.41 and 0.40 μm R_a for the front and back surfaces, respectively.

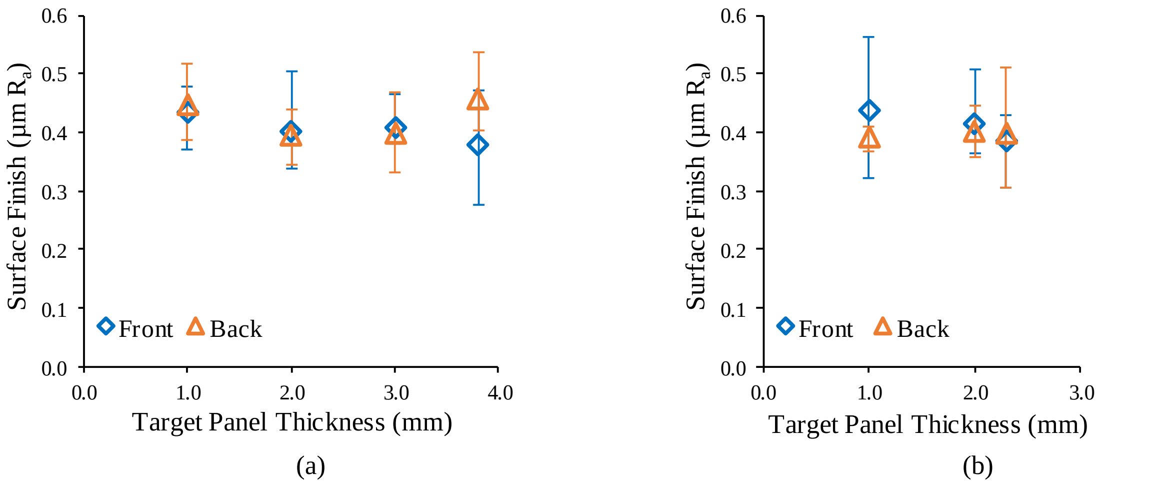


Figure 9. Measured surface finishes when using (a) 6.35 x 3.18 mm and (b) 12.70 x 12.70 mm AS4/PEEK strands

4.2 Thickness

The thickness measurements from each panel were normalized to the target panel thickness for comparison in Figure 10. There is not a definitive trend from the collected data. However, it is apparent that the 1 mm thick panels are the least dimensionally stable; for both strand sizes they have the largest deviation from their target thickness. The deviation of thickness in the panels with the larger strands – 12.70 x 12.70 mm compared to 6.35 x 3.18 mm – appears to be lower, but there is not enough data to establish a trend. Finally, the overall deviation is small in most panels. Most the thickness measurements fall within 5% of the target thickness. On an absolute scale, the maximum deviation seen from panel target thickness is 0.2 mm. The thickness data was also plotted as contour plots to compare the distribution of thickness throughout the panels. From these contour plots, it was seen that variation in thickness was not consistent between panels. One example of this is pictured in Figure 11, where both 3 mm thick 6.35 x 3.18 mm panels are compared.

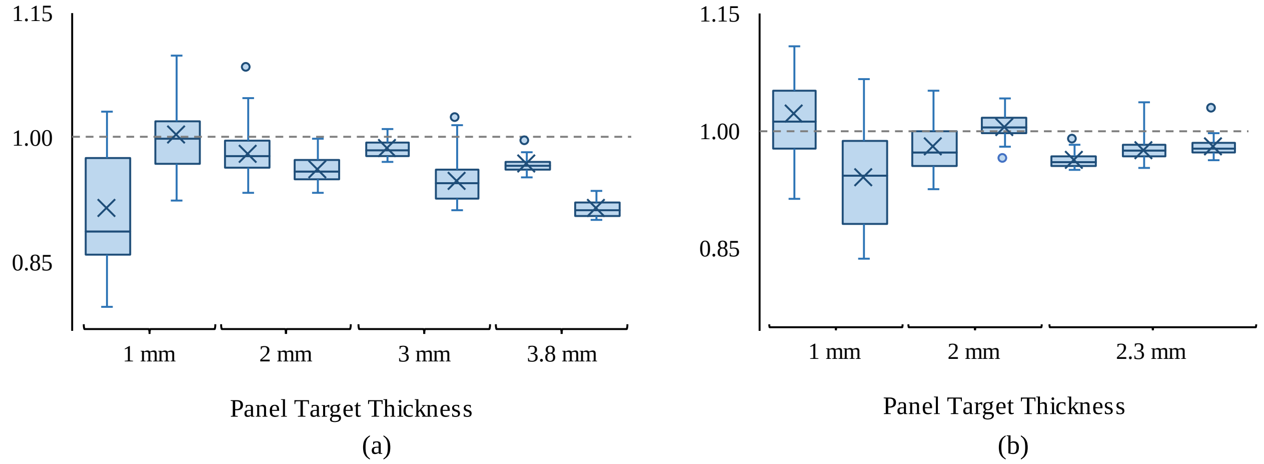


Figure 10. Normalized panel thickness when using (a) 6.35 x 3.18 mm and (b) 12.70 x 12.70 mm AS4/PEEK strands

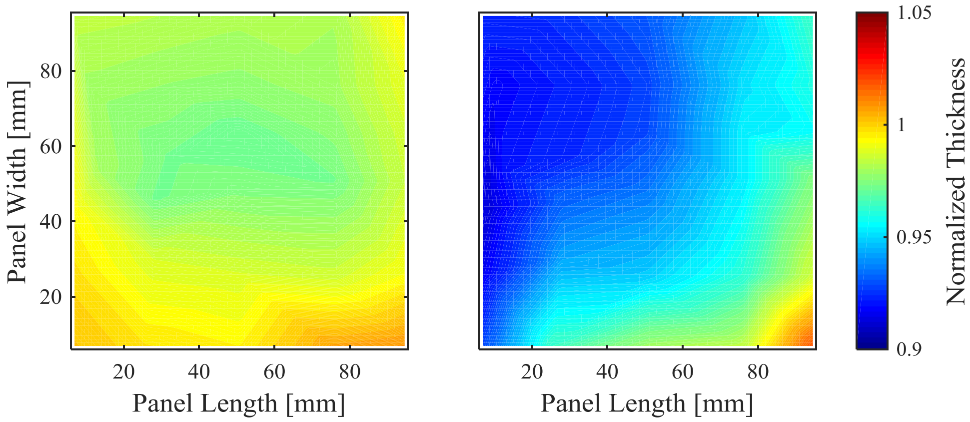


Figure 11. Normalized panel thickness as a fraction of target thickness plotted as a function of position on two 3 mm thick plates moulded with 6.35 x 3.18 mm AS4/PEEK strands

4.3 *Warpage*

The resulting warpage measurements are compiled in the graph shown in Figure 12.

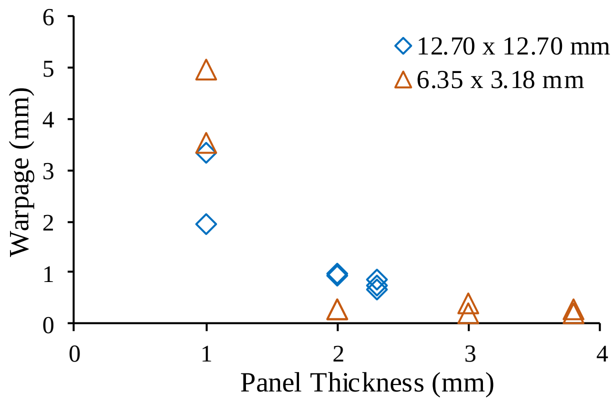


Figure 12. Measured panel warpage as a function of panel thickness for 12.70 x 12.70 mm and 6.35 x 3.18 mm AS4/PEEK strands

Observing the above graph, it appears that the 1 mm thick panels are unstable and unpredictable in warpage, just as they were when observed for thickness variation. They show a wide variation in warpage results. For the panels that are at least 2 mm thick, two trends are apparent. First, warpage decreases as panels get thicker. This trend is intuitive. As warpage is a result of residual stresses, stiffer plates should exhibit lower levels of warpage. The stiffness of the plate is closely tied to its thickness, with its moment of inertia increasing as a cubic function of thickness. The second trend observed is that warpage is lower for plates with smaller strand sizes; the 2 mm thick plates had approximately 0.3 mm of warpage when made with 6.35 x 3.18 mm strands but approximately 1.0 mm of warpage when made with 12.70 x 12.70 mm strands. From [9], it is believed that larger strand sizes create parts with higher Young's moduli. So, by the previous logic, plates with larger strands should have reduced warpage. However, the modulus increase from increasing strand size has a much lower impact on bending stiffness than the increased moment of inertia that results from thickness increases. Increasing the strand size can significantly reduce the number of strands that are randomly distributed within the plate and thus reduce the likelihood of a relatively homogeneous distribution. The 12.70 x 12.70 mm strands are eight times larger than the 6.35 x 3.18 mm strands, so there are roughly one eighth of the number of strands in the same panel thickness. Thus, the 12.70 x 12.70 mm strand panels are likely much more heterogeneous.

Observing the contour plots of the warped panels, like the examples in Figure 13, it is apparent that the warpage seen between panels is inconsistent. Considering the constant processing conditions, this indicates that the micro- and macro-mechanical stresses created during processing had a more significant impact on the final warped shape than the tool-part interaction.

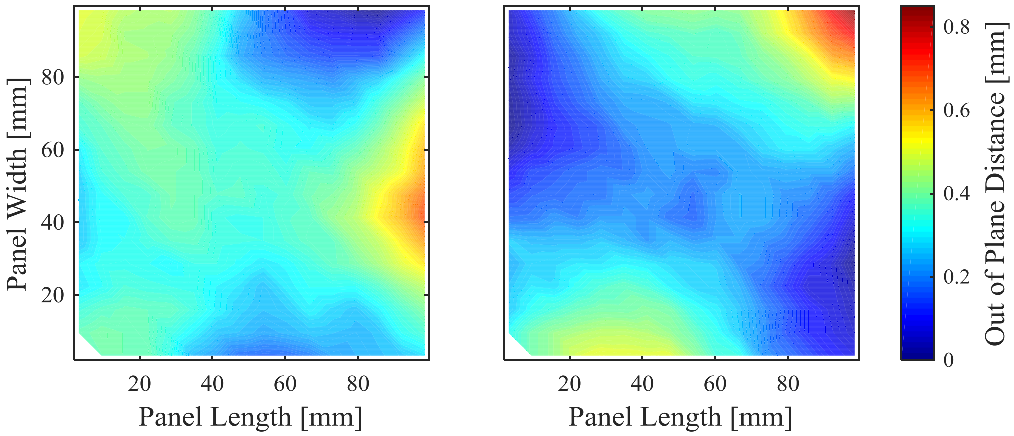


Figure 13. Measured panel warpage plotted as function of position on two separate 2.3 mm thick plates moulded with 12.70 x 12.70 mm AS4/PEEK strands

5 CONCLUSIONS

Compression moulded DLF composites act as a compromise between difficult-to-form continuous fibre composites and weak short fibre composites. However, due to the novelty of the process, much is still unknown about the dimensional stability and surface finish of DLF compression moulded parts. To address this unknown, flat plates were moulded at consistent processing conditions, varying strand size and plate thickness. The heterogeneous meso-structure of DLF composites was found to create variability in surface finish, thickness, and warpage. However, in the case of surface finish, all parts were relatively smooth, indicating that good quality surface finishes can be attained, provided proper processing conditions are utilised in conjunction with good quality mould surfaces. For thickness and warpage, target thickness had a more significant impact on dimensional stability. Parts should be 2 mm thick, or more, to promote dimensional stability. As well, shorter strands should be used for improved homogeneity.

6 ACKNOWLEDGEMENTS

The authors would like to greatly acknowledge the financial support provided by the Consortium for Aerospace Research and Innovation in Canada (CARIC), the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ) and industrial partners: Pratt and Whitney Canada Corp. and Hutchinson Aerospace & Industry Ltd. The authors thank McGill's Additive Manufacturing Lab and the Hutchinson Aerospace & Industry Ltd. Quality department for their assistance in providing inspection equipment. The authors would also like to thank Benoit Landry, Dominic LeBlanc, Gilles-Philippe Picher-Martel, and Marina Selezneva for their work designing the instrumented hot press, developing appropriate processing conditions for making defect-free parts, and demonstrating the viability of using DLF carbon/PEEK to make complex parts.

7 REFERENCES

[1] A. Miaris, K. Edelmann, and M. von Hayek Boelingen. "A350 WXB: Thousands of thermoplastic composite parts in an FRP aircraft." *Proceedings of the SAMPE Conference*, Seattle, WA, USA, 2014.

[2] M. van Wijngaarden, A. Jongbloed, and J. de Vries. "Thermoplastic Compound Compression Moulding." *Proceedings of the SAMPE Conference*, Seattle, WA, USA, 2010.

[3] D. Howell and S. Fukumoto. "Compression molding of long chopped fiber thermoplastic composites." *Proceedings of the CAMX Conference*, Orlando, FL, USA, 2014.

[4] N. Eguémann, L. Giger, M. Roux, C. Dransfeld, F. Thiébaud, and D. Perreux. "Manufacturing and Recycling of Complex Composite Thermoplastic Parts for Aerospace Application." *Proceedings from 7th International Technical Conference and Table Top Exhibition*, Lucerne, Switzerland, 2012.

[5] D. Howell and J. Gabriel. "Compression molded composites: processes, benefits and applications - an interview with tencate." *AZoM*, 2014.

[6] T. L. Greene. "Discontinuous long fiber composites for complex shape metal replacement." *Proceedings of the CAMX Conference*, Orlando, FL, USA, 2014.

[7] T. L. Greene, C. Wonderly, H. Kilic, and B. Keller. "Complex-shape metallic aircraft engine bracket replacement using compression molded discontinuous long fiber thermoplastic composites." *Proceedings of the CAMX Conference*, Dallas, TX, USA, 2015.

[8] B. Landry and P. Hubert. "Experimental study of defect formation during processing of randomly-oriented strand carbon/PEEK composites." *Composites Part A: Applied Science and Manufacturing*, Vol. 77, pp. 301-309, 2015.

[9] M. Selezneva and L. Lessard. "Characterization of mechanical properties of randomly oriented strand thermoplastic composites." *Journal of Composite Materials*, Vol. 50, pp. 2833-2851, 2016.

[10] N. Eguémann, L. Giger, M. Roux, C. dransfeld, F. Thiébaud, and D. Perreux. "Compression moulding of complex parts for the aerospace with discontinuous novel and recycled thermoplastic composite materials." *Proceedings of the 19th International Conference on Composite Materials*, Montreal, Canada, 2013.

[11] P. P. Parlevliet, H. E. N. Bersee, and A. Beukers. "Residual stresses in thermoplastic composites—A study of the literature—Part I: Formation of residual stresses." *Composites Part A: Applied Science and Manufacturing*, Vol. 37, pp. 1847-1857, 2006.

[12] G. Fernlund, A. Poursartip, G. Twigg, and C. Albert. "Residual stress, spring-in and warpage in autoclaved composite parts." *Technical Papers-Society Of Manufacturing Engineers-All Series*, 2003.

[13] W. Unger and J. Hansen. "The effect of cooling rate and annealing on residual stress development in graphite fibre reinforced PEEK laminates." *Journal of Composite Materials*, Vol. 27, pp. 108-137, 1993.

[14] G. Palardy, P. Hubert, M. Haider, and L. Lessard. "Optimization of RTM processing parameters for Class A surface finish." *Composites Part B: Engineering*, Vol. 39, pp. 1280-1286, 2008.