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Tool interface pressure during the forming of model composite corners

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Abstract

A new experimental technique is proposed to measure the pressure gradient in corner laminates with the aim of guiding manufacturing practices that can produce composites laminates to the desired thickness. A pressure mapping sensor was placed between a metal mould tool and a silicone sheet that acts as an idealised composite part. The compaction pressure loss in internal corners and rise in external corners is reported for the first time, covering a part thickness to radius ratio of 0.2 to 0.8 in the corner. A conclusive trend was observed in internal corners, where the pressure drop increases proportionally with the thickness to radius ratio. The sensor thickness, bulk, and contact with the tool created difficulties in measuring the true extent of the pressure rise for external corners. Stretchable thin film sensors might provide better alternatives for future studies looking to investigate pressure gradients in doubly curved geometries.

Keywords: D. Process monitoring; E. Consolidation; E. Tooling;
1 Introduction

Bag moulding of pre-impregnated reinforcement continues to be the most popular method of manufacture for high-performance composites. One major advantage of bag moulding is its inherent flexibility. A vacuum bag can be applied to a wide variety of shapes and can accommodate small variations in ply positioning or ply thickness that could lead to flaws in more constrained processes, such as those that use closed mould tooling. Despite this versatility, bag moulded parts are not immune to defects because applied pressure governs the quality of consolidation in fibre reinforced composites [1]. Incorrect pressure or inadequate vacuum during cure can lead to undesirable part quality, measured by important parameters such as fibre volume fraction, voidage, waviness, and cured ply thickness [2].

Unwanted defects due to resin and fibre flow are influenced by the total pressure reacted by the fibrebed and the hydrostatic pressure of the liquid polymer resin. Resin accumulation and voids are caused by the pressure gradients in a laminate. High pressure increases resin flow that causes resin rich regions with low fibre volume fractions, whereas voids are predominantly associated with lower pressures. Fibre wrinkling results from a lack of laminate ply slipping or shearing during compaction or can be imprinted by the consumable materials.

The published literature appears to support the idea that corners are more prone to defects than flat laminates [3,4]. Firstly, the difference in path length between the inner and outer radius of the corner leads to ply-bridging [5] or wrinkling [6] if no slip occurs between plies to accommodate the excess length. Secondly, lay-up and bagging errors can lead to undesirable consolidation in corners because of poor ply contact with the tool surface, and poor vacuum bag installation that causes bag bridging. Bridging can also be caused by 0° plies near the bag surface carrying tensile stresses. Finally, the through-thickness pressure gradient in the laminate will
vary from the bag to the tool surface around the corner radius imposed by design. All of the above factors contribute to variation in resin and fibre flow that amplifies thickness variations in corners.

Figure 1 illustrates the free body diagrams of an L-shape laminate subjected to a compaction pressure $P$ over an internal and external mould tool. Due to the exposed surface geometry, the internal corner laminate in Figure 1a is expected to have reduced compaction when compared to the external corner in Figure 1b. Consider the internal corner, the surface exposed to the applied compaction pressure, $S_{bag}$, is smaller than the contact surface at the tool side, $S_{tool}$. Therefore, in order for the laminate to be in equilibrium, the reaction stresses at the tool side, $P_{tool}$, is smaller than the compaction pressure applied on the bag side, $P_{bag}$. The laminate radial compressive stress is then lower at the corner in the case of an internal tool; corner thickening occurs due to this lower compaction and resin can migrate towards this region of lower pressure. The opposite phenomenon occurs for the case of external corners, where the surface at the tool side is smaller than that at the bag side. Higher laminate radial compressive stress develops, causing corner thinning because of higher compaction and resin migration away from the corner.

A great deal of work is presented in the literature to describe the consolidation of laminated composites. The early work by Loos and Springer [7], Gutowski et al. [8], and Kardos et al [9] laid a foundation to describe resin flow, fibre movement (e.g. squeezing, bleeding, shearing, slipping, and rotating) effects on volume fraction, and void suppression. More recent studies [10,11] have explored the visco-elastic nature of consolidation to better account for more complex consolidation events (e.g. wrinkles, and gas flow). A stand-alone model has even been proposed to help designers predict as-manufactured corner thickness based on mould radius and
flange length [12]. The analytical models and finite element analysis in the literature would benefit from further experimental investigation into consolidation pressure in corners.

1.1 Review of pressure measurements

The connecting thread through the collection of scientific literature is the load-sharing of applied pressure between the fibre network and the uncured resin. The portion of the applied pressure shared by the resin becomes the driving pressure for resin flow through the fibrebed according to Darcy’s law. A number of studies have explored in detail the relationship between resin pressure, resin viscosity, and fibrebed permeability in both liquid moulding and prepreg processing [13,14]. Even though the full pressure tensor plays a role in all composites processes, historically, prepreg processing has been more concerned about the through-thickness pressure gradient driving consolidation, whereas liquid moulding processing has focused on the in-plane pressure gradient governing preform wetting.

Of the three constituents in the load sharing relationship, either applied pressure or resin pressure needs to be measured in manufacturing conditions. Fortunately, the transverse fibrebed stress can be accurately accounted for through models [15] or directly measured for the reinforcing material [16].

Measuring the applied or resin pressure during composite moulding is complicated [17]. A number of researchers have drilled into the mould tool where a recessed pressure transducer measures the hydrostatic pressure in a cavity filled with uncatalyzed resin [1,16,18-24]. By measuring the pressure at the interface between the tool and first-ply, the through-thickness pressure gradient can be related to part thickness and fibre volume fraction. One sensor is often sufficient for prepreg processing if the in-plane pressure gradient is negligible, i.e. when processing flat, gently curved, and constant thickness laminates. Two or more sensors are
commonly used in liquid moulding to calculate the in-plane pressure gradient from the resin inlet to the vacuum outlet, or to detect the flow front and possible signs of race-racking. In practice, recess opening can play an important role in measurement quality. If the opening is too large, laminate deflection, laminate swelling or fibre contact with the transducer can be mitigated with a stiff screen [1]. On the other hand, if the opening is too small, cleaning between mouldings and avoiding entrapped bubbles in the recess becomes difficult.

The through-thickness pressure gradient calculated by a single recessed transducer has been validated by measuring the resin pressure locally in laminates [1,25-27]. A local approach uses miniature pressure transducers or embeds a rigid hypodermic needle into the laminate to monitor the resin pressure. While a miniature pressure transducer can make a direct measurement from the laminate, a hypodermic needle is filled with uncatalyzed resin and the hydrostatic pressure is measured in a reservoir at the other end. In addition to traditional Wheatstone bridge diaphragm pressure transducers, Fibre Bragg Grating sensors have been successfully evaluated to measure the reservoir pressure [26], widening the available measurement options. Using needles to measure the resin pressure broadens the available geometries to include tapered laminates where the through-thickness pressure gradient can be measured [28]. In practice, needle rigidity will limit this technique to 2D geometries, and careful selection of needle diameter is required to minimise disturbances to the local fibre volume fraction and part thickness.

Measurement of the applied pressure to complex shapes has been considered as an alternative to the local resin pressure approaches. Benefitting from full-field measurements, the pressure reacted in different regions of the laminate can be assessed.

Early work evaluated the usefulness of pressure intensity colour films as a means to identify the applied pressure reacted in the corner of an L-shaped mould [29]. The film develops a colour
variation related to the pressure uniformity between the substrate and mould. The applied pressure measured in corners using a rubber substrate was shown to be lower than in adjacent flanges, and this was correlated to corner thickening in laminates subsequently moulded to the L-shaped geometry. Interestingly, the highest pressure observed in the film was at the transition between corner and one flange. While this could be a drawback of the paper slipping between the mould and part, the distribution of the reacted pressure was successfully demonstrated, providing a discrete measurement once the film is developed. A major limitation of pressure intensity colour films is that only the peak pressure is recorded. Since this technique is unable to measure the relaxed fibrebed stress, it is restricted to qualitative pressure distributions.

Continuous measurements that account for fibrebed relaxation are possible when piezo-resistant or capacitive sensors are connected to a data acquisition system. Commercial offerings from Tekscan™ and XSENSOR® have been used by researchers to record the fibrebed stress reacted by moulds [30], fluid distribution during resin injection [30,31], pressure distribution by a vacuum bag placement [32], and pressure distribution under an automated deposition roller [33]. These sensors are flexible, making them suitable for flat or single curvature parts (e.g. corners), but they are inextensible, and therefore cannot be draped over doubly curved geometries (e.g. a hemi-sphere).

A summary of the available pressure measurement techniques is shown in Table 1. While there is no single measurement technique that provides all information needed to describe the manufacturing process physics for composites, sensors are available to quantify parameters that influence quality.
1.2 Objectives

This paper builds on the existing consolidation knowledge in the literature by providing experimental measurements of pressure reacted in internal and external corners for a model material representing a composite prepreg laminate. Typical corner thickness-to-radius ratios found in high-performance aerospace applications are investigated using a surface pressure mapping sensor. The measurements show how the corner through-thickness pressure gradient is affected by the thickness-to-radius ratio, and by the choice of internal or external tooling. The measurements are compared to analytical and numerical models presented in the literature. This knowledge can be used to design composite parts with geometries that are less affected by the pressure gradient in corners or as boundary conditions for high-fidelity simulations looking to predict fibre volume fraction, voidage, and waviness in complex geometries.

2 Experimental approach

Four sets of internal and external tools were manufactured from 2 mm thick aluminium sheet. The latter were bent to a 90° angle over a forming tool to obtain tools with radius \( R_m \) of 6 mm, 12 mm, 18 mm and 24 mm for the internal mould and 6 mm, 10 mm, 18 mm and 24 mm for the external mould (Figure 1). The composite part was simulated with a 5 mm and 10 mm thick \( t_f \) silicone 30 shore A hardness rubber sheet (Silex Silicones Ltd., Hampshire UK). The 10 mm thick sample consisted of two 5 mm sheets stacked together without any adhesive or lubricant between layers.

The material system and cure state of interest is a thermoset prepreg made of unidirectional fibres or fabrics during the initial stage of the cure cycle (i.e. temperatures ranging from room temperature to 150°C) and before the resin gels. The prepreg is a combination of a solid fibre form and a liquid resin. A large range of values for the elastic properties are reported in the
literature for this class of material [34-37]. The values depend on the fibre architecture and testing methods used. For the shear modulus, values reported are: 0.022-0.026 MPa for a unidirectional carbon fibre thermoset prepreg tape measured with a torsion test in a rheometer [34], 0.080-0.180 MPa for MTM45-1/HTS5613 prepreg with parallel plate rheology [35] and 0.400-1.000 MPa for IM7/8552 and IMA/M21 prepregs with off-axis tensile tests [36]. For the Young`s modulus, values reported are: 268-767 MPa for an out-of-autoclave Cycom 5320 5-harness satin weave carbon fibre prepreg tested in a bespoke cantilever beam fixture [37] and 20-25 MPa for a unidirectional carbon fibre thermoset prepreg tape measured with three-point bending test in a dynamic mechanical analyser [34]. Clearly, the prepreg is an anisotropic material with fibre dominated elastic modulus in the material in-plane directions and resin dominated out-of-plane elastic modulus and shear modulus.

Since the operation of the pressure sensor was limited to room temperature in dry conditions, silicone rubber was chosen as a model material to mimic the behaviour of the prepreg. Silicone rubber has an elastic modulus in the 1-30 MPa range and is almost incompressible with a Poisson’s ratio of 0.49. The combination of low elastic modulus and incompressibility for silicone rubber is believed to approach the elastic response of the fibre bed and the incompressible behaviour of the fluid phase in a prepreg. An elastic modulus of 3 MPa was measured using a dynamic mechanical analyser for a sample of silicone rubber used in the experiments which is the middle range of the measured data reported in the literature.

The pressure was measured using an XSensor PX200 (XSENSOR® Technology Corp., Calgary Canada), which was taped along the edges of the tool surface before the silicone sheet was placed on top of the sensor (Figure 2). The pressure mapping sensor is 1.35 mm thick, and has a sensing element every 2.5 mm in a 250 mm × 250 mm grid, which provides up to 10,000
individual pressure measurements. The pressure measurement range of this specific sensor is 1.4 to 103 kPa. The tool-sensor-part assembly was vacuum bagged to ensure that no bridging or wrinkles in the bag were present near the part. The XSENSOR X3 PRO software was used to record the pressure profile evolution with the application of vacuum. The steady state pressure distribution was recorded around 5 minutes after the application of vacuum and the raw data was exported to Microsoft Excel for analysis. The pressure recorded by the sensor was in agreement with an independent vacuum level measured through a breach valve installed in the vacuum bag.

2.1 Data reduction

The sensor data for the area under the part was extracted and a 20 mm section removed from the edges. The pressure signal was averaged across the part width (Figure 3) to obtain the variation of the average tool pressure ($P_{\text{avg}}$) as a function of the position from the corner ($s$) as shown in Figure 2. In order to compare the tool pressure measured with analytical or numerical solutions, the average tool pressure at the corner ($P_{\text{avg,corner}}$) was computed as follows:

$$P_{\text{avg,corner}} = \frac{\sum_{i=1}^{n} P_{\text{avg},i}}{n}$$

where $P_{\text{avg},i}$ is the average pressure in the corner area and $n$ is the number of points in the corner area defined at a position $-s_{\text{corner}} < s < +s_{\text{corner}}$ (see Figure 2). The average corner pressure computed using Eq. (1) was then normalised with the applied pressure ($P_{\text{applied}}$) obtained from the sensor data measured in the flange area:

$$P_{\text{norm,corner}} = \frac{P_{\text{avg,corner}}}{P_{\text{applied}}}$$

To compare the measured pressure variation to the simulation results along the tool, the measured pressure profile was also normalised with the applied pressure.
3 Results

Examples of steady state pressure distribution measured across the full sensor are presented in Figure 3. Two notable features are present. Firstly, the outline of the rectangular part can be clearly identified by a low pressure region around the perimeter of every part, regardless of the type of tooling (internal or external). This low pressure around the edge is characteristic of bag bridging that creates edge effects in bag moulded composite laminates. Secondly, a pressure gradient can be seen in the centre of the part, representing the corner location. Relative to the flange area, a lower reacted pressure is measured in internal corners, however a higher pressure at the tool-part interface is observed in external corners.

The magnitude of the reacted corner pressure and resulting pressure gradient through the laminate was influenced by both the part thickness and corner radius. Consider the internal mould shown in Figure 3 a) for a 6 mm radius internal tool and a 5 mm thick part, the contour plot shows regions of ambient pressure (14.5 psi or approximately 100 kPa) corresponding to the part flange location. A significantly lower pressure region (0-1 psi or less than 7 kPa) is measured in the corner area of the part. On the other hand, for a 6 mm external tool and a 5 mm thick part shown in Figure 3 b), the corner region is characterised by a transition from a low pressure (less than 7 kPa) to a high pressure in the middle of the corner (8.25 psi or 56 kPa) which is higher than the pressure measured under the part flanges (4 psi or 26 kPa). Similar trends are observed for the thicker 10 mm parts in Figure 3c) and Figure 3d).

Figures 4 to 7 show the distribution of reacted pressure along the internal and external moulds as a function of position. The corner apex was positioned at 0 mm in all moulds and the dashed vertical lines define the corner boundaries.
For the 5 mm thick parts placed on the internal tool (Figure 4), the corner causes a drop in pressure that is inversely proportional with tool radius. For a small tool radius (e.g. 6 mm in Figure 4 a)), the absence of pressure at the corner suggests that the part was bridging in the corner. The results for tool radius greater than 6 mm show a decrease in the pressure drop magnitude with an increasing tool radius in Figures 4 b), c) and d). Similar trends are observed for the 10 mm thick parts shown in Figure 6. Specifically, the pressure drop in the corner reduced as the tool radius increased (i.e. the through-thickness pressure gradient is more consistent through the part as the thickness to radius ratio decreases).

For the 5 mm thick parts placed on external tools (Figure 5), the corner causes an increase in reacted pressure that is again inversely proportional to the tool radius. For example, the smallest tool tested with a radius of 6 mm in Figure 5 a) shows a particularly sharp increase in pressure at the corner. Unlike the internal moulds, the magnitude of the corner pressure increase was not as strongly coupled to tool radius, but was characterised by the presence of pressure oscillations in Figure 5 b), c) and d). Similar trends are observed for the 10 mm thick parts in Figure 7, where a pressure rise is measured in all corners, and again the pressure oscillates in the corner region.

For both the internal and external tools, the contours show a transition zone when moving from the flange to the corner area where the measured pressure moves in the opposite direction to the corner. For example, a slight pressure rise was observed in the transition from the flange to the corner in all the internal moulds (Figure 4 and 6). Along similar lines, a slight pressure drop was observed in the transition from the flange to the corner in all the external moulds (Figure 5 and 7).
3.1 Comparison to analytical model

The experimental measurements were compared to analytical expressions from the literature for the average tool pressure at the corner derived by the force equilibrium [12]. For the case of pressure dominated corner consolidation, the composite layers are free to slip, and the analytical solution of the average corner pressure at the tool interface can be written as a function of the mould radius and nominal part flange thickness. The following expressions are updated for an internal tool:

\[ P_{avg,\text{theory}} = \frac{P_{\text{applied}}(R_m - t_f)}{R_m} \]  

(3)

and an external tool:

\[ P_{avg,\text{theory}} = \frac{P_{\text{applied}}(R_m + t_f)}{R_m} \]  

(4)

where \( R_m \) is the tool radius and \( t_f \) is the flange or part thickness.

Figure 8 presents the variation of the measured normalised average pressure as a function of the tool radius for the internal and external tool. The analytical solution is compared with the experimental data for the part thicknesses studied. Good agreement between the theory and the experiment is observed for the 5 mm thick internal part. For the 10 mm part, the analytical solution does not agree as well with the experimental data in Figure 8 a). The analytical solution predicts a lower normalised pressure for the internal tool compared to the measured pressure. For the external tool, the analytical solution predicts much higher normalised pressure, particularly for the 10 mm thick part in Figure 8 b). While the analytical model and experimental data agree with the reacted corner pressure trends, disparity between the simulated and measured pressure remains for the thicker parts tested in this study.
3.2 Finite element analysis

To investigate any effects of friction on the reacted corner pressure, a 2D plane strain model of the part-tool (i.e. silicone-tool) assembly was built in Abaqus. Figure 9 shows the typical model setup for the internal and external tool configurations. The parts were modelled with four-node plane strain elements (CPE4R). The tool was modelled as a rigid 2D analytical surface and the silicone sample as an elastic isotropic material (E = 3 MPa and ν = 0.49). Symmetry displacement conditions were applied at the part symmetry plane, fixed conditions were applied at the tool reference point. The vacuum pressure (0.1 MPa) was applied at the part top surface in contact with the vacuum bag. Two part-tool interaction conditions were simulated: a smooth part-tool interface was modelled as a frictionless interface and a rough surface was modelled by blocking tangential displacements at the tool-part interface. For both conditions, a hard contact interface condition was used where no penetration of the part and the tool was allowed with no transfer of tensile stress across the interface.

Figure 10 presents the results for the normalised average corner pressure from the FEA simulations compared to the experimental data. The smooth tool-part boundary condition FEA simulation is not in good agreement with the experimental data. This trend was also observed with the analytical solution (Figure 8). When rough boundary condition was applied to the FEA model, the predicted pressure profiles matched more closely the sensor data particularly for the external tool configuration.

Figures 11 and 12 present the normalised tool pressure profiles predicted by the FEA simulations with the measured data. In Figure 11, the pressure profiles are significantly affected by the tool-part boundary condition. For the 10 mm part on a 12 mm radius internal tool, the smooth interface solution matches well the experimental data (Figure 11 a)). With an increase in tool
radius, the rough interface solution is in better agreement compared to the smooth interface (Figure 11 b) and c)). For the 10 mm thick part on an external tool (Figure 12), the rough interface simulations match more closely the experimental data compared to the smooth interface. The FEA model could not capture the measured oscillations in the pressure profile from the sensor data, which was caused by wrinkles in the sensor, as discussed in the next section.

3.3 Discussion

Figure 13 presents the percentage error for the normalised average corner pressure between the sensor data and both the analytical and finite element solutions. In general, the error is larger for the internal tool and increases with the part thickness to tool radius ratio ($t_f/R_m$). For internal tools, the limiting case is defined by $t_f/R_m = 1$, as parts with a thickness greater than the tool radius cannot conform to the tool. When $t_f/R_m > 1$, the internal part corner is less than 0. For external tools, the limiting case is when the tool radius approaches 0 which would result in $t_f/R_m = \infty$.

The increased discrepancy between the experimental measurements could be caused by several factors. First, the effect of friction at the tool-part interface significantly affects the pressure profile at the tool surface. The analytical solution and the finite element simulations with smooth interface neglect friction. When friction is considered in the finite element simulation with a rough interface, the error is lower particularly for the external tool (Figure 13 b)). As the interface between the tool, the sensor and the part have some friction, the measured sensor data is probably not representative of an ideal zero friction case. Thus, the experimental result probably falls between a smooth (zero friction) and a rough (infinite friction) condition. In the paper by Levy and Hubert [12], the corner thickness deviation was modelled by considering the effect of
pressure and friction independently. The coupling between the two mechanisms was done by using a rule of mixtures that was calibrated from experiments were corner thickness deviations were measured for a wide range of part thickness and tooling radii. The sensor data from this work indicates that the effect of friction needs to be considered in the derivation of the expression for the pressure at the corner. Nevertheless, the analytical solution and the finite element analysis follow the same trend as the sensor data, which means that the expressions derived in literature do capture the effect of tool radius and shape on the corner pressure.

The second factor that can cause discrepancy is the effect caused by the presence of the sensor itself at the interface. The X-Sensor has a non-negligible thickness compared to the size of the parts and is embedded in a fabric. Even though care was taken during the experiments to apply a small amount of tension to the sensor with the aim of creating a uniform contacting surface between the sensor and the mould tool, Figure 14 shows wrinkles in the sensor itself when the vacuum bag was applied. This explains the oscillations in the pressure profile observed for the silicone sheets formed to the external tools (Figures 5 and 7). Sensor or bag bridging could also disrupt the pressure sensor signal and was observed for the internal tool at small tool radius (Figure 4 a) when the sensor thickness would have the most significant impact on the experimental measurement. Alternative or new sensing technologies that do not wrinkle or bridge (i.e. where the sensor is in intimate contact with the tool face) are needed to overcome the above drawbacks.

4 Conclusion

In this paper, an attempt was made to measure the pressure profile at the surface of a model prepreg material formed onto internal and external corner tooling using a pressure measuring mat. Even though the experimental approach used some simplifications, primarily substituting an
elastic silicone sheet for an uncured viscoelastic laminate, overall, the sensor data captured the trends expected from the theory for the first time. Specifically, the sensor showed to what extent internal tooling causes a reduction in consolidation pressure at the corner and reported how external tooling increases the corner pressure gradient. Also, the data quantified how larger tool radius tends to decrease the pressure change from the nominal flat consolidation pressure.

The XSensor that was used in this study was a useful tool to measure interface pressure for representative composite parts, however, the physical interaction between the sensor and the specimen can cause errors in the measured pressure. The measured data was compared to analytical solutions and finite element analysis, which highlighted the importance of friction on the corner pressure. Friction was observed to decrease the pressure intensification or reduction caused by the internal and external tools, respectively. The choice of silicone rubber as a material model for prepreg is not ideal. Prepregs are highly anisotropic and have a wide range of behaviour during the curing process. More sophisticated material models could be designed to more accurately represent prepregs. Future developments could explore alternative sensor technologies to measure the pressure reacted over corners or doubly curved surfaces to help define mould tools and manufacturing practices that can produce composite laminates to the desired thickness.

Data access statement

All underlying data to support the conclusions are provided within this paper.

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### Table 1. Summary of pressure measurement sensors for composite manufacture

<table>
<thead>
<tr>
<th></th>
<th>Recessed transducer</th>
<th>Hypodermic needle</th>
<th>Pressure intensity colour films</th>
<th>Piezo-resistive or -capacitive film</th>
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Figure 1. Free-body diagrams of an L-shape laminates. $R_m$ and $t_f$ represent the mould tool radius and flange thickness, respectively, and $S_{bag}$ and $S_{tool}$ the surface area of the bag side and tool side of the laminate in the corner. An internal corner is shown in (a) and an external corner shown in (b). The green arrows represent the material flow direction.
Figure 2. Sensor raw data and pressure profile extraction procedure. The corner area is defined for \(-S_{\text{corner}} < s < +S_{\text{corner}}\).
Figure 3. Steady state X-sensor pressure contours for a) 5 mm part, 6 mm internal tool, b) 5 mm part, 6 mm external tool, c) 10 mm part, 18 mm internal tool and d) 10 mm part, 18 mm external tool. The contour plot units are directly exported from the software and reported in psi to observe the raw data.
Figure 4. Average pressure profiles for 5 mm silicone parts on an aluminum internal tool. The dashed lines represent the corner boundary. Tool radius: a) 6 mm, b) 12 mm, c) 18 mm, d) 24 mm.
Figure 5. Average pressure profiles for 5 mm silicone parts on an aluminum external tool. The dashed lines represent the corner boundary. Tool radius: a) 6 mm, b) 10 mm, c) 18 mm, d) 24 mm.
Figure 6. Average pressure profiles for 10 mm silicone parts on an aluminum internal tool.

The dashed lines represent the corner boundary. Tool radius: a) 12 mm, b) 18 mm, c) 24 mm.
Figure 7. Average pressure profiles for 10 mm silicone parts on an aluminum external tool.

The dashed lines represent the corner boundary. Tool radius: a) 10 mm, b) 18 mm, c) 24 mm.
Figure 8. Comparison for normalised average corner pressure between analytical solution and measured data, a) internal tool, b) external tool.
Figure 9. Finite element model definition for internal a) and external b) tools. Sliding displacement conditions are imposed at the part symmetry plane. The arrows represent the applied pressure ($P_{\text{applied}}$). The tool is modelled as a rigid 2D analytical surface with fixed displacement boundary condition.
Figure 10. Comparison for normalised average corner pressure between FEA solution and measured data, a) internal tool, b) external tool.
Figure 11. Normalised tool pressure profile for the X-sensor and FEA analysis for 10 mm thick silicone sample on a internal tool. The solid and dotted lines correspond to FEA with smooth and rough tool boundary condition respectively. Corner boundary defined by the dashed line. Tool radius: a) 12 mm, b) 18 mm, c) 24 mm.
Figure 12. Normalised tool pressure profile for the X-sensor and FEA analysis for 10 mm thick silicone sample on an external tool. The solid and dotted lines correspond to FEA with smooth and rough tool boundary condition respectively. Corner boundary defined by the dashed line. Tool radius: a) 12 mm, b) 18 mm, c) 24 mm.
Figure 13. Percentage error for the normalised average corner pressure between analytical solution and measured data for: a) internal tool and b) external tool.
Figure 14. Wrinkles in sensors material in external corners: a) excess length causes wrinkles when vacuum bag is applied, b) pressure map with artefacts that were particularly strong along the dashed line, and c) oscillating pressure response along the line of interest.