Development of structural overmoulding for thermoplastic composites

Baril-Gosselin, Simon*
Automotive and Surface Transportation Research Centre
National Research Council Canada, Boucherville, Canada
* Corresponding author (Simon.Baril-Gosselin@nrc-cnrc.gc.ca)

Keywords: *Thermoplastic Composites, Overmoulding, Mechanical Testing*

1 ABSTRACT

The work investigates the use of injection overmoulding to produce structural thermoplastic composite components that feature a geometry representative of an automotive part. The hybrid component is composed of a glass fibre/polypropylene composite insert that is overmoulded with a polypropylene polymer that is loaded with long glass fibres. The investigation focuses on understanding the effects that composite preheating, polymer reinforcing and composite distribution have on the specific strength and rigidity of hybrid components. Results show that significant inter-diffusion between the materials is essential for the viability of components and that the use of composites should be limited to load-critical areas only. The work also highlights processing challenges when overmoulding on composite inserts.

2 INTRODUCTION

Injection overmoulding is a process in which a polymer is injected around an insert (i.e. substrate) to create a hybrid component. Recently, this technology has sparked great interest in the world of thermoplastic composite manufacturing because it allows the addition of features such as structural ribs, attachment points and complex 3D geometries. It can also be exploited for reducing manufacturing costs by producing highly integrated net-shape composite components specifically designed for replacing complex assemblies. Even though several demonstrator parts have been produced by the industry [1-3], the development and sharing of scientific knowledge for the process of overmoulding on composites are still in their infancy [4-6].

This work presents an assessment of the injection overmoulding process with thermoplastic composite inserts for the automotive industry. The development was performed on a generic component designed in-house featuring a composite insert and overmoulded ribs that improve buckling resistance (Figure 1). The component was subjected to a series of mechanical tests, including full-scale testing in compression and bending, to understand how the manufacturing process and part design influence the mechanical performance of overmoulded composites. More specifically, the work studied the effects of the adhesion between the ribs and composite insert, the reinforcement of the overmoulded polymer and the distribution of composite inserts within components. All results are presented in terms of specific proprieties (i.e. weight-based) because the volume of the component is imposed by the geometry of the injection mould cavity and because the work focused on automotive lightweighting.

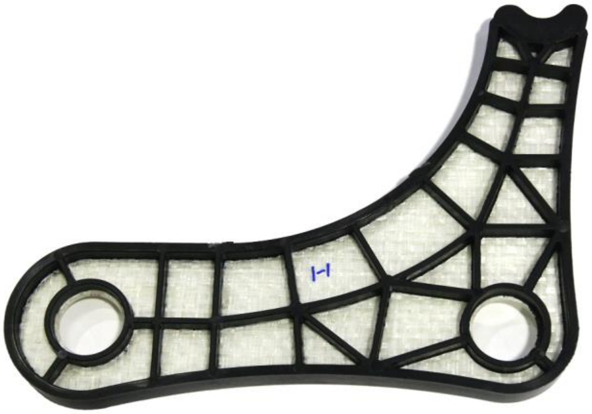


Figure 1. Stamp-formed thermoplastic composite (white) overmoulded with structural ribs (black)

3 METHODOLOGY

3.1 Component

Development for the injection overmoulding process with thermoplastic composite inserts was performed using a generic component geometry inspired by a lower control arm for passenger vehicles. The component has an L-shape skin with holes for attachment points and features a network of ribs, on one side only, to stiffen the structure. In this work, the skin was reinforced in part or totally by a continuous fibre thermoplastic composite insert (Figure 2). Three levels of reinforcements were compared: 1) full-skin reinforcement, 2) localised skin reinforcement and 3) no reinforcement.

A glass fibre reinforced polypropylene composite was used for the inserts. For the cases of full-skin reinforcement, the composite featured a plain woven architecture with an orthogonal lay-up. Conversely, for the cases of localised reinforcement, the composite was made with unidirectional tape with all fibres oriented in the longitudinal direction.

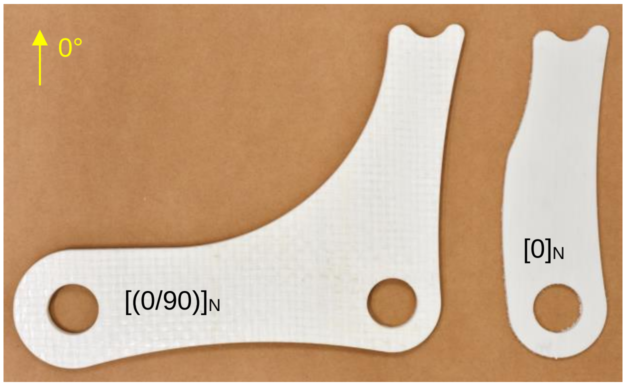


Figure 2. Thermoplastic composite inserts and lay-ups: full-skin (left) and localised skin (right) inserts

The ribs and unreinforced regions of the skin were filled with a polypropylene loaded with long glass fibres (~12 mm in length). The fibre loading was varied from 0 wt% to 60 wt%. A similar polymer to that of the composite matrix was selected to increase compatibility and adhesion between the composite insert and overmoulding. The addition of long fibres strengthened the polymer and reduced warpage.

3.2 Fabrication

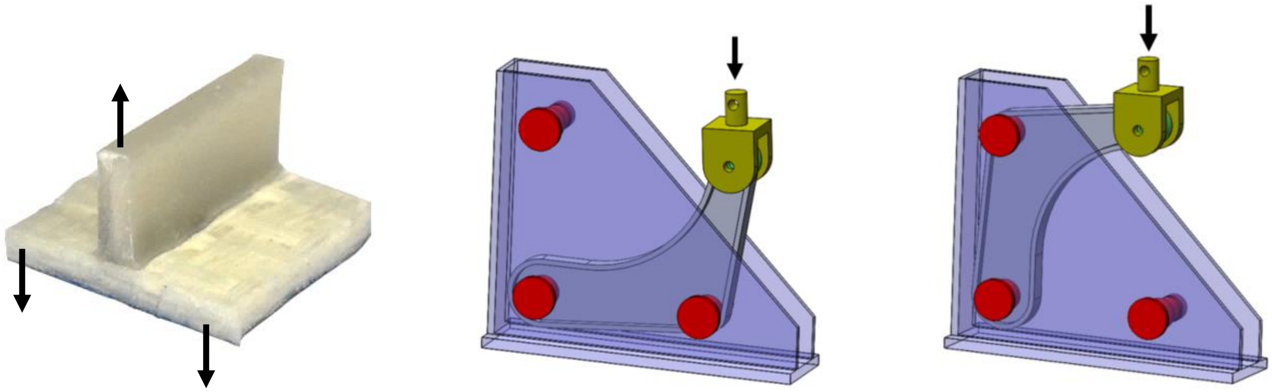
Components were manufactured in 3 steps: 1) composite insert fabrication, 2) preheating of inserts and 3) injection overmoulding.

Continuous fibre thermoplastic composite panels were first consolidated by compression moulding. Inserts were then extracted from the panels and trimmed to their final geometry. Prior to injection overmoulding, the inserts were heated in an infrared oven until they reached their desired temperature. Afterwards, inserts were transferred to the injection mould and press (Engel 150 t), and their surface temperature was measured using a laser thermometer. Finally, the mould was closed and molten polymer was injected in the cavity, creating the net-shape component. The polymer melt and mould temperatures were 240 °C and 80 °C, respectively. On average, the entire moulding cycle lasted less than 90 s.

3.3 Testing

Two types of mechanical tests were performed: 1) rib-to-composite skin adhesion and 2) structural testing on full-size components.

Adhesive strength of the overmoulding was characterised by pull-out tests. T-shape specimens (20 mm × 20 mm) composed of a composite skin and polymer rib were extracted from the moulded components and pulled until failure using a universal testing machine (Instron 5582) (Figure 3). Loads were measured using a 25 kN load cell. The loading rate was 1 mm/min and 5 specimens were tested per condition.



T-shape specimen for pull-out tests Compression of component Bending of component

Figure 3. Configurations for adhesion tests and structural components testing

Structural testing on full-size components was based on representative loading scenarios for a lower control arm. Components were tested until failure on a universal testing machine (Instron 5582) in compression to assess the buckling resistance and in bending. Loads were measured using a 100 kN load cell. Depictions of the test configurations appear in Figure 3. The loading rate was 5 mm/min and 3 components were tested per condition.

The mechanical performance of the components is presented in terms of specific properties (i.e. properties divided by the mass) because the total mass of components changes based on the distribution of composite inserts and fibre loading.

3.4 List of experiments

Three series of experiments (Table 1) were devised to assess the effects of the composite insert temperature, fibre loading of the injected polymer and distribution of the insert within the component.

Table 1. Description of the three series of experiments

Series	Type	Specimen	Investigated parameters
Insert temperature	Pull-test	T-shape specimens	Insert temperature (25° to 210 °C)
	Compression	Component (full insert)	Insert temperature (25° and 175 °C)
Fibre loading	Compression and bending	Component (full inserts at 175 °C)	Glass fibre loading (0 wt% to 60 wt%)
Distribution of inserts	Compression and bending	Component (inserts at 175 °C)	Insert distribution (no insert, full skin, localised insert)

4 RESULTS AND DISCUSSION

4.1 Effect of insert temperature

Results for the pull-out strength of T-shape specimens appears in Figure 4. In the range tested, adhesion improved greatly with increasing insert temperature. The pull-out strength was maximised when the insert was fully melted, at which point it was seven times higher than when using unheated inserts.

The change in mechanical performance was also observed through the fractured surfaces. Unheated inserts led to a fragile bond between the ribs and composite skin. Fracture resulted from an adhesive failure where very few artefacts remained on the separated materials. Conversely, as the insert temperature increased, greater inter-diffusion occurred between the polypropylene chains of the overmoulded polymer and composite matrix. Preheating the composite insert near or above its melting point resulted in a welded interface and cohesive failure. Fracture occurred within the composite, mostly through delamination between the fibres and the matrix. Pulled-out fibres could even be seen on the separated rib.

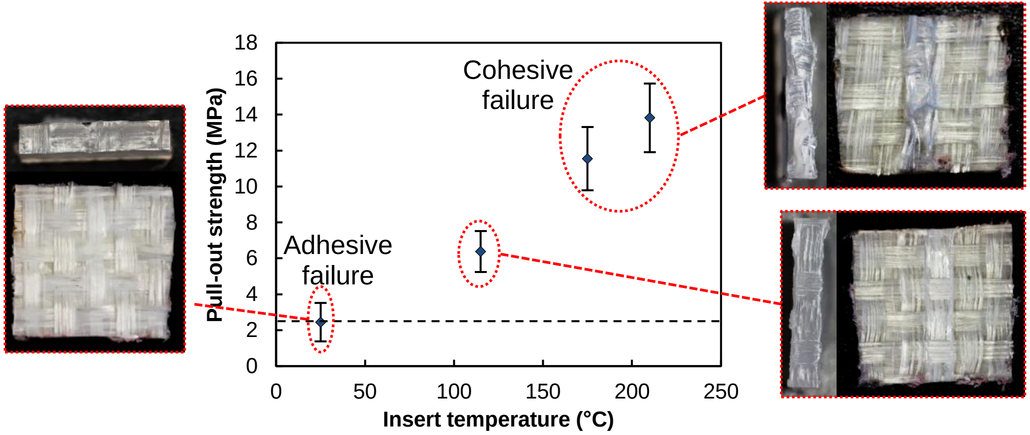


Figure 4. Pull-out strength and fractured surfaces of T-shape specimens

The effect that the interfacial strength between the composite and overmoulded ribs has on the performance of full-size components was investigated through compression tests. Specific strength and rigidity were compared for cases where the inserts were unheated and preheated at 175 °C (Figure 5). Heating the inserts increased strength and rigidity by 50 % and 35 %, respectively, and reduced variability significantly. The improved adhesion prevented the ribs from separating from the composite skin, which delayed buckling of the component.

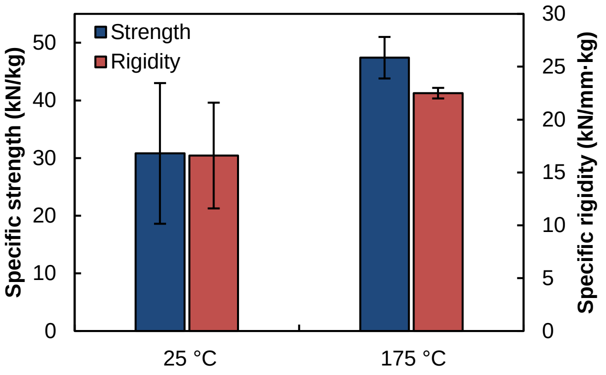


Figure 5. Specific compression strength and rigidity based on composite insert preheating temperature for components featuring a glass fibre content of 40 wt% within the overmoulded polymer

Despite the improved performance, preheating can affect the architecture of a composite insert, which can presumably influence the mechanical behaviour. Near or above its melting point, the composite insert expands (i.e. springs back from deconsolidation) and becomes highly flexible, making it prone to deformations caused by the overmoulding process (Figure 6). For example, the composite insert can flow and migrate into openings (e.g. ribs) when compressed during mould closure. Deformations can also be caused by the highly viscous injected polymer, which strikes the insert at a high velocity. Hence, the design of overmoulded components must optimise the amount of insert preheating to ensure a minimum level of adhesion while ensuring that the harsh injection process does not affect the structure of the composite reinforcement.

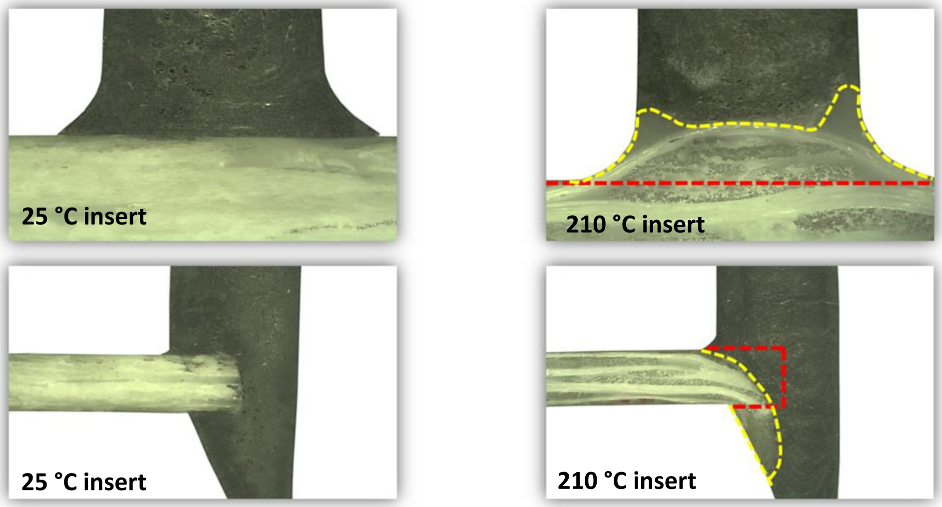


Figure 6. Cross-sections of components showing the composite skin insert (light colour) and overmoulded polymer (dark colour) for different insert preheating temperatures, where the dotted red and yellow lines represent the original and distorted insert locations, respectively.

4.2 Effect of fibre loading

Full-size components were tested in compression and bending. The effect that the glass fibre loading has on the mechanical performance, both in terms of specific strength and rigidity, appears in Figure 7. In bending, the specific rigidity increased nearly linearly with the fibre content while the specific strength plateaued at a fibre loading of 40 wt%. Hence, at higher fibre loadings, the increased strength provided by the fibres was counterbalanced by the increased weight resulting from the high fibre density. In compression, the specific rigidity plateaued at a loading of 20 wt%. However, the specific strength peaked at a loading of 30 wt% before decreasing. From this, it is clear that any improvement in strength from adding glass fibres was overshadowed by the added weight.

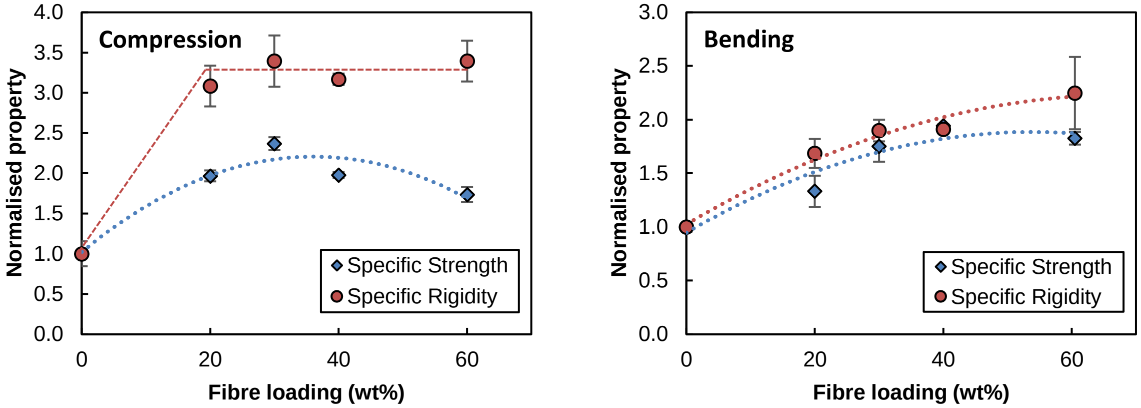


Figure 7. Normalised specific strength and rigidity values in compression (left) and bending (right) of components featuring different levels of fibre loading

The reason behind the drop or lack of improvement in strength despite using higher fibre loadings relates to processing difficulties. Above a fibre loading of 30 wt%, the polymer/fibre compound becomes highly viscous and phase separation can occur. This results in the creation of voids within the injected component (Figure 8). Voids are mostly localised in the core (i.e. middle) of the component and ribs, where the shear stresses are lower during injection and where fibre alignment is minimal (i.e. where the fibres are all entangled). The negative effect of high fibre loadings was mostly observed when testing in compression because the entire part and ribs were stressed, whereas bending was less affected because stresses were greatest on the exterior surfaces of the component where there are fewer voids.

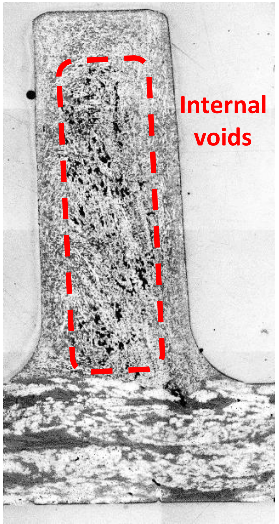


Figure 8. Micrograph of a rib cross-section with a 60 wt% fibre loading that features internal voids in its core

Considering that the best fibre content was approximately 30 wt% in compression and 40 wt% in bending, it is clear that optimisation of the fibre loading for the overmoulded polymer is complex and needs to take into account the geometry of components and force distribution within them.

4.3 Effect of the distribution of composite inserts

Full-size components were tested in compression and bending to observe the effect that composite inserts have on the mechanical behaviour of injected parts. Results for cases without inserts, with a full-skin insert and with a partial insert appear in Figure 9.

In compression, the use of any type of composite insert reduced the specific strength. The reduction was less important for the partial insert because it adds less weight to components compared to the full-skin. The use of a full-skin insert improved rigidity but the benefits were counterbalanced by the added weight, resulting in a net-zero gain in performance. However, the use of the partial insert improved specific rigidity by 60 % due to its reduced weight compared to a full-size insert and its highly oriented fibres. Hence, tailored inserts can be beneficial for quasi-static loading.

In bending, the use of composite inserts decreased the specific strength and did not provide any benefits to the specific rigidity. The main reason being that the inserts were never located in the regions that were stressed the most by the bending experiment. For this bending case, forces were distributed mostly in the contour ribs. Hence, for that loading scenario, the tested composite inserts only added non-useful mass to the components.

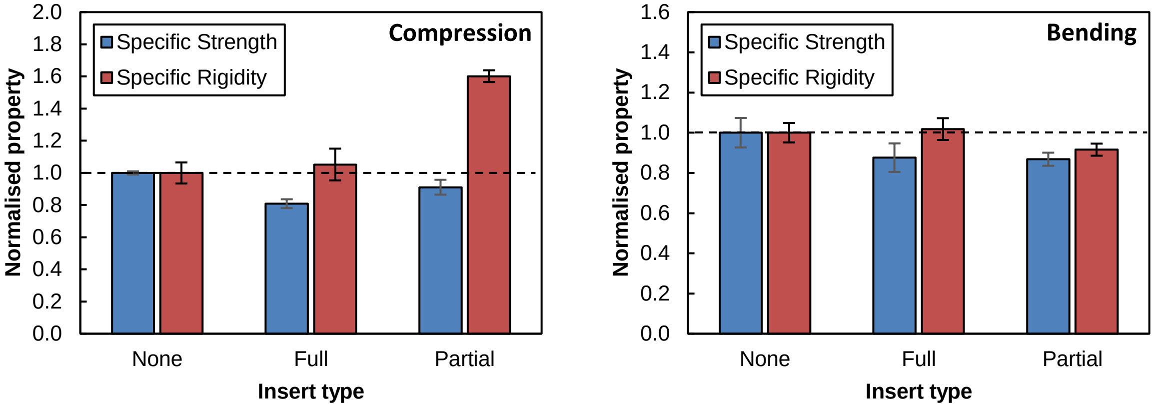


Figure 9. Normalised specific strength and rigidity values in compression (left) and bending (right) of components featuring different types of composite inserts

In this work, even if the partial composite insert was designed to improve the performance in compression, no improvements in specific strength could be achieved. This outcome can be explained in part by the type of loading scenario and internal structure of components. First of all, it is important to note that in these compression experiments, all material cross-sections were stressed, which includes the skin, the ribs and their interface. Even though the interface can be strengthened by heating the composite insert prior to overmoulding, it nevertheless remains the weakest link. This can be explained by looking at the internal structure of the components (Figure 10). In overmoulded components, the injected polymer flows only in the ribs, and the fibres that are outside of the core align themselves parallel to the composite inserts. No fibre crosses into the insert to strengthen the interface. Conversely, in components that do not feature any insert, the injected polymer flows within the skin and crosses into the ribs, strengthening the transition. Hence, when designing an overmoulded component it is critical to understand how the placement of inserts will affect the flow of the injected polymer, and to ensure that weaknesses (e.g. off-axis reinforcements or weld lines) are not located in highly stressed areas.

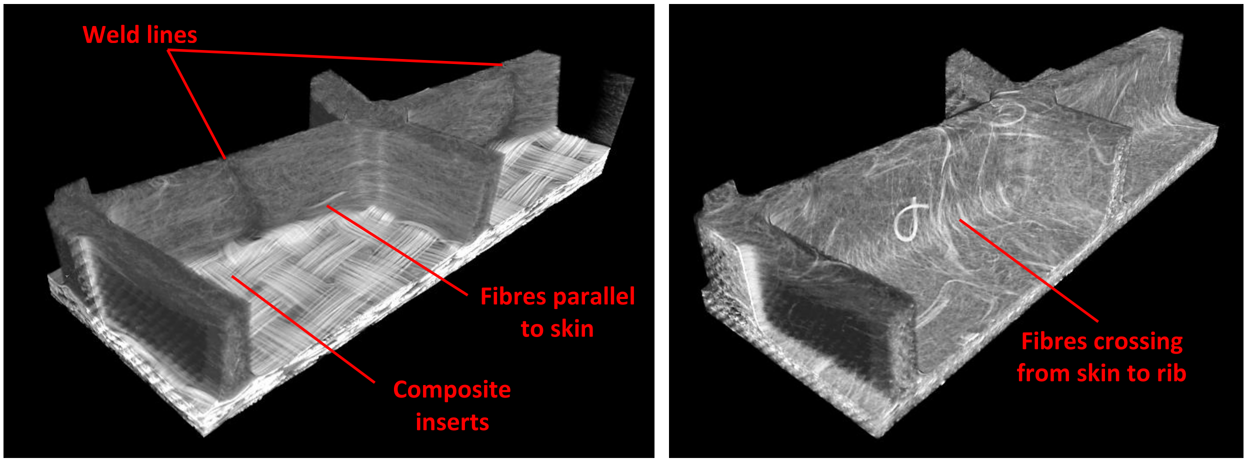


Figure 10. X-ray micro-tomography of a region of the components showing fibre distribution with and without composite inserts

5 CONCLUSION

In this work, overmoulded thermoplastic composite components were produced through stamping and injection moulding. Parts were produced successfully with a cycle time of less than 90 s. Different tests were conducted to investigate challenges of producing structural components made from this manufacturing process. Major findings were:

- Good adhesion between the composite insert and overmoulded polymer is critical for maximising the mechanical strength of components, because poor adhesion leads to material separation and early buckling.

- Preheating of the composite insert is required to achieve a decent amount of inter-diffusion and adhesion between the composite and overmoulded polymer. However, too much heating can also distort the composite insert and make it vulnerable to the impinging polymer during injection.

- Reinforcing the overmoulded polymer is essential to reduce warpage and strengthen components. There is an optimum fibre loading to minimise weight, and maximise strength and rigidity of components. The fibre loading depends highly on the part geometry and stress distribution.

- Smart distribution and tailored design of composite inserts are key to maximise the performance of overmoulded composites. One of the challenges is that fibres are denser and often more expensive than the polymer. Hence, the use of composites in non-load critical areas results in unnecessary weight and cost increases for components.

6 REFERENCES

[1] Lilli Manolis Sherman. “The new lightweights: Injection molded ‘hybrid’ composite spur auto innovation”, Plastics Technology, 11/2/2012.
[2] Ginger Gardiner. “Injection-forming for high performance, unitized thermoplastic structures”, Composites World, 7/30/2019.
[3] Ginger Gardiner, “Skeleton design enables more competitive composite autostructure”, Composites World, 4/8/2019.
[4] Remko Akkerman, Mark Bouwan and Sebastiaan Wijskamp. “Analysis of the thermoplastic composite overmolding process: interface strength”, Frontiers in Materials, Vol 7, Article 27, 2020, doi: 10.3389/fmats.2020.00027
[5] Björn Beck, H. tawfik, J. Haas, Y-B Park and F. Henning. ”Automated 3D skeleton winding process for continuous-fiber-reinforcements in structural thermoplastic components“, *Advances in polymer processing 2020, Proceedings of the International Symposium on Plastics Technology*, Aachen, Germany, pp 150-161, March 2020
[6] Jacek Andrzejewki and Marek Szostak. “Preparation of hybrid poly(lactic acid)/flax composites by the insert overmolding process: Evalution of mechanical performance and thermomechanical properties” Journal of applied polymer science, 2021, https://doi.org/10.1002/app.49646