The new hybrid technology: thermoplastic composite injection overmolding

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ABSTRACT

Advanced materials such as exotic metals and fiber reinforced thermoset composite components have become well known within the automotive, energy, defense, space, and aerospace industries over the past several decades. However, continued advancement of traditional materials within these and other industries is highly dependent on design flexibility, strength to weight, quality, environmental impact, and total cost of ownership (TCO). Recently, numerous requirements have emerged relative to environmental footprint and cost competitiveness, which are driving the need for new material technologies and advanced manufacturing techniques.

Hybrid components made by Thermoplastic Composite Injection Overmolding (TPC-IOM) benefit from high strength and stiffness of thermoplastic composites while taking advantage of high design flexibility and cost effectiveness of injection molding, resulting in best-in-class TCO. An important element consists in the right choice of polymers regarding cost versus performance for both the composite and the overmolded parts. The advantages of TPC-IOM over traditional material and component manufacturing technologies will allow continued growth of thermoplastic composite components and expansion into broader industrial applications.

1. INTRODUCTION

This paper will focus on the design, simulation, and manufacturing of a TPC-IOM demonstrator part made with multiple material combinations, applicable to structural applications using high-performance thermoplastic composites and compounds. We will discuss in some detail the design process, simulation, and manufacturing techniques as well as testing of the demonstrator. The demonstrator shows the key benefits of the technology such as injection mold stamp forming, injection overmolding of complex features and edge sealing (net shaped part), simultaneously performed in a single molding operation. We will also highlighted some of the key challenges in the development of structural TPC-IOM and processing of high-performance materials. This paper will also acknowledge TCO of TPC-IOM versus current material technologies, future possibilities to streamline manufacturing processes and demonstrate several of the wide variety of high-performance material options that are available with TPC-IOM.

1.1 Total Cost of Ownership (TCO)

Integrating the TCO concept into the development of parts is gaining more and more traction. Besides meeting the technical requirements, newly designed components must contribute to the financial viability of products across multiple industries. The focus is shifting from the pure cost of a part or an assembly towards the financial impact over the lifetime of the component. The total
cost includes the respective costs of the design, raw materials, production, assembly into a larger device, operation, maintenance, and waste disposal or recycling.

An accurate analysis depends first and foremost on the component itself and the functionalities it must ensure. In the context of this paper, we can only share the fundamental concept of how TCO applies and provide qualitative indications of how it applies to hybrid components. In most cases, several, if not all, of the presented elements come into force at the same time.

The considerations of TCO are made in comparison with a component made from metal. Given the intrinsic benefits the presented hybrid technology is most suitable for applications requiring high mechanical performance and geometric complexity. Today, typically only metal offers such a combination of properties or characteristics. Thus, the reference are parts from titanium, steel, aluminum, or specialty alloys.

The first and often most easy to assess element for the TCO analysis is the purchase price for the component. In most cases the TPC-IOM hybrid part can appear to be more expensive than the metal version – unless the latter is produced from a rare and expensive alloy and / or has high levels of complexity driving the need for multiple secondary operations. The processing of hybrid parts is highly automated and cost efficient, larger volumes lead to the allocation of the non-recurring investment costs for tooling, material handling and process automation to a greater number of parts. The economies of scale for these processes are rather significant, which is less so the case for components made from metal.

The presented hybrid technology enables designing of parts that include sophisticated 3D sections - which are typical for pure injection molded products. It thus permits the integration of additional functionalities into the part; beyond the mechanical requirements it must fulfil. These functionalities can be the fastening to a larger structure, integrated metal fasteners, grommeted through holes for cables, edge sealing and many other requirements. Thus, the total number of parts for a device or larger structure can be reduced with corresponding cost savings. At the same time, in combining several parts or functions into one component the assembly of the overall device increases in value and becomes less costly. Similarly, and as described earlier, the hybrid technology provides new degrees of freedom to designers: 2D parts whose fastening has been too complex for a composite and hence were made in metal, can now be developed in TPC-IOM, at a lower overall cost.

The most important saving stems from weight reduction. A part that can now be produced from thermoplastic materials and that has been metallic before, will be lighter by a factor of 1.5 - 2.5 based on previous metal to plastics experience from the authors. While weight saving is fundamental in almost all transportation applications, it is very critical in electric vehicles (EV) and of utmost importance in Aerospace and Space. Every kilogram saved in aircraft programs leads to savings and increase value through the full product lifecycle for each stakeholder.

This element of TCO alone provides a large margin to use TPC-IOM widely. On the same token, applying the technology to a larger number of components will contribute to increasing the range of the aircraft or EV – providing a gain in performance.
Furthermore, polymers have many inherent properties which metals do not have such as corrosion resistance, excellent dielectric properties, thermal insulation, low coefficient of friction and wear resistance. All these characteristics may help to further reduce cost associated with a device made with the presented technology and materials.

Overall, the TPC-IOM technology provides significant opportunities for cost savings. These become most evident when considering the total cost of ownership over the whole lifetime of a part or device. Besides the possibility to design components for vehicles or other in a different, often more elegant way, the hybrid technology brings strong economic benefits.

2. EXPERIMENTATION

2.1 Demonstrator design

For the initial phase of the study a generic omega shaped demonstrator geometry of 75mm x 25mm x 15mm was selected. The design of our demonstrator considers several elements that demonstrate the advantages of TPC-IOM such as edge sealing (net shaped part), in mold forming of the thermoplastic composite and injection molding a complex rib structure. (See CAD image Figure 1) Additionally, the part intentionally contains a number of real-life challenges such as varying cross sectional rib thickness’ with injection from the thin towards the thick rib section and areas of lower density in the molding, relatively long flow length with areas of “backfilling” of the ribs, tight radius compound bends in the thermoplastic composite and the combination of stamp forming and injection molding in a single process step. The design also allows for non-destructive testing and mechanical property testing of various areas within the part to determine the amount of adhesion between the TPC and IOM.

Figure 1. CAD image of demonstrator part design showing orientation of TPC and IOM

The TPC insert was designed to be suspended into a pair of infrared heaters using a flat spring clamp on one of the narrow edges and then loaded by robot (or manually) into the injection mold tooling. The two holes in the TPC insert are for retention of the part within the injection mold.
2.2 Material selection

The material chosen for the first demonstrator is Solvay’s APC-PEKK FC tape [ref 1] consolidated into 1.66 mm panels. Stacking was accomplished in 3 different ply configurations (0/90)3S, (90/0)3S and quasi-isotropic. Based on an initial focus on one-step TPC stamping and injection-overmolding, Solvay’s Ketaspire® KT880 CF30 PEEK with 30% short carbon fiber [ref 2] was selected as injection molding compound. Key considerations for this combination of materials are melt compatibility (polyetherketone family), melt temperature and crystallization temperature for the two materials (See table 1). The higher melting temperature of the PEEK IOM compound compared to the PEKK composite aims at improved melt adhesion with the PEKK TPC by enabling increased surface of the composite to remelt and create interface healing when the compound is injected over the TPC insert.

Table 1. Melt temperature and glass transition temperature of PEKK TPC and PEEK IOM

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<th>APC PEKK-FC</th>
<th>KT-880 PEEK</th>
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<tbody>
<tr>
<td>Tm (°C)</td>
<td>337°C</td>
<td>343°C</td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>159°C</td>
<td>147°C</td>
</tr>
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</table>

Other material combinations, specifically higher temperature Ketaspire® PEEK compounds, are being considered for our demonstration process to expand towards two-step IOM process, which allows a separate stamping of the TPC insert with limited preheating prior to overmolding. Furthermore, the demonstrator is designed to investigate low-viscosity polymer combinations, such as Solvay’s Ryton® PPS compound and thermoplastic composite tape laminates.

2.3 Manufacturing simulation

An injection molding simulation was performed using Autodesk Moldflow® to check the overmolding for possible defects. Early in the process, this helped troubleshoot knitline and air trap locations, as well as verify the part could be filled successfully. (See figure 2) Later, it was used again to help dial in the final process settings and verify the gate freeze time in order to dial in the packing time.
Figure 2. Moldflow® simulation predicts filling and packing based on PEEK viscosity and shear.

For the overmolding polymer, material properties for Ketaspir® KT-880 CF30 were already generated for Moldflow®, which accounts for the relationship between viscosity & shear rate as the material flows through the cavity. It is also possible to perform a draping simulation using Aniform to verify the composite would not kink or sag during the forming operation.

Another powerful component of Autodesk Moldflow® is that it is able to map the orthotropic fiber orientation of the composite to the final curved shape. When combined with the already existing fiber alignment predictions for the overmold, we are able to get a better prediction of the final part shape after molding. Using these tools, we are able to predict the warpage of both components as they cool and solidify. (See figure 3)

Figure 3. MoldFlow® can predict the orientation of fibers in the overmolded component.

2.4 Lamination and stamping-overmolding process

Initially, APC PEKK thermoplastic composite tape is stacked to laminates by thermal spot welding and consolidated into 500mm X 300mm X 1.66mm panels using a contained steel compression tool and oil-heated press in a thermal compression molding cycle. Three different ply stacking
configurations have been selected including, biaxial (0/90)3S, (90/0)3S and quasi-isotropic (0/+45/90/-45/0/90) s. The different ply orientations were chosen to investigate the influence of fiber orientation of the laminate surface ply on the interface performance and the potential deformation mechanisms of the laminate due to different substrate layers when stamped into the cavity with injection channels.

The laminate coupon dimensions 83.8 mm x 30 mm were cut using a 3 axis CNC mill with diamond machine tooling configured geometry for machining composites. The flat coupon geometry was derived from flatting using an inverse stamping simulation to account for local deformation mechanisms.

Prior to actual stamping and overmolding, all blanks have been dried in an oven for at least 12h at 125°C [ref 3] to minimize potential deconsolidation during subsequent infrared preheating.

For stamping, the coupons have been heated beyond melting point using a double sided short wave IR heater system consisting of two 255mm x 255mm infrared panels outfitted with an on/off sensor, PID temperature controller and optical pyrometer on each side to enable closed loop surface temperature control of the coupons (see figure 4). Investigated IR heating variables for the TPC stamping process were IR heater set temperature, dwell time in the IR heater and transfer time between the heater and the IOM process (cool-down) [ref 4]. In general, the IR heating variables were optimized to achieve a laminate draping temperature of 375°C when being formed in the tool cavity. The blank temperature evolution and actual draping temperature was verified by embedding thermocouples into a test blank including sensors under first ply and in the center of the TPC ply stack as highlighted by the red lines in Figure 5. The thermocouple allowed verification of thermal ramp curve, peak temperature in the core at the top, center and bottom of the TPC and cooling curves to help verify actual draping temperature. (See figure 6)

Figure 4. Photo of infrared heater and PID control system use in this experiment.
Figure 5. Test blank with embedded thermocouples

Figure 6. Temperature uniformity survey.
As the investigation focused initially on one-step stamping and overmolding, the parts were transferred from the IR heating system directly to the injection molding tool, which was equipped with two locating pins for retention of the blank without initial tool contact and stamping of the flat blank into the final part geometry during rapid tool closure. Injection mold was machined from standard P20 with a single cavity mold base with cold sprue, runner and edge gate. (see figure 7) The injection mold tooling cavity depth was sized to the volumetric shrink rate of the PEEK IOM compound such that the TPC and the IOM elements would create a flush and continuous surface on the final part. IOM was accomplished on a 65 ton horizontal Nissei hybrid electric injection molding machine which is outfitted with a 3 axis robot which will enable transfer of the TPC blank from the IR heater into the injection mold.

Figure 7. Injection mold for TPC – IOM Demonstrator.

2.5 Quality analysis and testing [ref 5].

Prior to coupon extraction and stamping, all consolidated tape laminates have been C-scanned and thickness mapped to confirm pristine laminate quality. For all panels, a porosity level < 0.2% and initial laminate thickness of 1.66 +/- 1% was confirmed.

After stamping and injection-molding, a selection of parts has been scanned using a XRIS robotized Xray system capable of performing 3D computerized tomography with a voxel size of 21µm. The system was used to determine potential porosity in both injected ribs and the composite reinforcement, as well as evaluation of the interface integrity under ribs and for the edge overmolding. Also, the 3D shape of the stamped and overmolded parts has been measured using a 3D laser scanner, enabling a correlation with the warpage simulation in Moldflow® and determining the influence of shrinkage of both compound and composite insert.
For quantitative determination of the interface strength, a pull-off test is in development for both vertical pull-off and interface shear loading of extracted single rib segments in web and flange areas of the outer straight ribs (see figure 8). By testing the different locations along the rib, the influence of flow-length, flow renewal of the compound during the injection process and the interface healing will be determined.

![Diagram of tensile pull and three point bending specimen extraction](image)

Figure 8. Tensile pull and three point bending specimen extracted from final part.

Furthermore, a full-part 3-point bending test is in development to investigate overall part performance including the different injection molded features.

2.6 Stamping and injection-overmolding configurations

Prior to overmolding trials, a series of 21 stamping trials have been executed in the injection molding cavity without compound injection to determine the stamping quality of the laminate (radius formation, consolidation quality, edge behavior) and deconsolidation mechanisms under the unfilled rib geometries. These pre-trials have been focused solely on the biaxial laminate coupons with both 0° and 90° ply orientation at the surface, as the biaxial laminate exhibited higher sensitivity to local deformation into rib cavities. Table 2 summarizes the investigated parameter configurations for stamping:

<table>
<thead>
<tr>
<th>IR heater set temp.</th>
<th>Dwell time</th>
<th>Transfer time</th>
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<tr>
<td>TPC 400 °C</td>
<td>40-70 seconds</td>
<td>fixed</td>
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Table 2. Parameters for TPC IR heating and forming process.
Focus lied on the investigation of local deformation mechanisms, surface appearance and consolidation quality in the compressed laminate areas, as well as deconsolidation mechanisms on the free edge and in the rib areas. Furthermore, the stamping pretrials were used to optimize the blank suspension concept and determine the preform stability.

For initial evaluation of suitable injection overmolding parameters, as well as evaluation of filling pattern and correlation with the filling simulation a series of short shots were produced.

Based on the pretrials, a design of experiment was determined for a series of 42 coupons each using the three laminate configurations with investigation of the following injection molding and stamping parameters (See table 3):

Table 3. Parameters for IOM process

<table>
<thead>
<tr>
<th></th>
<th>Melt temp.</th>
<th>Tool temp.</th>
<th>Packing pressure</th>
<th>Cooling time</th>
</tr>
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<tbody>
<tr>
<td>IOM</td>
<td>370 °C</td>
<td>198 °C</td>
<td>41 MPa</td>
<td>120 seconds</td>
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</table>

3. RESULTS

3.1 Blank stability and Retention Concept
IR heating work holding surface area was increased to reduce local stresses causing deformation of the TPC during IR heating. IOM tool work holding contact surface area was increased by making the TPC retention holes smaller relative to the holding pins in the IOM tooling to improve retention of the TPC in the IOM tooling.

3.2 TPC stamping - Influence of fiber orientation and process parameters. [ref 6]
Once work holding of the TPC blank in the IOM tool was refined the stamping quality of the TPC was quite good. The 90,0 and QI TPC blanks provided the best bending radii quality. While the 0,90 orientation consistently showed fiber pull out on the radii. (See figure 9).
Figure 9. Finished demonstrators (From left to right) Q1, (0/90)S3 and (90/0)S3

Edge micrographs supported the local investigation of laminate deconsolidation mechanisms under the injection ribs, as well as the quantification of radius quality in the omega section and edge deformation mechanisms of the blank after the stamping step alone and after both stamping and overmolding (see figures 10 and 11). Additionally, robotized X-Rays (reference section 2.5) were conducted and revealed good part quality. (See figure 12)

Figure 10. Forming edge effects and rib section after stamping (no overmolding)
3.3 IOM Filling Results

A complete short shot analysis was completed prior to IOM a complete part. This analysis verified the part design challenges discussed in section 2.1 above and the results of the Moldflow® simulation in section 2.3 above. The jetting was eliminated by increasing the gate size and the optimization of the venting of the IOM tool. (See figure 13)

Figure 13. Picture show improvement in “jetting” condition.
4. CONCLUSIONS

In this paper, we have addressed the different steps of manufacturing a TPC-IOM hybrid demonstrator part, combining thermoplastic composites and a short carbon fiber thermoplastic compound. We have covered the design of the demonstrator, and specific considerations targeted at taking advantage of each component from a manufacturing and a material performance standpoint. We also provided detailed information on the optimization of the injection molding process (driven by simulation) and of the stamping process. We have highlighted how different tools can help streamline the development & manufacturing process. This has allowed us to address the complexity of multiple parameters of multiple processes to reach a final part. Specifically, a careful analysis of material temperature profile (melting, crystallization), combined with Moldflow® simulation, allowed us to optimize both the stamping & molding process to achieve strong interface bonding, hybrid part strength & stiffness as well as dimensional stability.

We would also like to highlight the short 3-month development time was required from the early design stage to the latest trials with optimized parameters, making the approach both commercially viable and attractive.

The results of this work have provided us with the confidence to continue to optimize the process around this demonstrator and to develop our next generation demonstrator which will be even more complex and dynamic.

5. REFERENCES

3. TPRC Thesis / Paper (drying, IOM base settings)