INNOVATIVE PREDICTIVE SOLUTIONS FOR HYBRID THERMOPLASTIC COMPOSITE TECHNOLOGY

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Abstract

Increasingly tighter requirements on CO2 emissions urge the automotive industry to seek radical weight savings [Ref 1, 2]. This has led to investigation of many new metal and plastic material systems, including continuous fiber reinforced thermoplastic composites. Multi-material hybrid solutions, combining continuous fiber composites with short fiber composites via overmolding technology, have been shown to be attractive. The overmolding technology enables design freedom for functional integration in combination with high performance lightweight composites.

Despite the fact that continuous fiber reinforced thermoplastic composites principally meet the performance requirements from industry, confidence still seems to be lacking for widespread adoption today. Insufficient maturity of the manufacturing process and predictive methods for these relatively new materials are two of the main reasons. Therefore, a unique test component was developed, enabling the demonstration of a complete manufacturing process chain as well as predictive capabilities, providing confidence for any generic future component in a car.

The use of the unique component for the demonstration of a hybrid manufacturing process will be shown, as well as the new, innovative predictive solutions covering the complete process chain. Typical conditions with extensive experimental validation will be showcased.

Industry Needs and Current State of Technology

Continuous fiber reinforced thermoplastic materials are attracting a lot of attention from the automotive industry already for several years. They are attractive due to their high performance and lightweight. These new materials require, however, new robust manufacturing processes that must comply with short cycle times of about 1 minute required for the mass production in this industry. In addition, new predictive methods need to be developed, providing the necessary confidence for accurate predictability of the manufacturing process and (mechanical) part performance. In 2013, SABIC has interviewed major OEMs, tiers and equipment suppliers, asking them for input on the main hurdles for the use of composites in the automotive industry. This has shown that design predictability, part cost and cycle time (manufacturing process) are by far the most important attention points for successful implementation of continuous fiber reinforced thermoplastic composites (Fig. 1).

It has been shown elsewhere [Ref. 3, 4] that hybrid overmolding of continuous fiber reinforced composites would yield cost-effective lightweight solutions as desired by the automotive industry. This technology takes the advantage of the high strength and stiffness of continuous fiber materials in the load direction, while integrating many detailed functions via the overmolding process. During hybrid overmolding process, continuous fiber reinforced thermoplastic laminate (local) insert(s) is (are) applied only at locations requiring high performance and molded over with a thermoplastic polymer resin possibly reinforced with chopped fibers, e.g. via injection molding (Fig. 2).
Figure 1: Automotive market blueprinting study results on key challenges around application of continuous fiber reinforced thermoplastics.

Figure 2: Hybrid overmolding technology for thermoplastic hybrid components. 1: Pre-cut continuous fiber reinforced thermoplastic insert picked up by robot. 2: Heating in oven. 3 + 4: Thermoforming of heated insert in mold, so called “one-step” process assuring low cost and 1 minute cycle time. 5: Injection overmolding with (chopped fiber reinforced) thermoplastic material. 6: Demolding of the part.

**Manufacturing** solutions for hybrid overmolding with thermoplastic composites is addressed by another ACCE paper from SABIC [Ref. 4] and will not be covered here. The reader is referred to this paper for new developed methods for handling of inserts during transfer from the heating oven to the mold as well as for fixation in the mold after hand-over of the insert from the robot.

Current **predictive engineering solutions** for thermoplastic hybrids are still in development and confidence is lacking. Especially at OEMs the confidence in predictability and variability is still not good enough for widespread adoption. Continuous fiber thermoplastic hybrid components may fail in many ways, e.g. tension, compression, in-plane or out of plane shear. However, the prediction capabilities are not yet proven for all **main failure modes**. This is essential for providing
confidence in predictive capabilities for any generic car component. Predictive solutions are needed, proven for all main failure modes in continuous fiber thermoplastic hybrid components and covering all the steps of the hybrid overmolding process.

The next section will focus on the generation of experimental validation data followed by predictive methods. Another section will address the evaluation of results. Finally, remaining challenges will be explained with related recommendations.

**Experimental Validation Data with Unique Demonstrator Component**

In order to build the required confidence for developing any generic car component, predictive solutions need to be proven for all main failure modes in continuous fiber thermoplastic hybrid components. This was realized by validating and evaluating the predictions using experimental results gathered with a unique demonstrator test component.

A highly engineered multi-purpose beam was developed to build confidence for multi material hybrid systems. It enables practical demonstration of the complete manufacturing process chain as well as the validation of multiple composite failure modes occurring in hybrid overmolded components with processed material properties (Fig. 3). It is unique, as the majority of the existing test components fail in only one specific way or are designed specifically for a particular application and not for a generic one. The main challenge was to design one test component, enabling testing of individual composite failure modes independently, despite the high difference in failure strength between the laminate (Continuous Glass-Polypropylene) and overmolding material (long glass polypropylene). With a difference in strength of more than a factor 20, one needs a properly dimensioned test component to promote failure, for example, in the composite and not in the much weaker overmolding material.

![Figure 3: Hybrid beam – Highly engineered test component for validation of multiple composite failure modes in hybrid overmolded components. Red: continuous fiber thermoplastic insert. Green: thermoplastic overmolding resin.](image)

Beams were manufactured and mechanically tested in 4 point bending type of loading for multiple failure modes. Different failure modes were achieved besides the highly engineered design, either by changing the way the thermoplastic UD inserts are applied (Fig. 3, 4) or by adding new features to the beam via secondary operations like joining (Fig. 5) or by varying the test set-up (Fig. 6).

For example (see Fig. 3), beam design with special ribbing pattern and asymmetric application
of inserts (narrow and thin at flanges vs wide and thick at top surface) prevented buckling of the flanges with UD inserts under loading for compressive failure mode (Fig. 6). This ensured validation of uniaxial compressive failure of UD inserts in flanges rather than failure under buckling loading. Similarly, tailored application of inserts combined with beam design ensured that GF-PP UD insert failed in tension/shear and not the overmolding material LGF-PP.

It has to be underlined that it would not be possible to test multiple composite failure modes independently with just one average beam design without intensive engineering efforts.

**Figure 4**: Different failure modes were achieved by changing the way the thermoplastic UD inserts (Red) are applied. Note the asymmetric application of inserts on left drawing for tensile or compressive uniaxial failure in UD inserts.

**Figure 5**: Beam variants with new features added by joining. 4 point bending (Fig. 6) of these versions enable testing and validation of joined interfaces on hybrid overmolded parts. Red: Thermoplastic UD insert. Blue: Steel.

**Figure 6**: Set-up for 4 point bending testing for respectively compressive, tensile and shear failure modes in UD thermoplastic insert.

Handling of thin/thick, small/wide, short/long and multi-lay-up thermoplastic UD composite inserts was successfully demonstrated on this beam with the manufacturing technology solutions for hybrid overmolding. These solutions are targeting successful handling of the insert, stable
processing window and dimensional stability. They are addressed by another ACCE paper from SABIC [Ref. 4] and will not be covered further here. The reader is referred to this paper for more details.

However, the predictive capabilities for the manufacturing process will be covered here as part of warpage/mechanical performance prediction. To limit the size of this paper, prediction of a few main aspects of the manufacturing process – like filling behavior and dimensional stability – will be evaluated here against experimental results.

**Predictive Solutions for Hybrid Thermoplastic Technology**

Predictive solutions were developed at SABIC to provide the necessary confidence in the capabilities for all main failure modes in continuous fiber thermoplastic hybrids. First, predictive methods were developed and evaluated using available commercial software packages. These solutions will be referred here as the “current/conventional approach.” In addition, an integrated simulation chain was developed, covering all the steps of the hybrid overmolding process with thermoplastic inserts, up to and including the mechanical performance prediction. This latter one will be referred here as the “new approach.”

Note that predictive solutions not consist of CAE modelling only. A predictive solution includes usage of CAE software packages, combined with accurate material data, proper material modelling and experimental verification (Fig. 7). Material data is the input for simulations and required to be accurate to avoid “garbage in => garbage out” condition. Therefore, significant effort was devoted for accurate material data characterization. The conventional and new approaches were then utilized for performance prediction and experimentally validated with a unique test component able to produce all main failure modes.

This paper will focus on 2D predictive methods as this is seen to be more suitable for the automotive industry with large components to be modelled. 2D modelling is easier to build and faster to analyze and post-process. As a consequence, different design variants can be developed and evaluated very fast during development phase of car components. This will reduce the time needed for application development. Moreover, fiber orientation predictions appeared to be more accurate by experience with Moldflow® mid-plane (2D) modelling using accurate material database. Fiber orientation is input for anisotropic mechanical performance predictions with chopped fiber resin for overmolding.

![Figure 7: Predictive engineering process: CAE software packages, combined with accurate material data, proper material modelling and experimental verification.](image)

**Current Approach with Commercial Software**

Currently, there are alternatives of commercial software packages that can cover heating and draping steps of the hybrid overmolding process as shown in Fig. 2. For the studies in this paper,
the software package PAM-FORM™ was used for draping simulations. This software enables prediction of forming processes with dry textiles or prepregs.

Also alternatives are available for the prediction of overmolding process (step 5, Fig. 2). The software package AUTODESK Moldflow™ was used for the studies in this paper. Moldflow™ enables prediction of overmolding process, e.g. in combination with injection molding or injection compression molding. Moldflow™ offers an integrated solver for warpage¹ predictions although with limited capabilities for modelling the thermo-mechanical and rheological properties of UD insert. One important limitation is the mechanical behavior for the insert, which is allowed to be isotropic only instead of orthotropic anisotropic.

There are several commercial software packages available for warpage and mechanical performance predictions, required for validation of the part performance. Software package ABAQUS™ was used here in combination with MSC Digimat™, enabling mechanical performance prediction using by Moldflow™ predicted fiber orientation. MSC Digimat offers capabilities for mapping the predicted fiber orientation from Moldflow™ and for use in ABAQUS™. ABAQUS™ can also be used for warpage predictions using the overmolding results from Moldflow™ with significant loss of accuracy due to limitations for predicting the so called “corner effects”. ²

The above mentioned software packages are selected based on several reasons, which are beyond the scope of this paper. Nevertheless, the key message is here that commercial software packages from different suppliers are used for prediction of different steps of the process chain (Fig. 2). This is generally the case if, for example, the best in class software packages are preferred to use for each process step. Currently, there is generally no connection between the selected independent software packages. The exception is the link between Moldflow™ and ABAQUS™ among the commercial software packages used for results in this paper (Fig. 8). Nevertheless, this is still far from capturing the whole process chain of hybrid overmolding. In addition, limitations in Moldflow™ for modelling the thermo-mechanical properties of continuous fiber thermoplastic inserts reduces the accuracy of warpage prediction and requires custom developed tools.

Figure 8: Current Conventional Approach - Interconnectivity between the commercial software packages used in this paper.

¹ Warpage: deformations of produced component after manufacturing due to internal stresses caused by shrinkage differences in constituent materials.
² Corner effects: Reduction of the internal angle of a corner in a molded component, after molding with thermoplastic resin.
New Approach with Fully Integrated Simulation Chain

It is preferred to have the link between each process step, such that the effects of previous steps are taken into account in latter steps for hybrid overmolding (Fig. 2). To realize this, a research project was started in cooperation with the research institute INPRO. This project has led to a new innovative approach with tools and methods enabling the so called Integrated Simulation Chain, covering the steps of the complete hybrid overmolding process (Fig. 9). These tools and methods are incorporated into a software that links and manages the whole chain of simulations with independent commercial software packages.

In addition, tailored algorithms were developed enabling proper modelling of the thermo-mechanical properties of continuous fiber thermoplastic inserts, e.g. for warpage predictions.

The Integrated Simulation Chain enables mapping of significant information and data types between subsequent simulations for each step (chain) of the hybrid overmolding process (Fig. 10). Moreover, exchange of information between non-consecutive steps is possible.

![New Innovative Approach - Integrated Simulation Chain](image-url)

*Figure 9: New Innovative Approach - Integrated Simulation Chain linking and managing the whole chain of simulations with independent commercial software packages.*

![Integrated Simulation Chain](image-url)

*Figure 10: The Integrated Simulation Chain - mapping of information and data types between subsequent simulations for each step (chain) of the hybrid overmolding process.*
Evaluation of Results for Conventional and New Approaches

All steps of the hybrid overmolding process (Fig. 2) were applied during the manufacturing of the test beams. Beams were then mechanically tested in 4 point bending for validation of multiple failure modes. The results from experiments were then compared with the predictions following conventional and new approaches.

Forming simulations were reasonably in good agreement with the experiments, which was expected as the shape for draping was a relatively simple hat shape (\(\sim\)\(\Gamma\)) cross-section. There were no remarkable thickness variations, wrinkling defects and orientation changes of fibers. Relatively straight planar inserts, used in the beam variant shown in Fig. 3, also did not require any significant forming.

The filling behavior from overmolding simulations were in relatively good agreement with the experiments and were almost identical for both the conventional and the new integrated approach (Fig. 11). This is a logical result as there were no remarkable thickness variations and wrinkling defects during the forming process that might affect the filling behavior. A good correlation was seen from the beginning to the end of filling in general.

![Figure 11: Filling behavior- Overmolding simulations with 2D and 3D modelling vs experiments with good correlation. The simulation results are identical for both the conventional and new integrated approach.](image)

Unlike the filling behavior, significant differences were found between the two different predictive approaches for mechanical warpage prediction (Fig. 12). This is mainly related to the algorithms in the new approach enabling proper modelling of the thermo-mechanical properties of continuous fiber thermoplastic inserts, during overmolding simulation. The inserts can be modelled as orthotropic anisotropic material instead of isotropic modelling with the conventional approach. The prediction with the new integrated approach was in good agreement with experiments regarding the maximum out-of-plane deformation. Note that the warpage deformation was observed to be dominated by the high mechanical performance of the UD inserts. On the other hand, about 23% more maximum warpage deformation was predicted with the conventional approach. This was the case for this beam with such a heavy ribbing, for which limited warpage deformations would be expected. This indicates that larger differences in prediction may be expected for more warpage sensitive parts.
In addition, the new approach was also able to capture the asymmetrical torsional warpage deformation, which was missed by the conventional approach (Fig. 12). It is important to note that warpage is a very critical aspect for the manufacturing process. The produced part will not fit in the assembly stage if the part shows large warpage deformation. This will lead to more prototyping costs, longer development times and complicated assembly processes, and might affect the mechanical performance.

![Figure 12: Warpage - Deformations plotted perpendicular to the reference plane defined by the three grey spheres on beam at top. The new approach was able to capture both maximum out-of-plane and torsional deformations (asymmetric deformation pattern) with reasonable accuracy. More accuracy with the new approach is mainly due to better modelling of Thermo-mechanical properties of UD inserts.](image)

Structural performance prediction capabilities focus on the stiffness and strength (initiation of damage) prediction rather than post failure behavior after initiation of cracks. For most of the potential applications, post failure behavior prediction is not necessary as initiation of damage is seen as the criterion for a go / no go decision. Post failure behavior is, for example, required for assessing energy absorption capabilities of components. This topic will be focused in a latter publication considering the large content size and the overall progress.

The structural performance predictions with the conventional and new approaches were practically the same as there were no remarkable thickness variations, wrinkling defects and orientation changes of fibers during the forming process. However, significant differences would be expected for more complex draping shapes than it is the case for the test components considered in this paper. Note that the conventional approach allows tough mapping of predicted fiber orientation from Moldflow™ to ABAQUS™, using MSC Digimat™, for anisotropic simulations.

Stiffness predictions are normally evaluated at part level while the strength assessment requires local evaluation of stress state in the component. Nevertheless, local stiffness prediction is key for an accurate strength prediction as this delivers the local stress field. Consequently, local stiffness/deformation capabilities have been validated for better understanding of what happens at local scale (Fig. 13). The local strain field was measured using the ARAMIS Digital Image Correlation (DIC) system from supplier Gom. Reasonably good correlation was found between
predicted and experimentally measured local deformation fields. This provides good confidence for prediction of local stiffness and stress fields.

![Figure 13: Mechanical Performance – Local deformation field validation. Reasonably good correlation with experiments. Local strain vs 4 point bending indentor displacement is plotted for compressive loading mode.](image)

In addition to the good correlation for local deformation, the global deformation behavior of the hybrid beam was also predicted reasonably well. The measured and predicted initial stiffness values were determined between 600N and 2000N force levels and compared at room temperature for two main loading modes: tensile and compressive (Fig. 14). The results provide a high level of confidence for global structural performance prediction.

![Figure 14: Mechanical Performance – Stiffness correlation at RT for Tensile and compressive loading modes. Stiffness measurement range: 600-2000N. Reasonably good correlation with experiments.](image)

The final step in the scope of this paper is to demonstrate the ability to predict failure initiation in continuous fiber thermoplastic hybrid components. The hybrid beam components used for reaching these failure modes are shown in Fig. 15. The results for the two most important failure modes are shown in Fig. 16, respectively for tensile (left) and compressive (Right) loading.
Figure 15: The hybrid beam components utilized for reaching the failure modes are shown in Fig. 15. Red: Continuous glass fiber reinforced PP made UD laminate inserts. Blue: Discontinuous long glass fiber reinforced PP.

Figure 16: Mechanical Performance – Tensile and compressive failure modes. Black: Measurement. Blue: Predicted at RT. Orange: Predicted at 85 °C (HT). Reasonably good correlation with experiments.

The results provide a good level of confidence for the development of any car component up to and including the initiation of damage. Only the compressive strength prediction shows a deviation of about ~13% from the experimental results. The compression strength is a typical failure mode that might show such deviations as it is sensitive for imperfections like fiber waviness. The proven level of accuracy is reasonably good if compared with the accuracy levels achieved with the existing material portfolio used in the automotive industry.
Challenges with Predictive Solutions

The new approach requires linking of multiple software packages from different suppliers, and the developed tools need to be maintained for changes or adaptations in the linked packages. The maintenance efforts can be reduced by annual updating, although this limits the flexibility to switch to newer versions and capabilities of the linked software packages.

Although there are suitable damage initiation methods available, proper modelling for further evolution of the damage is still missing. Current models show dependency on type of component and used finite element size in simulation. Nevertheless, this is not a major roadblock for many applications, for which damage initiation is the criterion for go / no go decision.

Conclusions and Recommendations

Predictive solutions were developed for continuous fiber thermoplastic hybrids and a unique test component was developed and utilized for experimental validation. The results provided good confidence for predicting the main failure modes as well as the hybrid overmolding manufacturing process.

The filling behavior from overmolding simulations were in relatively good agreement with the experiments. Regarding the warpage prediction, the newly developed Integrated Simulation Chain approach delivered good match with the experiments. The conventional approach yielded a weaker correlation.

The mechanical performance predictions correlated in general reasonably well with the experiments, providing confidence for the development of any car component up to and including the initiation of damage.

It is a must to have accurate predictive capabilities for both the insert and overmolding material to ensure proper predictions with hybrid components.

New material modelling methods are recommended for proper modelling of the behavior after the initiation of damage. Nevertheless, this is not a must for many applications as mostly initiation of damage is seen as the criterion for a go / no go decision.

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