Hybrid LFT-D and GMT glass reinforced nylon composite for optimization of part molding and performance

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Abstract

In this study, materials were selected from long fiber thermoplastic-direct (LFT-D) and glass mat thermoplastic (GMT) classes that were comprised of Polyamide-6 (PA6) as the matrix material and glass fiber (GF) as the reinforcement. Common matrix and fiber constituents allowed for the investigation of the combination of the two materials in one part. The mechanical properties of the combination of the two materials as well as the adhesion between the two materials was studied. The results indicate that the mechanical properties of combination of the two materials lie between that of LFT-D and GMT material on their own. Thus, depending on the requirements of an application, the use of GMT material in LFT-D can be optimized (rather than LFT-D or GMT alone) for reduced cycle time, better mechanical properties, reduced cost, and reduced part warpage.

Introduction

Emphasis on the reduction of fuel consumption and greenhouse gas emissions has been a key factor for automotive industry to move from conventional heavier materials to lightweight alternatives such as composites. Manufacturing processes like LFT-D are becoming ever more present as they are suited for high volume production necessary in the automotive industry. For similar reasons, the material class GMT is also a key player with its own niche applications. Both materials consist of discontinuous randomly oriented fibers distributed in a thermoplastic polymer matrix. However, the LFT-D process has shorter cycle times, and the LFT-D material is generally more suited to fill parts with complex geometry due to better flow. Whereas GMT materials have better mechanical properties due to typically higher fiber loading and length but are generally more expensive and require longer cycle times to manufacture parts. Both material classes were evaluated in this study, and both comprise of PA6 (Polyamide-6) as the matrix materials and GF (glass fiber) as the reinforcement. Common matrix and fiber constituents allowed for the investigation of the combination of the two materials as a hybrid in one part. This combination gives an opportunity to study the mechanical properties of the combination as well as the adhesion between the two material classes.

Hybridization in thermoplastics

Injection molding (IM) and LFT-D processes are very sought-after thermoplastic manufacturing processes in the automotive industry. They are well suited for high volume manufacturing of complex geometries being cost effective and short cycled. These processes have their own limitations with respect to the reinforcement introduced into the thermoplastic polymer. Flow of material induces fiber alignment (anisotropy), the fiber lengths are relatively shorter in IM (<5 mm), and the fiber loading classically maxes out around 40% and 50% by weight for IM and LFT-D respectively.

Hybridization allows combining these well-established processes with high-performance CFRT (continuous fiber reinforced thermoplastic). Injection over-molding of CFRT tapes and organosheet material has been in production for some time now. CFRT materials provide superior directional material properties suited for structural applications. The localized placement of these CFRT allows for tailored use of these normally more expensive materials with relatively cheaper over molded reinforced polymer systems in LFT-D or IM (Figure 1). However, for semi-structural applications these more expensive CFRT material may still prove to be an excess and the cost of material and cost of processing may not be justified.

In this study the LFT-D GMT combination has been explored. LFT-D is relatively a newer process when compared to injection molding. Although, there are some limitations around LFT-D compared to IM like difficulty in molding thin walls, anisotropy induced by flow of material, the fiber lengths distribution being a wider spectrum [1] [2], the process offers some superiorities of its own. The ability to do in-line compounding of raw materials such as polymer, additives and reinforcement is beneficial, and the fiber lengths can also be much longer (~2 inches) in LFT-D extrusion compression molding compared to IM and can be adjusted using process optimization. Cost and mechanical properties of GMT materials lie somewhere between CFRT materials and LFT-D/IM. Thus, for the semi-structural applications it will be beneficial to form an LFT-D GMT hybrid formulation which is cost effective and provides suitable performance. The LFT-D GMT hybrid is also able to maintain the much desirable high flow ability of the LFT-D material.

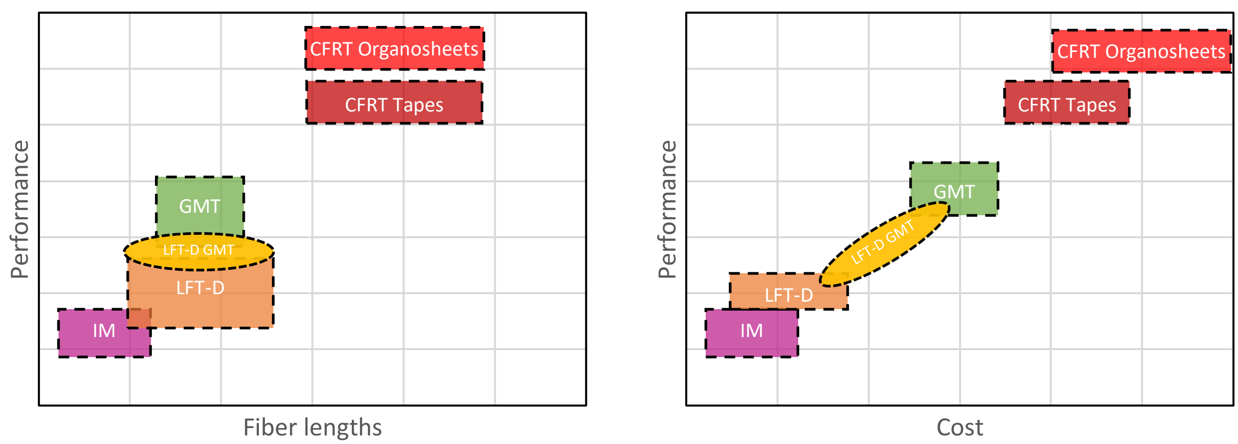

Figure 1 Comparison of relevant thermoplastic composite material systems[8][9]

Materials used

In this study commercial product from Lanxess called Tepex Flowcore which has 60% by weight two inch long glass fibers that are randomly oriented in a PA6 matrix represents the GMT material class. The LFT-D material discussed here is 40% by weight long fiber glass reinforced PA6. The LFT-D material was produced at Fraunhofer Project Centre for Composites Research on a Dieffenbacher LFT-D line using JohnsManville 886 StarRov 2400 tex glass roving and Ultramid 8202 HS BK PA6 from BASF. With the chosen material for the LFT-D process only 40% by weight fiber loading was executed for consistency of the process. Higher fiber loading is achievable, but LFT-D process is not as suited for fiber loading above the 40% value.

Experimental molding

Experimental molding of parts for further evaluation were conducted using a square plaque mold and a seat back component mold for LFT-D compression molding/over-molding. Molding process parameters were consistent with both part geometries. Benchmark parts were made on both molds using individual LFT-D and GMT material systems. The GMT component of the molding or over molding process was heated in a HK circulating air oven and then compression molded either individually or with the LFT-D plastificates coming out of the Dieffenbacher LFT-D line. All the materials were hand transferred into the mold for molding in this study. The transfer process can be automated in a production scenario.

Table 1 Processing parameters

Parameter	GMT	LFT-D	Hybrid LFT-D + GMT
GMT heating temperature, °C	286	-	286
GMT heating time, min	12	-	12
LFT-D extruder temperature, °C	-	300	300
Mold temperature, °C	150	150	150
Molding pressure, bar	300	300	300
Molding closing time, s	90	90	90

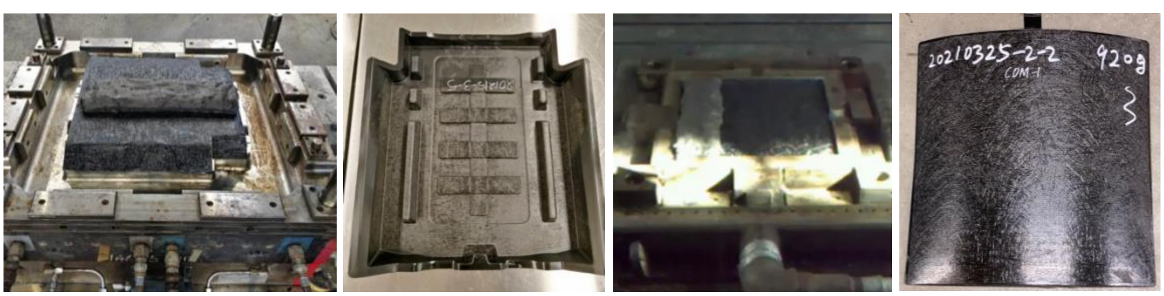

Figure 2 LFT-D plastificates placed on top of GMT material in the seat back and square plaque mold with respective parts

Seat back parts

For the seat back parts (Figure 2) the intent was to use total material equivalent to design volume of the part. The part volume was 1,063 cm^3. Pure LFT-D parts were filled at design volume without any issues during molding. Due to limited flow behavior of the GMT material the mold had to be over filled with 1,320 cm^3 of material, obtained from 2 sheets of 2 mm thick GMT blanks cut into a tailored shape, to obtain full parts with pure GMT. A 1 mm thick sheet of GMT cut into a tailored shape was used along with the LFT-D material to come up with the total volume of 1,063 cm^3.

Table 2 Composition breakdown for seat back parts

Material type	Nominal part volume, cc	Part weight, grams	LFT-D: GMT, by vol.
Pure LFT-D	1,063	1,510	1 : 0
Pure GMT	1,063	2,262	0 : 1
Hybrid LFT-D GMT	1,063	1,572	0.73 : 0.27,

Square Plaque parts

For the square plaque (Figure 2) parts the target part thickness was 3 mm and the intent was to use 1 mm thick GMT sheet in the over-molded hybrid parts. Based on final part thickness, the hybrid over molded part consisted of 40% by weight LFT-D and 60% by weight GMT.

Table 3 Composition breakdown for square plaque parts

Material type	Nominal part thickness, mm	Nominal part wt., grams	LFT-D : GMT, by wt.
Pure LFT-D	3	875	1 : 0
Pure GMT	3	1,035	0 : 1
Hybrid LFT-D GMT	3	920	0.6 : 0.4

Experimental analysis

Optical Microscopy

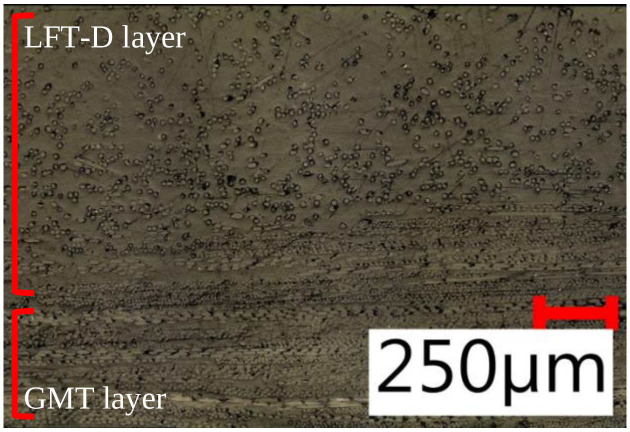

Figure 3 300x Microscopic view of section of hybrid LFT-D GMT over molded sample

In the over molding process there is likelihood of structural disintegration induced by air gaps and voids where the two material types meet [3]. To investigate for any obvious anomalies, multiple specimens were obtained from the seat back parts made with hybrid material type and cross-sectioned to examine the interface between the two materials. The samples were mounted in epoxy and polished to 1500 grit for optical microscopy. No recognizable separation markers such as a distinct weld line or voids were observed, which implies the any air trapped between the material system was forced out during flow of material. The glass fiber concentration is different for the two materials and can be clearly seen in the cross-section.

Warpage analysis

Warpage analysis was implemented on the single material type benchmark parts (GMT and LFT-D) and the over-molded hybrid parts made in the seat back mold. No hydraulic ejector pins or air poppets were used as those ejection assist accessories could induce additional warpage in the molded part during the demolding process. The parts were demolded after they released off the cavity upon shrink induced by cooling. However, this dwell could have introduced additional warpage as one side of the part was in contact with the heated mold and the other side was exposed to ambient air. This factor along with the thickness of pure GMT parts being higher than pure LFT-D parts and hybrid parts were considered when analyzing the warpage. After the parts were cooled, they were 3D scanned using a Faro laser line probe and used as the input for the warpage analysis.

Deformation energy metric

A method which calculates the deformation energy was adopted to compare the magnitude of warp between single material and hybrid material parts. A global summative method [4] and [5], which considers the whole part geometry for the analysis was employed. The scanned part is aligned to the nominal geometry via the centre section ribs (Figure 2) as this is deemed to be the stiffest section and least prone to warp. Thus, the point of zero warp is also located within this region. Then, the deviation from nominal of approximately 2000 probes are applied as displacement boundary conditions for a structural analysis of the nominal part in Abaqus. The mesh used for this structural study employed C3D10M tetrahedral elements with a mesh size of 4 mm. This process mimics the change in shape of the parts from the nominal CAD and allows for that change to be measured using total strain energy, however, a dummy isotropic material will be used for all material configurations such that the deformation energy is purely a geometric measure for comparative purposes. This method may also reveal some information relating to the sensitivity of warp for each deformation mode as it will account for differences in local geometric stiffnesses. The total strain energy in Abaqus is represented by the following equation:

$$\text{ALLIE} = \text{ALLSE} + \text{ALLPD} + \text{ALLCD} + \text{ALLAE}$$

where ALLSE is the recoverable strain, ALLPD is energy dissipated through plastic deformation, ALLCD is energy dissipated through creep, swelling, and viscoelasticity, ALLAE is artificial strain energy used to remove singular modes. The relevant equations for ALSLSE, ALLPD and ALLCD are integrated over volume and time. The results from the analysis for the parts made during the experimental molding represented in terms of deformation energy are summarized in Figure 5. At first glance it is interesting to note that the warpage magnitude associated with hybrid LFT-D GMT parts is very similar to that of the parts made with only the reinforcing material, GMT. In this case, replacing approximately just 25% of the LFT-D volume with GMT in the tailored blank configuration can lead to warp magnitudes very close to the GMT parts.

Contour plots of part warp can be seen in Figure 5 and reveal more information about the warp behavior. The shape of the warp is different for the three different types of parts. The LFT-D and GMT parts experience signficicant warp in the left and right outer flanges, while the hybrid part does not. The LFT-D part also has significant warp along the bottom and top of the part, whereas the GMT part does not. The hybrid part shows appreciable warpage along the bottom flange and a different characterstic shape in the center of the part where there the part is slightly convex.

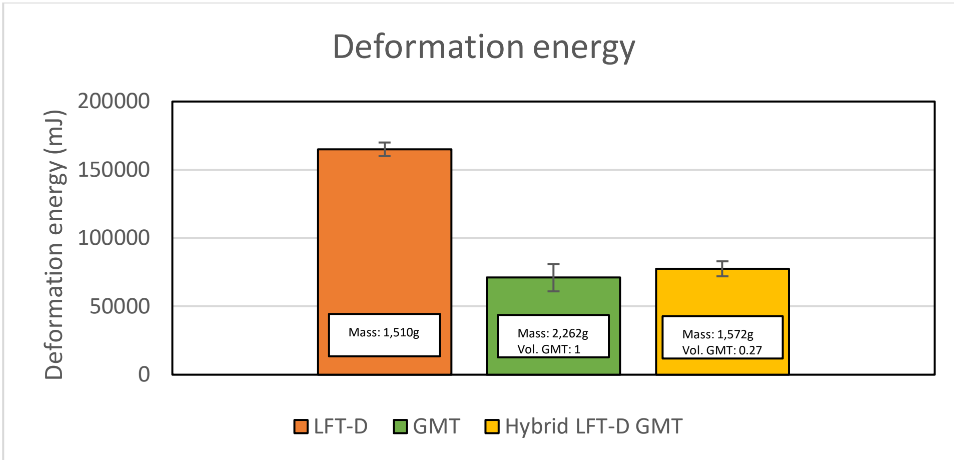

Figure 5 Summary of warpage from deformation energy metric

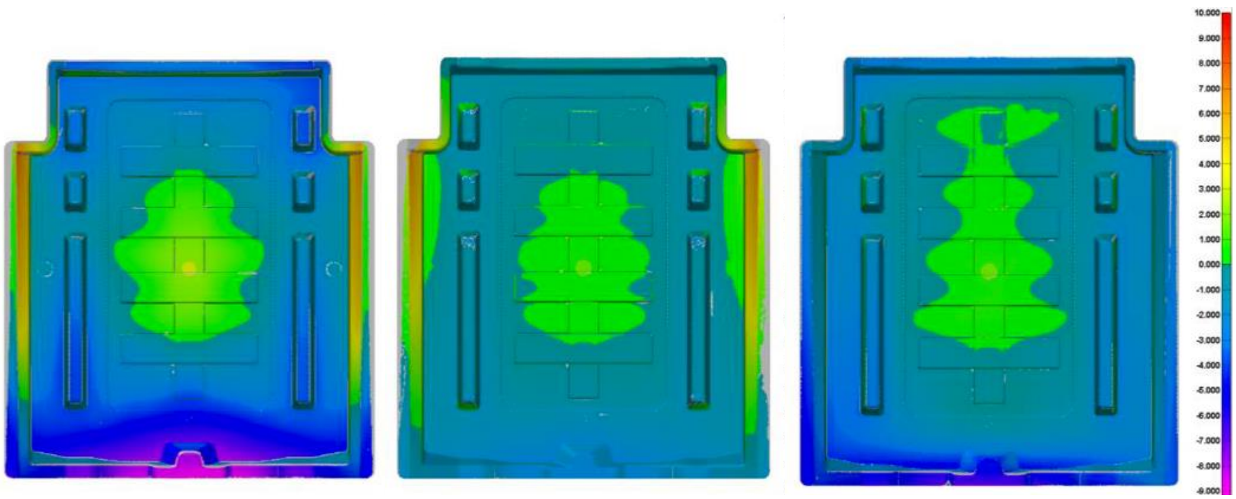

Figure 4 Warpage contour (Left to Right) LFT-D, GMT, and hybrid LFT-D GMT

Experimental material testing

The square plaque parts produced for each of the material system were subjected to mechanical testing to compare material properties between the three systems. Tensile tests were performed to characterize tensile strength and elastic modulus. Three point bending flexural testing was done for flexural strength and flexural modulus. The corresponding standards followed were ASTM D638 – 14 and ASTM D 790 – 17. For each of the material types, specimens specified in Table 4 were tested on an MTS Criterion Model 45 electromechanical universal test system and in the case of tensile testing, strain was measured using a Imetrum IM-LENS-MT010 video extensometer. Test specimens were dried for 24 hours at 80°C to remove any moisture.

Table 4 Specimens for material testing, 180 total specimens tested

<table>
<tr><th></th><th>0°</th><th>45°</th><th>90°</th></tr>
<tr><td>Tensile</td><td rowspan="2">6 specimen per plaque, 5 plaques</td><td rowspan="2">6 specimen per plaque, 5 plaques</td><td rowspan="2">6 specimen per plaque, 5 plaques</td></tr>
<tr><td>Flexure</td></tr>
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Tensile Testing

As per ASTM D 638 using cross head rate of 5 mm/min and the load cell used was 100 kN.

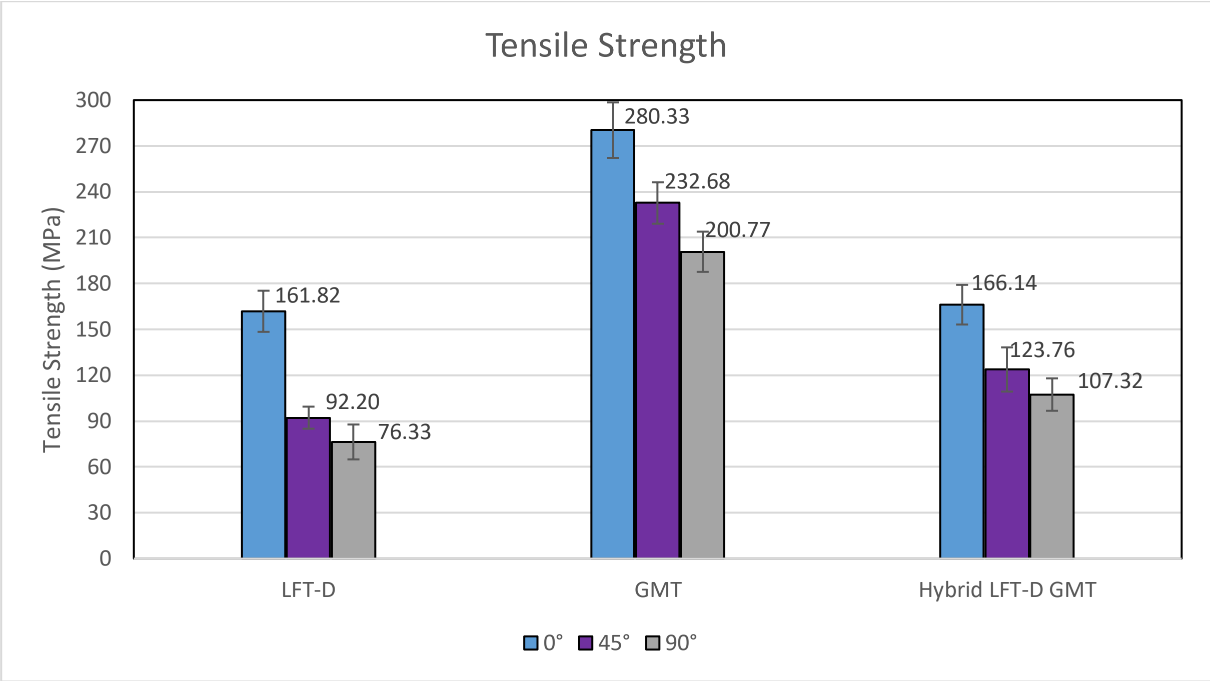

Figure 6 Tensile strength of LFT-D, GMT, and hybrid LFT-D GMT system in 0°, 45° and 90° direction. Error bars represent one standard deviation.

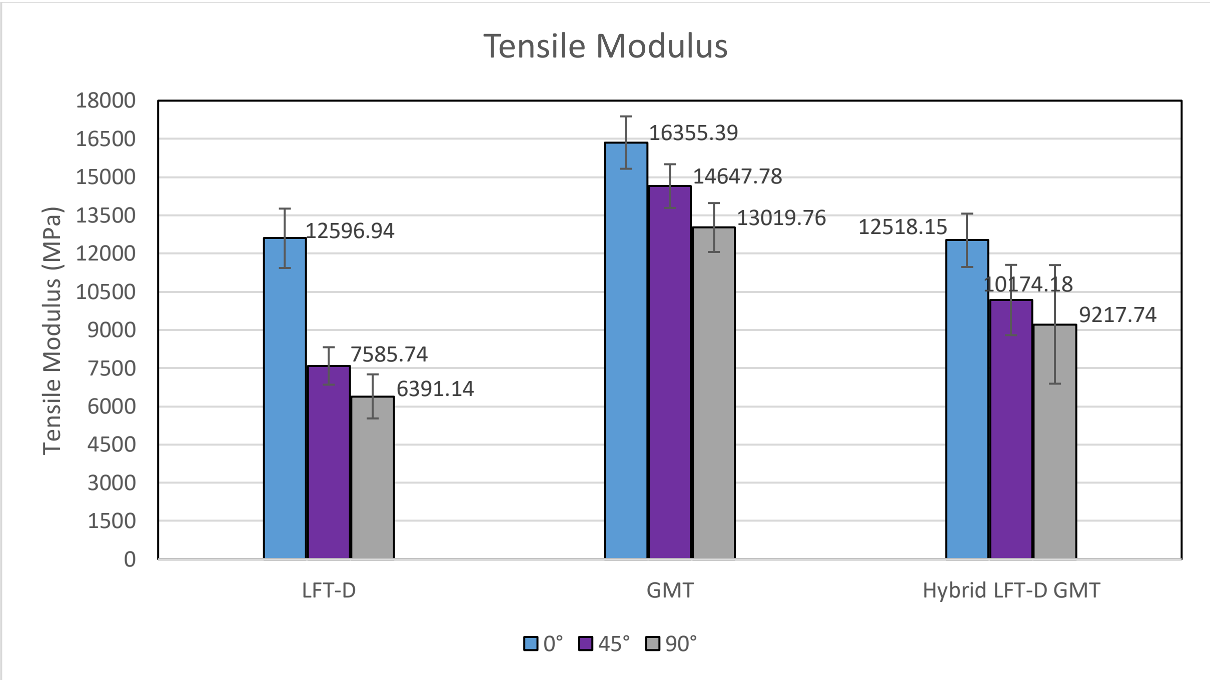

Figure 7 Tensile modulus of LFT-D, GMT, and hybrid LFT-D GMT system in 0°, 45° and 90° direction. Error bars represent one standard deviation.

Flexure Testing

As per ASTM D 6790 using cross head rate of 1.25 mm/min and the load cell used was 100 kN.

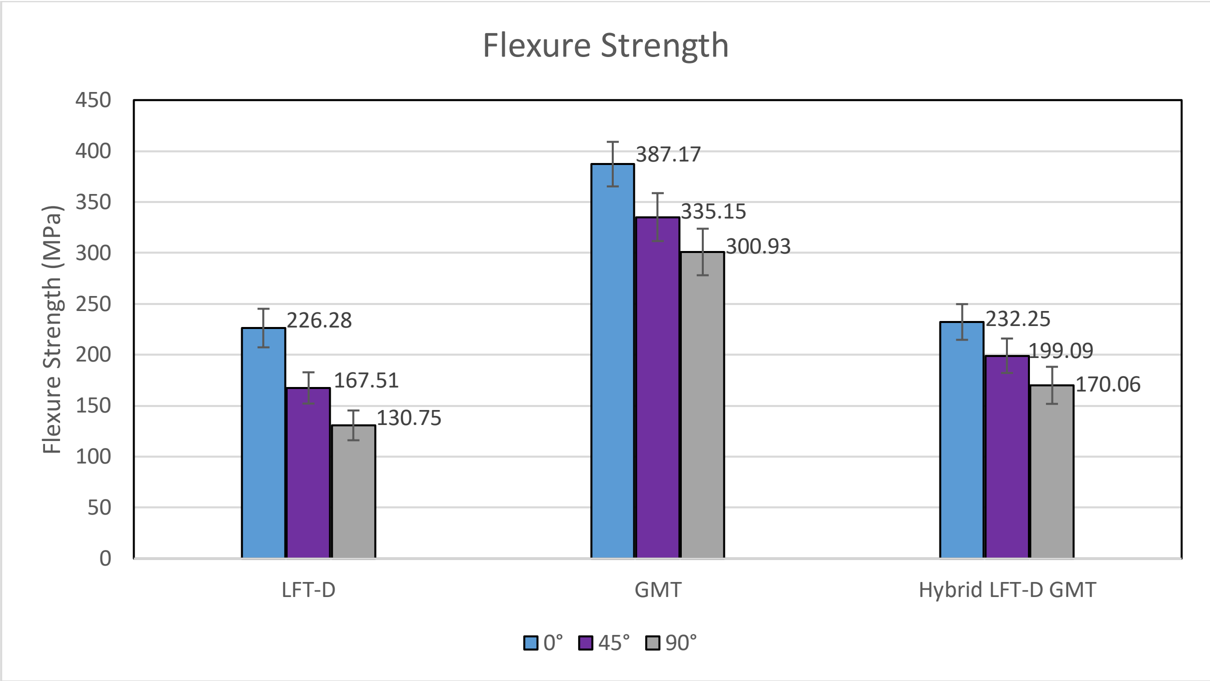

Figure 8 Flexural strength of LFT-D, GMT, and hybrid LFT-D GMT system in 0°, 45° and 90° direction. Error bars represent one standard deviation.

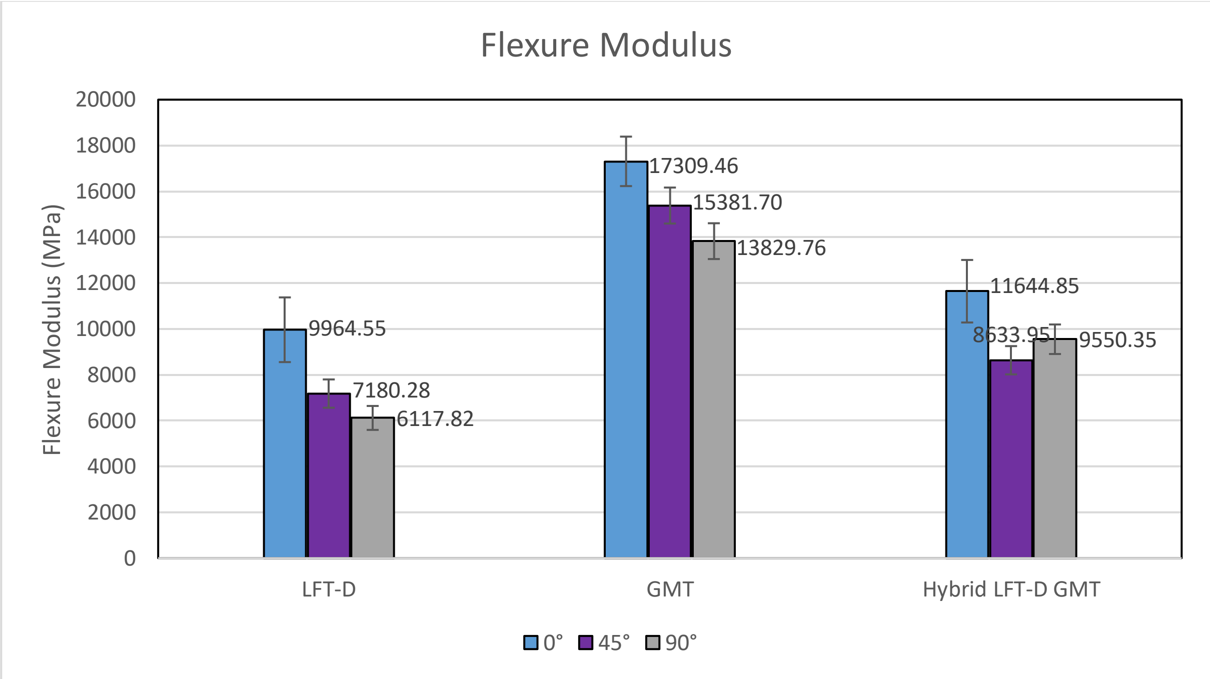

Figure 9 Flexural modulus of LFT-D, GMT, and hybrid LFT-D GMT system in 0°, 45° and 90° direction. Error bars represent one standard deviation.

Analysis of mechanical testing

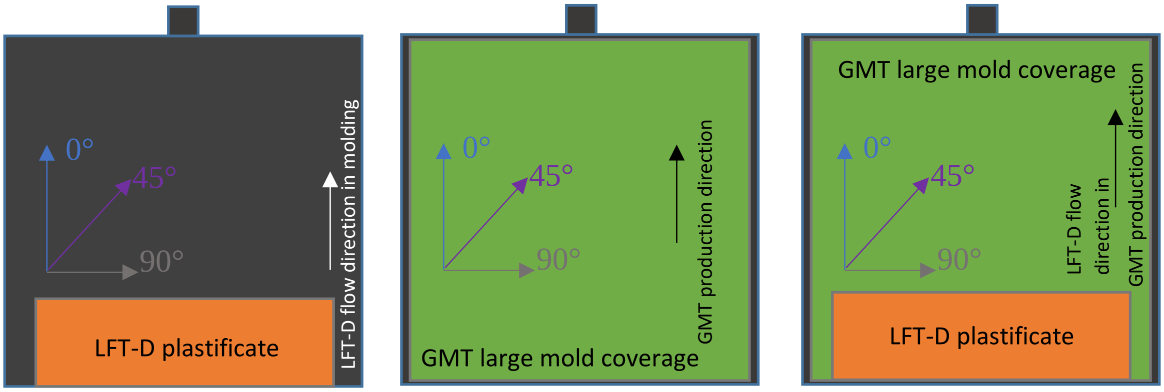

Figure 10 Direction assignment as per charge placement for various material systems in square plaque mold

When comparing the pure GMT to pure LFT-D material, test results consistently suggest that GMT material had superior mechanical properties compared to the LFT-D material. The superior mechanical properties can be attributed to the higher fiber content in the GMT materials compared to LFT-D material. The enhanced performance in the 90° direction in GMT compared to LFT-D is also caused by the presence of longer fibers in GMT in the 90° direction [6]. The anisotropy is also less prominent in the GMT material compared to LFT-D. The anisotropy in the LFT-D material can be attributed to the longer fiber lengths strongly aligned in the direction of the flow. Whereas the anisotropy in the GMT materials is intrinsic to the GMT manufacturing process in which the fibers tend to align in production direction, which is visually noticeable on the raw material. The direction parallel to the production direction was assigned as 0°.

The mechanical properties of the hybrid LFT-D GMT material as expected, are between that of standalone LFT-D and GMT materials but closer to LFT-D material. However, the anisotropy in the hybrid material is less than that in standalone LFT-D material. This is due to higher fiber content in the crossflow direction coming from the GMT portion. Approximately, 15% less anisotropy in the tensile strength between 0° and 90° in hybrid material compared to pure LFT-D. Roughly 14% less anisotropy in the flexural strength between 0° and 90° in hybrid material compared to pure LFT-D is observed.

Conclusion

The current study agrees with literature that mechanical performance of GMT material is superior to that of LFT-D [7]. The superior mechanical properties of the GMT material also impart less warpage to the part. A tailored material replacement approach has been demonstrated in this study which allows enhancement in material properties and reduction in part warp by replacing roughly 25% of the LFT-D material with a superior GMT material. This approach allows the user to leverage the benefits of both material systems; the LFT-D portion is suitable for filling more complex geometries due to better flow and the GMT portion reduces part warpage to levels close to that of a pure GMT part. The minimal amount of GMT material used in the hybrid combination compared to material required for a pure GMT part can be prepared for the over-molding process at a much faster pace to match LFT-D cycle time. Thus, the proposed material combination can support high volume automotive scale manufacturing while maximizing the benefits from the two material types used.

Future work

To extend the investigations further the interface between the two materials used in the hybrid systems should be looked in greater detail. In addition to the quantitative measurements of the warpage through deformation energy metric, a warpage pattern comparison method can help identify warpage in single material and hybrid combinations.

Acknowledgement

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