NEW MOLDING PROCESS OFFERS UNIQUE LEVELS OF DESIGN COMPLEXITY, MECHANICAL STRENGTH, COST REDUCTION FOR LONG-FIBER THERMOPLASTIC COMPOSITES

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Abstract

As energy costs continue to be unstable, the need for lightweighting in the automotive segment and the broader transportation industry is ever present, as is the need to develop materials and manufacturing processes that can improve performance, aesthetics and cost. Polymer composites can be an important materials/process option for achieving such goals.\[1\]

The mechanical benefits gained (with resulting ability to reduce nominal wall thickness and therefore part weight) by preserving fiber length in the final part are well documented in the literature and evidenced by the growing market for a broad range of composite materials / processes in transportation. No family of composite materials have grown faster over the past decade than long-fiber thermoplastics (LFTs) - both in pellet form (for injection molding) and with inline-compounded (ILC) direct molding processes (D-LFT) for injection and compression molding.\[2\] However, post-mold fiber lengths attained with traditional LFT injection methods are typically restricted to 5 mm / 0.2 in., while compression molding is limited in its three-dimensional (3-D) design capabilities and associated post-mold trimming requirements.

A new variant on injection-LFT technology has emerged to offer significant benefits over traditional thermoplastic composites molding processes through rapid cycles, excellent surface finish and 3-D design opportunities. This is achieved in a closed molding process similar to LFT injection, yet produces parts whose mechanical properties are closer to those produced by D-LFT compression molding, since post-mold fibers are far longer – typically 10 mm / 0.4 in. even in very-complex designs, and up to 50 mm / 2.0 in. in simpler structures. The generic name for this new technology, 3-D-LFT, is derived from the abovementioned benefits: 3-D injection molding design capabilities coupled with the mechanical properties typically only found in D-LFT compression molding.

This paper summarizes the research and results of a comprehensive study on the effects of and benefits demonstrated by this new molding process through an analysis of its design flexibility, material formulation and fiber-length retention, as well as cycle times and shear reduction. These benefits are illustrated through a case study using test piece results as well as operating parameters obtained from molding a large, complex, long-glass fiber polypropylene (LGF-PP) part.

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Technology Overview

The ability to preserve post-mold fiber length and still achieve high-levels of cost-effective parts integration (which, in turn, is achieved through design complexity and tooling action) have been a driving factor in the development of LFT injection molding. The large installed base of injection-molding capacity also provided the ideal springboard for LFT introduction to push the frontiers of material performance achieved in a closed-mold environment. However, one of the challenges in terms of retaining fiber length has been the amount of fiber attrition that occurs when the melt is forced (under high pressure) through check valves, narrow channels, hot-runner systems and small gates, all of which tend to twist and break fibers. Special attention has been given over the years to reducing fiber attrition through measures such as valve design, increased runner and sprue sizes, as well as larger gates. However, these measures often only lead to incremental improvement in fiber lengths and negatively impact cycle times and the ability to fill intricate parts and long flow lengths before freeze-off occurs. This, in turn, affects part and process economics. Another disadvantage of LFT injection is the number of gates required, hot-runner and mold complexity, as well as the sheer size and cost of presses and molds that are necessary to form large parts, all of which makes it an expensive approach for small to medium production volumes.

Many advances have been made to LFT injection molding over the years to improve post-mold fiber length retention and hence mechanical properties. However, even today it still cannot achieve the toughness and stiffness exhibited by parts that are compression molded with glass-mat thermoplastic (GMT) composite with continuous (random or woven) glass or chopped-glass mats. On the other hand, even with chopped-glass mat, GMT has trouble achieving good glass penetration in tall, thin design features, as its longer glass tends to bridge across intricate design details. Furthermore, as a semi-finished good, GMT can be a fairly costly material input. On the thermoset side, sheet-molding compound (SMC) and bulk-molding compound (BMC) have similar challenges filling complex, intricate designs, plus both materials require significant post-mold finishing, are heavier and more brittle than GMT, and have recycling limitations. Additionally, there are few resin choices commercially available for compression molding.

As a result of the capital cost, production volume, and material performance limitations of closed-mold injection processes, as well as the design and materials limitations of compression molding of materials like GMT, SMC and BMC, D-LFT compression molding was developed and is, by and large, the process of choice whenever fiber lengths in excess of 5 mm / 0.2 in. are required in the final part. However, D-LFT compression molding comes with its own set of drawbacks, including, limited draw depths, potential for product inconsistency (owing to at-press compounding), need for post-production finishing steps such as cutting and trimming, as well as the effort involved in molding complex 3-D parts with undercuts and through-holes.

Generally, LFT injection molding is used for smaller, more complex parts with lower material property requirements, whereas D-LFT compression molding is focused on larger parts that require higher mechanical properties.
The 3-D-LFT process was developed to capture the major advantage of compression molding – fiber-length retention – while overcoming all of the abovementioned disadvantages of compression molding by basing it on traditional injection molding. Hence, machines utilizing this new technology are 90% similar to conventional injection molding machines (see figure 1 below), with the major difference being the way in which molten material is injected into the closed mold.

Figure 1: Illustration of a 3-D-LFT machine with a standard plasticizing screw

Figure 1: A new composites injection-molding process produces parts whose fiber-length retention is typical of that seen in compression molding even with high 3-D design complexity as is typical of injection molding and this is accomplished with rapid cycle times in closed mold
The 3-D-LFT process uses a series of pistons to introduce the melt into the mold rather than a hot runner system (see Figure 2 above). The final piston-face becomes part of the bounding wall of the mold, enabling the gate size to be increased up to 100 mm / 3.94 in. in diameter without the need to cool a sprue (see Figure 3 below). The gate is thus large while material is being injected, and closed completely while cooling takes place, which is why the phrase “large gate/no gate principle” was coined. As with conventional injection, the melt stream is transferred into a metering section, from which a measured volume of material is then transferred into the mold and packed out with the packing piston.

Corollary benefits of this molding method include faster fill-times, lower fill pressures and melt velocity, lower material shear and a reduction in the clamp force required to process even large parts vs. conventional injection molding machines. Additionally, parts produced in the 3-D-LFT process show excellent, random fiber dispersion, which helps ensure consistent mechanical properties in the X, Y, and Z axes. The most important features, however, are that post-plasticization fiber-lengths are retained and carried into the final part while the number of weld-lines is minimized due to the single injection point.

A further benefit of the new technology is that it works equally well whether used to transport and inject material from a D-LFT twin-screw extruder or from a single-screw extruder fed with LFT pellets. Both types of systems have been developed and successfully used to manufacture parts with long fibers and exceptional mechanical properties. This new process thus enables complex injection-molded parts to retain post-mold fiber lengths in excess of 10 mm / 0.4 in. on average without sacrificing cycle time or design flexibility.
Material Possibilities

The new technology is able to process all of the thermoplastic materials used in traditional LFT or D-LFT injection or compression molding. The market for LFT materials is dominated by glass-reinforced polypropylene compounds primarily due to low cost and ease of processing.[7] Polyamides (PA, commonly called nylons) represent the only other significant class of commercial LFT materials and they are used in higher temperature, higher performance applications.[8] Other engineering thermoplastics with limited applications in the LFT field include thermoplastic polyurethane (TPU), polyoxymethylene (POM, commonly called acetal), polybutylene terephthalate (PBT), polyethylene terephthalate (PET), polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) composites.[9]

Forming of hydrophilic resins like PET and PA has mostly been limited to closed processes like injection molding due to the detrimental effects moisture uptake can have on finished part mechanical and aesthetic properties. However, when it is desirable to increase mechanical performance (by retaining greater fiber length in molded parts), some suppliers have offered D-LFT or GMT grades for compression molding. Since the new 3-D-LFT technology is an entirely closed-mold process, it provides molders and end users with the ability to work with higher performing resins like PET and PA without exposure to moisture during forming, yet still achieve higher mechanics typical in compression molding. This can be done without sacrificing design complexity, cycle time, or capital cost.

3-D-LFT Process Performance: A Case Study

Overview and Methodology

Pallets were selected as the first commercial product to be manufactured using the new technology, firstly because of the vast opportunity for a cost-effective, high-performance pallet, and secondly, because it would showcase the abilities of the technology in terms of mechanical properties (through fiber-length retention) and design flexibility. Based on economic feasibility, it was determined that the pallet needed to be a single unit that could be produced in one process step with a cycle time of 90 sec or less and consist of a LGF-PP composite. It was also desirable for the pallet to weigh 18 kg (40 lbs) or less in order to keep raw material costs down. Further, the pallet needed to be able to:

- Be edge-racked up to 1,250 kg / 2,800 lbs while deflecting less than 12.7 mm / 0.5 in.,
- Carry a static load of 10 MT / 22,000 lbs or more with no deformation, and
- Be able to withstand impact sustained during rigorous usage

as per the standards defined by the Grocery Manufacturer’s Association specification.∗

Using these requirements, it was determined that the pallet’s mechanical properties would have to meet or exceed 100 MPa / 14,500 psi in tensile strength and 2.68 J/cm / 5.01 ft-lbs/in notched Izod impact strength, which could only be attained if average fiber lengths exceeded 10 mm / 0.4 in. in the final part.

Several design options were analyzed and compared based on functionality and economic viability. The final pallet design that was chosen is a very large, complex part with multiple ribs, thin walls, through-holes and design features that would be impossible to mold in one step with compression molding (see figure 4 below). It was also important to find a design that would provide real-world process and performance validation of the 3-D-LFT process vs. traditional LFT injection molding.

The mold consists of 4,382 separate components, weighs 24.7 MT / 54,500 lbs, and features a single, large opening (100 mm / 3.9 in. diameter) through which material is injected with the 3-D-LFT technology. The total volume of the pallet is 16.32 l / 996 cu in. and it has a surface area of 1.2 m² / 12.9 ft². Rib structures of 2.0 mm / 0.08 in. thick and 55 mm / 2.17 in. depth were incorporated into the pallet design, while the feet are 5 mm / 0.2 in. thick and 160 mm / 6.3 in. deep. The final mass of the pallet, as molded, was 16.2 kg / 35.7 lbs.

![Figure 4: One-piece pallet design featuring multiple ribs and through-holes.](image)

A glass-fiber-reinforced polypropylene was selected as the base material for the one-piece pallet due to its cost / performance ratio and easy processing. However, various tests were also conducted with LGF-PA in smaller applications in order to determine whether the same fiber-length retention could be achieved.

The methodology used in the development of the pallet material formulation was to utilize test pieces and test parts molded on a 180-metric ton 3-D-LFT system by feeding pultruded pellets with fiber-lengths varying from 11mm / 0.43 in to 25mm / 0.98 in. ASTM test pieces were used to determine mechanical properties (tensile strength, flexural strength and impact strength) by molding them on the same 180-metric ton 3-D-LFT system and testing them in accordance with the relevant ASTM test standards, while the retention of fiber lengths in complex designs would indicate that these properties could be approximated in the final part. Glass fiber and additive packages from a number of suppliers were evaluated, and a specific combination was selected based on small-scale testing.

The test piece mold is standard but features a large 40 mm / 1.6 in. diameter gate (see figure 5 below), whereas the test part was developed specifically with very shallow draft angles (to test the ejection of polymers such as PET), thin-to-thick melt flow paths, variable wallstock transitions (1.7 mm / 0.07 in. to 6.2 mm / 0.24 in.), and cross-ribs with no radii to test fiber attrition when melt direction changes suddenly (see figure 6 below).
Finally, the one-piece pallet was molded on a 2,000-metric ton 3-D-LFT system fed by a twin-screw extruder similar to those found on standard D-LFT machines.
Mechanical Properties of LGF-PP

The first step in determining the material formulation for the one-piece pallet was to evaluate the various commercially available glass fibers with a range of additive packages. The best cost / performance formulation was then selected and compared based on glass-fiber loadings.

Table I: Mechanical Properties for Formulations with Different Glass Loadings (by weight)

<table>
<thead>
<tr>
<th>Material</th>
<th>Izod Notched (J/cm / ft-lbs/in)</th>
<th>Tensile Strength (MPa / psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21% LGF-PP</td>
<td>2.03 / 3.80</td>
<td>88 / 12,760</td>
</tr>
<tr>
<td>28% LGF-PP</td>
<td>2.72 / 5.09</td>
<td>104 / 15,080</td>
</tr>
<tr>
<td>36% LGF-PP - A</td>
<td>3.01 / 5.63</td>
<td>130 / 18,850</td>
</tr>
</tbody>
</table>

Figure 7: As would be expected, higher fiber loadings deliver marked improvements in mechanical properties

It is clear from these test results that the required mechanical properties for the pallet would be reached with a glass loading of 28% or higher. In subsequent tests, material formulations were optimized and surpassed the results of the initial results. The final properties of the material formulation chosen for pallets are given in Table II below.

Table II: Mechanical Properties Chosen for Pallets

<table>
<thead>
<tr>
<th>Material</th>
<th>Izod Notched (J/cm / ft-lbs/in)</th>
<th>Tensile Strength (MPa / psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36% LGF-PP - B</td>
<td>3.66 / 6.84</td>
<td>127.9 / 18,545</td>
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</table>
Fiber-Length Retention

The 3-D-LFT injection system was specifically designed to minimize fiber breakage – from the plasticizing unit right through to the system’s large gate/no gate principle. The 180-metric ton system was not optimized for any of the materials tested, but rather used a standard plasticizing screw coupled to a 3-D-LFT injection unit. The test part was molded with a number of material formulations on this machine configuration. Below are some images of 30% LGF-PP and 50% LGF-PA test part halves after burnout.

Figure 8: Burnout half-section of a 50% LGF-PA test part

Figure 9: Burnout half-section of a 30% LGF-PP test part showing excellent glass penetration
The next step was to determine the extent of fiber-length retention in a large, complex part such as the one-piece pallet. Due to constraints on the 2,000-to 3-D-LFT system, the pallet was molded with only 21% glass loading by weight in an 80 melt-flow index (MFI) polypropylene, which resulted in a final weight of 16.2 kg / 35.7 lbs. The smallest cross-sectional area of the pallet is 9.6 cm² / 1.49 sq in. while the gate size was 100 mm / 3.9 in. in diameter. Cutouts were taken from the pallet (see figure 10 below) at the point that represented the longest flow (1.2 meters / 3.9 ft.) and the polymer was burnt off to reveal the resulting retained fiber lengths (see figures 11 & 12 below).

![Figure 10: Area where cutout was taken from the pallet (1.2m / 3.9 ft flow-length from gate)](image)

In both tests, the images clearly show that fiber-lengths are preserved, with minimal fines and short fibers present. The conclusion of these tests is that the new process is able to preserve the fiber lengths contained in the material after it exits the plasticization stage into the final part. Unlike standard LFT injection molding, the new process does very little damage to fibers during the injection stage, which means that mechanical properties of the molded parts should be closer to those seen in D-LFT compression molding than with injection LFT.

Given the previous restrictions of the 2,000-metric ton system that prohibited the initial pallet design to be molded with more than 21% glass loading, a new 3-D-LFT pallet machine is currently being built that will make it possible to mold LGF-PP composites with even higher glass loading levels (28-50% by weight).
Figure 11: Cutout section from the pallet

Figure 12: Burnout of 21% LGF-PP cutout
Shear and Weld-lines

Optimizing the number of gates, gate design, gate positioning and the use of gate valves to limit fiber attrition in injection molding represents a tradeoff between fiber lengths and cost, complexity and cycle times, and these measures are also often unable to consistently keep fibers longer than the critical length necessary.

The 3-D-LFT technology’s gate is an order of magnitude larger than conventional injection molding gates, which makes it possible to fill at higher rates with significantly lower injection pressures and thus reduced shear. The one-piece pallet was molded with a 100 mm / 3.9-in. diameter piston resulting in an effective gate opening of more than 28 cm² / 4.34 in.². This large gate was achieved jointly through the size of the injection piston and the design of rib structures below the entry point of the melt into the tool. In order to match the low shear generated by the 3-D-LFT process, a standard LFT injection molding machine would require approximately 28 injection points whose diameters would need to be 10 mm / 0.4 in. each. However, with so many gates, the number of weld-lines would also increase exponentially, creating weak sections throughout the part – a highly undesirable and risky situation for a part that will be subject to high levels of static and dynamic loading.[10]

The ability to fill the mold quickly through a single, large gate, which reduces glass breakage as well as injection forces and material shearing while shortening cycle times, thus has a major impact on residual stresses and subsequent fiber-length retention, as well as limiting weld-lines and weak sections in the part.

Cycle Time

Cycle time is another critical cost driver in most applications. The large gate/no gate principle of the new process allows for much faster mold-filling rates without introducing unwanted shear into the material at the gate. This inherent ability of the 3-D-LFT process, coupled with clever product design, can effectively contribute to significantly faster cycle times compared to standard LFT injection molding.

Due to rapid mold filling, less material prematurely freezes-off / solidifies against the mold walls, so surface finish quality is enhanced while lower mold temperatures can be used without increasing stresses in the part. The rapid filling also contributes to more uniform cooling and therefore less molded-in stresses, which has a positive effect on warpage.[9]

The separation of the plasticizing and injection stages is another aspect that reduces cycle time. The metering cylinder is recharged while packing and cooling take place. This means that as soon as the mold closes after ejecting the previous part, the next shot is ready. This functionality is especially useful in large parts, as the time taken to plasticize the next shot can be considerable.

The one-piece 16.2 kg / 35.7 lb pallet, molded with 21% LGF-PP, has a complete cycle time of 70 seconds. This is possible because the entire volume of the mold (16.32 liters / 996 cu. in.) is filled within 7 sec, after which packing, cooling and part ejection takes place for the rest of the cycle.
Clamping Force and Injection Pressure

The one-piece pallet was molded at a peak injection pressure of 240 bar / 3,400 psi on a machine with 2,000-metric ton clamping force. It would be quite challenging to mold this part on a similar standard injection molding machine at the same cycle time of 70 sec and with the same part performance. In addition, multiple injection points would need to be used, which would drastically increase the number of weld-lines, and experience shows that glass fiber retention would be lower and hence mechanical performance would correspondingly be reduced as well. It is estimated that the 3-D-LFT process used to mold the pallet reduces the necessary clamping force and peak injection pressures by at least half as a result of its very large gate and subsequent fast fill rates.

Shot Weight Flexibility

The separation of the plasticizing, measuring and injection processes in the 3-D-LFT technology allows for considerable flexibility in terms of shot weight capacity, and means that a much wider range of shot weights can be accommodated than would typically be possible with standard injection molding machines.

Pallet Performance

The commercial viability of the pallet was dependent on a key set of factors. Table III below compares these initial criteria with actual measured performance of the pallet.

Table III: Initial Pallet Criteria vs. Actual Performance

<table>
<thead>
<tr>
<th></th>
<th>Initial Criteria</th>
<th>Actual Pallet Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Strength</td>
<td>&gt; 2.68 J/cm / 5.01 ft-lbs/in</td>
<td>2.03 J/cm / 3.80 ft-lbs/in</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>&gt; 100 MPa / 14,500 psi</td>
<td>88 MPa / 12,760 psi</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt; 18 kg / 40 lbs</td>
<td>16.2 kg / 35.7 lbs</td>
</tr>
<tr>
<td>Cycle time</td>
<td>&lt; 90 seconds</td>
<td>70 seconds</td>
</tr>
<tr>
<td>Racking load</td>
<td>1,250 kg / 2,800 lbs</td>
<td>&gt; 2,750 kg / 6,000 lbs</td>
</tr>
<tr>
<td>Max, deflection</td>
<td>12.7 mm / 0.5 in.</td>
<td>&lt; 10 mm / 0.4 in.</td>
</tr>
<tr>
<td>Static load</td>
<td>10 MT / 22,000 lbs</td>
<td>&gt; 10 MT / 22,000 lbs +</td>
</tr>
</tbody>
</table>

It is clear from this data that although the initial material did not meet the target for impact or tensile strength, the pallet was quite successful in all other ways. The material strength issue was likely caused by system constraints that did not allow higher glass loading than 21%. In the next generation design, system changes will eliminate the glass-loading constraint (allowing up to 50% glass-loading levels), which should easily boost strength performance. Previous work has shown that boosting glass loading to 36% increases impact strength to 3.66 J/cm / 6.84 ft-lbs/in and tensile strength to 127.9 MPa / 18,545 psi and comprehensively surpass the required criteria.
Even though the pallet molded on the 3-D-LFT system had only 21% glass reinforcement by weight, it is the first commercially viable composite pallet that can rack the required weight of 1,250 kg / 2,800 lb without needing additional reinforcements such as steel bars. It is also the lightest pallet in the world capable of meeting the required racking specifications – in fact, the pallet is able to carry double the required load and still conform to the standard.

*Figure 13: Pallet carrying 10 MT / 22,000 lbs static load with no deformation*

*Figure 14: Pallet racking 2.75 MT / 6,000 lbs while deflecting less than 10 mm / 0.4 in. in the middle*
Conclusion

The new 3-D-LFT technology developed by LOMOLD represents a combination of material, machine and process advancements that promise to revolutionize the LFT industry. It is a turnkey solution that caters for a vast range of products and can replace a number of traditional processes by allowing lightweighting through increased mechanical properties and complex design, while shortening cycle times and producing finished parts in the mold by eliminating the need for post-mold finishing. It further increases material formulation possibilities, as moisture-sensitive polymers like nylon and PET can be processed without exposure to air (as in conventional injection molding) while retaining greater fiber lengths and hence increasing mechanical performance in the final part (as with compression molding).

The capability of the 3-D-LFT technology to mold large parts while retaining fiber-lengths is demonstrated by the successful molding of the pallet in a production environment. A new machine is currently being built that will allow either LFT pellets or molten material from a D-LFT extruder to be fed to the 3-D-LFT injection unit, which will significantly increase the flexibility of the system. Work is also continuing on further lightweighting and functional enhancement of the pallet through intelligent design based on the results from the first pallet.

References


