INJECTION MOLDED LONG GLASS FIBRE POLYPROPYLENE COMPOSITES FOR AUTOMOTIVE FRONT END CARRIER APPLICATIONS

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Abstract

The introduction of long-fibre reinforcements into the matrices of polymeric materials has lead to the development and introduction of many engineered solutions for applications which had once solely been the province of metal designs. The combination of long glass fibre with a highly economical and processable polymer such as polypropylene has significant advantages for both the designer, in terms of weight reduction, design flexibility, and cost savings, as well as to the moulder, in terms of efficiency and productivity. The utility of this polymeric solution is further enhanced when it can be combined with unique bonding materials to allow it to be bonded with metal for structural enhancement. This paper will review the development of a long glass fibre polypropylene polymer in concert with the development of a unique adhesive solution to form a polymer-metal hybrid solution. This utility and effectiveness of this solution will be demonstrated in the structural, modular application of an automotive front end carrier.

Introduction

There is a recent trend in the automotive design, well-founded on the basis of cost/assembly time efficiency, ease of assembly at the OEM, incorporation of technology and complexity, and solution-based engineering, to gravitate toward a modular approach to systems. Front End Modules (FEMs) are one such example of an opportunity for a modular approach, as a significant amount of vehicle functionality can be packaged within an FEM if the OEM chooses to go with an “open” body-in-white architecture. The Front End Carrier (FEC) is the main component of FEM, providing the mounting functionality to all the parts of FEM in addition to delivering structural integrity to the front end. The modular approach expands the freedom of the engineering design, allowing for a multitude of potential solutions. One such possible engineering design, which will be the primary topic of this paper, is the utilization of long-glass-fibre polypropylene as an FEC substrate material in a bonded hybrid approach to an FEM. The benefit of this novel bonding technology is that it enables the use of low cost glass reinforced fibre filled polypropylene as a structural material for the FEC as it allows the bonding of steel to low energy surfaces without any surface pre-treatment.

The beneficial incorporation of long glass fibre reinforcement in polypropylenes has allowed the utilization of this lower cost, widely available, highly processable polymer in engineered applications demanding structural, thermal and precise dimensional performance such as the FEC. Long glass fibre thermoplastic composites can be used in applications where design and material are optimized for metal replacement or other material substitution opportunities.

This paper will demonstrate properties attainable in long glass fibre polypropylene (LGF-PP) composites, and some of the applications on which the composites have been successfully validated, with a particular focus on front-end carrier panels. The paper will also review the latest developments in low-energy surface adhesive technology which allows the PP to be bonded directly to metals without any surface pre-treatment. The paper will detail the advantages that these composites can attain when they are designed as an integrated system and paired to this innovative bonding technology in a front-end carrier application.

Polymer Design and Development Considerations

The replacement of metal and consolidation of components in order to gain weight savings and reduce cost in the vehicle are key initiatives driving a need for LGF (long-glass fibre) materials. Glass filled thermoplastic composite volumes have been growing at comparatively high rate, greatly fueled by an expanding number of automotive applications. The key reasons that glass reinforced thermoplastics have gained acceptance so readily in the marketplace are a combination of the elements of attractive economics, recyclability, ease of moldability/processability, and excellent balance of properties that the polymeric composite can offer. The long glass fibre matrix constrained within the thermoplastic composite contributes to mechanical strength and dimensional stability, whilst the base polymer resin provides the toughness and processability required to efficiently manufacture a wide variety of complex part designs and applications. The final part performance of such polymeric composites is influenced ultimately by such factors as glass fibre length, processing technique, and resin formulation. In turn this formulation technology includes the base thermoplastic resin, coupling chemistry (or “mega-coupling” chemistry[1,2]), processing additives, environmental performance enhancers, and colorants. Specifically, the use of long glass fibre reinforcement in polypropylenes has allowed the use of a lower cost, widely available, highly processable polymer (such as polypropylene) to be used in engineered applications demanding structural and precise dimensional performance. The potential benefits of this technology solution include part consolidation and weight reduction, as well as improved economics. Long glass fibre thermoplastic composites can be, and are increasingly being used, in applications where design and materials are optimized for metal replacement or other material substitution opportunities.

There are two primary methods of delivering long glass fibre composite thermoplastic parts: direct compression/injection and traditional pellet injection molding processes. The direct compression/injection processes include specialized extrusion-compression and/or extrusion-injection molding equipment utilizing glass roving; whereas the pellet injection molding processes utilize pre-compounded pellets (albeit of a 10-15mm length to maximizes the ultimate fibre length) to deliver the long glass fibre into the application through the use of standard traditional injection moulding machine technology.

LGF-PP Products and Processes

As a material solutions provider, Dow Automotive provides a portfolio of products and services in long glass fibre technology that include pultruded pellet grades for injection molding processes as well as DLGFPP (direct long glass fibre polypropylene) systems for direct compression/ injection molding processes. For this paper, the focus is placed upon the fully compounded, pultruded pellet injection molding processes and the development of the resin formulation necessary to meet the application needs and functionality of a bonded front end carrier design.

For pultruded pellet injection molding processes, long glass fibre pellets can be made available in a multitude of different grades with varying glass loadings (e.g. 20-60% by weight); although for front end carriers the higher stiffness and load bearing requirements tend to push the polymer design toward the higher long glass loadings – typically either 30 or 40%. In order to optimize properties, the fully compounded, pultruded pellets start with a nominal 11mm fibre length before molding in order to maintain a sufficient fibre length through the injection moulding process. It is also possible to use higher glass loading “concentrate” products, such as a 60% glass grade, specifically formulated with the appropriate additive levels to meet the needs of the desired application, and let them down in a controlled manner with a specified polypropylene resin either directly at the press or in an appropriately mixed off-line blender to deliver the desired end glass content and reduce the overall amount of compounding and heat history of the polymer.

The balance of material properties produced by long glass fibre composites may allow substitution from engineered resins like PC/ABS blends, ABS, SAN, and SMA to lower cost feedstock resin options, like polypropylene, or perhaps may allow reduction of wall thickness in part designs. Applications for long fibre reinforced thermoplastics continue to grow with new automotive applications in development such as front end carriers, instrument panels, door modules, lower and overhead console reinforcements. There have been Long Glass Fibre Reinforced Polypropylene (LGF-PP) solutions developed for all of these applications. We have developed a fundamental understanding of the effect of polymer architecture, formulation expertise, performance modeling and different processing methodologies involved and their effect on property performance.

When one looks at polypropylene from a general point of view, one sees the advantages of a widely available, relatively lower cost, easy to process, and recyclable material that has become a staple in automotive architecture. However, in general, unfilled polypropylene has rather low impact and stiffness properties, and therefore polypropylene resins are often modified to improve their mechanical properties. For example, in order to improve the impact properties, polypropylene resins are often elastomer filled – in which the elastomeric phase could be added in the reactor (copolymer production) or could be added through an additional compounding step. Adding elastomer, however, has an adverse effect on the stiffness of the polymer and does nothing for the dimensional variation properties (thermal expansion and shrink). In order to improve the stiffness and dimensional characteristics of polypropylene, the polypropylene is compounded with chopped glass or other minerals such as talc resulting in a short-fibre reinforced polypropylene.

Long glass fibre reinforced polypropylene is a composite technology which has the capability to improve both impact and stiffness properties of the polypropylene base resin. Figure 1 schematically illustrates the qualitative differences in properties for modified polypropylene resins:

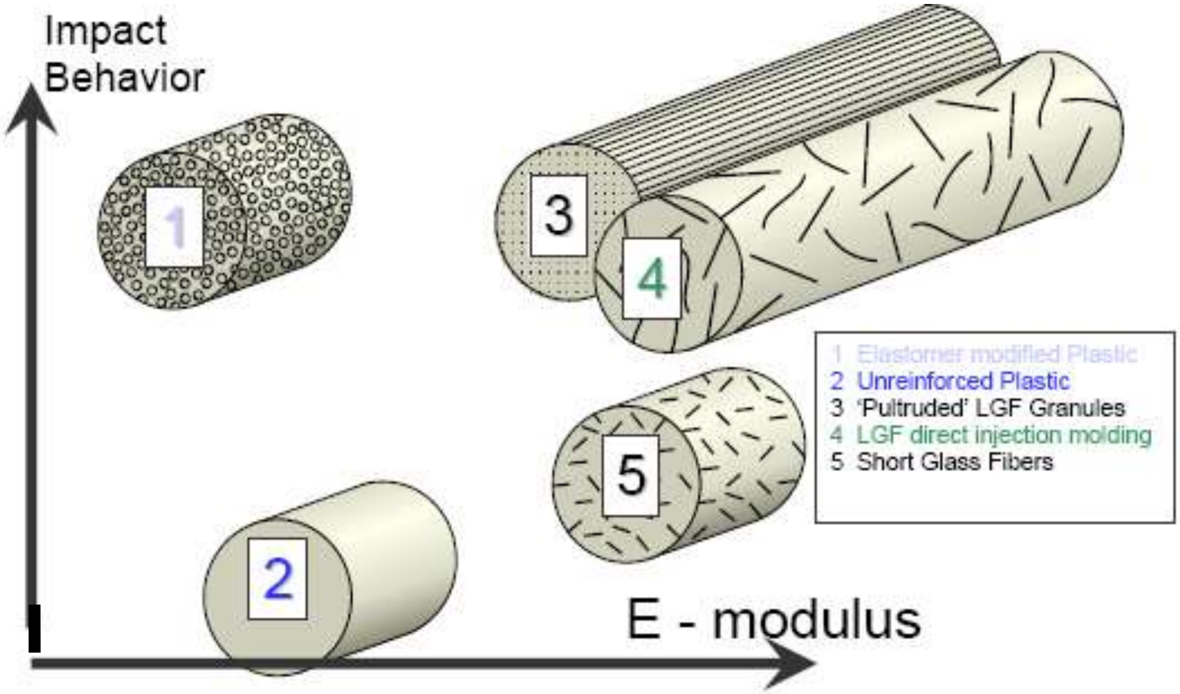


Figure 1: Effect on mechanical properties of modified polypropylene resins.[3]

In the specific case of DaimlerChrysler front end carrier applications, the polymer design centred around a 40% LGF polypropylene solution which could meet the requirements of the specification MS-DB21 (Type A) for injection molded long glass fibre filled polypropylene.

DLGF9411 40% Long Glass PP Product Development

In the front end carrier application there are several customer-driven critical to quality (CTQ) design parameters which ultimately drive the quality functional deployment (QFD) design strategy of the composite resin. These CTQ items include stiffness, property retention after heat aging, impact strength, dimensional capability, part performance and processability. It goes without saying that all of this design is done against the omnipresent backdrop of the minimization of overall system cost.

With these CTQ items foremost in mind, a polymer design evolved with careful consideration given to the formulation balance of the following:

1. Polymer Matrix Architecture – including PP types and blend ratios,
2. Thermal Stabilizers - additive type and level to meet the aging requirements
3. Additives - compatibilizers, coupling agents and process aid additives to optimize the performance of the material and manufactured part
4. Glass Reinforcement - type and sizing of glass.

The final glass loading in the formulation was predetermined to be 40% by weight for the proper balance of stiffness and dimensional capability in the design.

The end polymer formulation was then not only subjected to screening with the DaimlerChrysler MSDB-21 screening, but was also tested against the General Motors' Engineering Standards specification of 40% Long Glass Fibre Reinforced, Heat Stabilized Polypropylene, GMP.PP.112. The results of the polymer tested against these two specifications are shown below in Table I. Note that the difference in values is primarily attributed to the different test methods.

Adhesive Selection for LGF-PP

In order to maximize the utility of the LGF-PP polymer that has been developed for structural applications it is desirable that a mixed material hybrid solution be implemented with the composite and metal. This allows the designer to utilize the advantages of the polymer composite (light weight, processable, design flexibility) and the metal substrate (high fatigue strength for latches, high strength/weight ratio, etc). The question is how then should the two material be combined – and Dow set about to develop a unique bonded solution which would yield the best results.

The act of reliably bonding low energy surfaces such as polypropylene or polyethylene without any surface pretreatment to metal surfaces presents great difficulty to the industry. However, innovative adhesive chemistry has been developed to achieve that goal. This adhesive material is known as Low Energy Substrate Adhesive (BETAMATE™ LESA). This is an acrylic-based two component adhesive with a mix ratio of 1:1 of adhesive and curative. The adhesive is capable of bonding to low energy substrates such as polypropylene and polyethylene without the need for surface treatment and primer applications and has been described in other papers[4,5]. The ideal adhesive solution exhibits good wet-out, a bond strength which exceeds the tear strength of the substrates to which it is bonded, some elasticity to allow for thermal growth differences between substrates, excellent durability through environmental aging and a fast cure to reduce cycle time, and the adhesive development focused on delivering against these performance requirements.

Table II demonstrates the mechanical properties of the adhesive that was developed for the application. The relatively higher elongation to failure (19%) gives significant toughness to the adhesive causing the plastic rather than the bond itself to fail in lap shear tests.

Figure 2 graphically represents the increase room temperature strength of adhesive as a function of time. Sufficient lap shear strength of 0.35 MPa is achieved in 2 hours of cure time after which the bonded parts can be handled in the sub-assembly processes.

Table I: DLGF9411 (40% LGF) Physical Property Data as per DaimlerChrysler and GM Specifications

Physical Property	**Condition**	**Method**	**MS-DB21**		**GMP.PP.112**	
			Results	Spec	Results	Spec
Specific gravity	-	ASTM D792/ISO 1183	1.21	1.17-1.28	1.21	1.17-1.26
Ash (filler content) (%)	-	ASTM D2584	40	37-43	40	37-45
Izod impact (J/m / kJ/m^2)	Notched, 23°C	ASTM D256 /ISO 180/1A	222	160.2, min	18.2	11, min
Tensile strength at break (MPa)	5 mm/min	ASTM D638/ISO 527-1/2	115	68.9, min	113	95, min
Flexural modulus (MPa)	1.3 mm/min	ASTM D790 / ISO 178	7950	6270, min	9130	6070, min
DTUL (°C)	1.82 MPa	ASTM D648 / ISO 75	155	146, min	154	140, min
Multiaxial impact a. Maximum load (N) b. Total Energy (Nm)	2.2 m/s, 23°C	ASTM D3763	a. 1700 b. 11.5	a. 1588, min b. 5.7 min	N/R	
Multiaxial impact a. Maximum load (N) b. Total Energy (Nm)	2.2 m/s, -40°C	ASTM D3763	a. 2100 b. 10.1	a. 1588, min b. 5.7 min	N/R	
Heat aging Property Retention (%) Tensile Strength Notched Izod, 23 C	500h @ 150°C /1000H @ 140c		96 % N/R	60% retention	108% 99.8%	75% retention
Elongation at Break (%)	5 mm/mmin	ASTM D638/ISO 527-1/2	2.3		2.0	N/R
Mold Shrinkage (%), after 24hr	Para/Perp				0.12 / 0.79	
Coefficient of Linear Thermal Expansion (mm/mm/C x 10^{-6})	Para /Perp				14.7 / 42.5	

TABLE II: Mechanical properties of Betamate™ LESA

Mechanical Properties	
Tensile Strength – psi (MPa)	2,814 (19.4)
Elongation %	19
Young's Modulus, psi (MPa)	180,572 (1245)

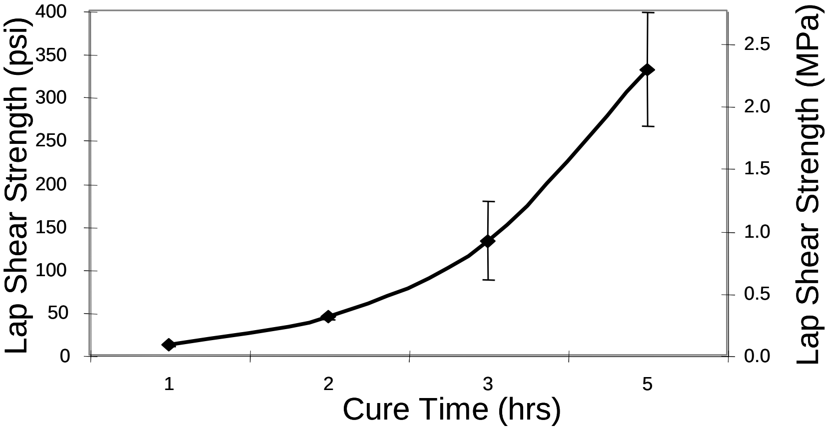


FIGURE 2: Lap Shear Strength of LESA as a Function of Cure Time

The advantages that the adhesive provides in terms of strength, structural integrity and stiffness of a hybrid structure are evidenced in Figure 3 below. In this case simulations of several Jeep Wrangler (JK) FEC samples were constructed, and then evaluated by increasing the load on a constrained fixture until failure. This was done to determine the maximum load that the structure could handle before failure, and then also provide an indication of the failure mode itself, and thus an indication of the efficacy of the bond between the metal and the composite. The load carrying capacity of the FEC was subsequently compared against a no adhesive rivet-only mechanical attachment solution. In addition to the stiffness improvement that was seen, the adhesive improves the load carrying capacity of the structure by up to 170% as demonstrated in Figure 3. The failure mode seen in all of the bonded samples was a substrate failure with no failure observed in the bonded joint. This is indicative of a very robust bond joint, and demonstrates the utility of the adhesive in the design.

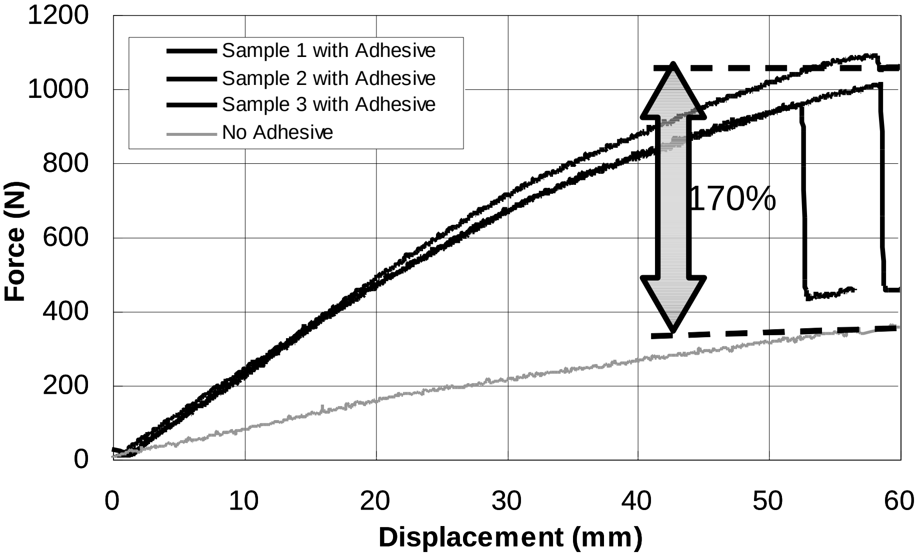


Figure 3: JK FEC Load Simulation – Adhesive Vs. Mechanical Attachment[4]

The Composite/Metal Bonded Hybrid Approach to FEM's

With the innovations described in the thermoplastic composite and adhesive arenas described above, the opportunity existed to synergistically combine these developments to produce a system solution for automotive applications. One such opportunity exists to join the steel and the plastic in a FEC is through bonding technology (Figure 4). The adhesive in this technology enables the joining of steel and plastic to form a closed box section, which has the highest moment of inertia - yielding better bending and torsional modulus performance than open box solutions such as overmoulding. Adhesive bonding provides a continuous joint between steel and plastic, thereby distributing the load uniformly across the interface and reduces difficulties with stress concentrations, as is problematic and load-limiting with mechanically attached or heat staked hybrid systems. In addition, the system architect obtains design flexibility to design the steel and plastic independently other than the considerations necessary for the adhesive bonding. Based upon the performance requirements and the method of mounting the hood retaining latch (a function best served by metal), plastic can be used on one to three faces of the box section with the remaining area being steel or metal. The use of a bonding technique is very volume-efficient and allows the designer to work in a limited packaging space, creating structures which have high stiffness to weight ratios. The choice of the most efficient method of combining metal to plastic is important in order to achieve the maximum contribution from all the members of FEC.

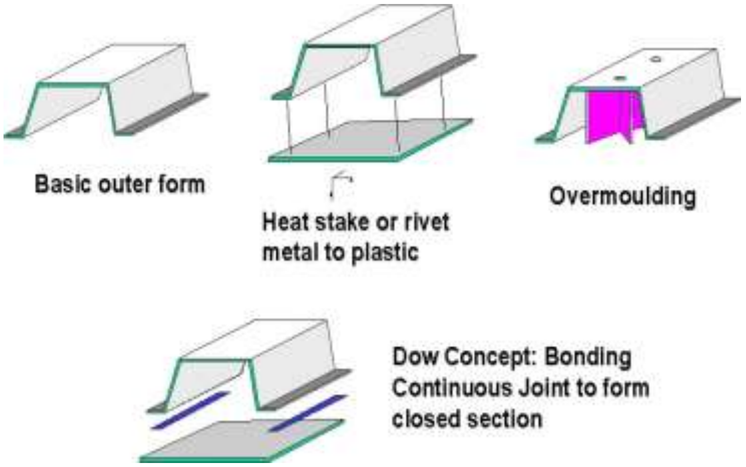
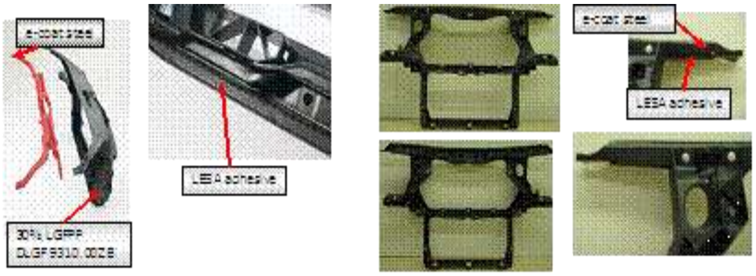


FIGURE 4: Metal/Plastic joining techniques [5]

LGF-PP APPLICATIONS

The first application of a bonded technology FEM solution was demonstrated in the Volkswagen Polo vehicle launched in 2005. High stiffness was achieved by bonding a thin piece of steel to the plastic carrier made from 30% LGFPP. In the application the adhesive is applied on the plastic surface and steel is bonded intimately to the plastic with the LESA adhesive. The structure provides significant advantages in terms of cost and weight savings to traditional FEC structures which were evaluated in the vehicle's design phase. This bonded structure replaced a glass mat thermoplastic structure in the previous model design.

The first application of FEC bonding technology in North America was incorporated in the Jeep Wrangler (JK) by the tier 1 integrator Decoma, who moulds and bonds the FEC as well as assembles and sequences the FEM module itself. The previous front end of this vehicle model had a closed BIW architecture with an all-steel welded system that consisted of eight components and was relatively heavy. The bonded steel/plastic assembly module is now mounted to the vehicle directly in the trim shop in a simple operation by the OEM and features a reduction in two components and is 15% lighter than the original design. In addition to over 15% weight savings, the bonded assembly offers a 25% cost savings compared to the traditional all steel structure[6].



VW Polo Launched April 2005 **Dodge Nitro Launched September 2006**

Jeep Wrangler, Launched 2006

FIGURE 5: FEC Bonded Hybrid Applications (VW Polo, DCX Jeep Wrangler, DCX Dodge Nitro)

The VW plastic composite hybrid part example shown in Figure 5 is a two piece design made from either 30% LGFPP and is bonded to the upper closed section steel cross member by LESA. In order to avoid additional any fixturing costs during adhesive curing, the steel and plastic parts are held together by rivets in different planes. The load transfer path between the lower cross member and plastic to the upper cross member is effectively and evenly distributed through the adhesive bead.

Another effective use of FEC bonding technology was exhibited on the front end of Dodge Nitro. In this scenario, the plastic is a one piece carrier made from 40% LGFPP which is bonded to the stamped steel upper cross member using LESA as illustrated in Figure 5 and 7. High bending and torsional stiffness along with high load carrying capacity was achieved by the effective use of steel plastic and adhesive to form a closed box section using two bond lines in two different planes.

The FEC's discussed earlier are backbone of the FEM's and provide structural and dimesional integrity to the vehicle. In addition they hold several different components of the front end which may include cooling modules, headlamps, attachments for the fascia and radiator grille, molded in elements for the attachment of temperature sensors and thus provide functional diversity. The applications discussed earlier have effectively implemented bonding technology by using different bond geometry designs to join steel and LGFPP together and achieve cost, weight savings and performance improvements. The design flexibility achieved by bonded structures becomes even more attractive when the tiers have to work within the constraints of a limited packaging space but still have to meet the weight, hood pull, hood slam, and crash and durability performance requirements.

DLGF9411 LGF-PP Pellet Customer/Application Validation Trials

While the polymer design phase of the project had succeeded in its goal to meet the specification requirements set forth by the OEMs for the application, another key metric for the determination of the suitability of the substrate resin was the actual part quality, processability and functional performance of the material in the desired application. In the case of the 40% LGF-PP pellet application, the qualification of the polymer resin material was targeted on the two novel DaimlerChrysler front-end carrier (FEC) system applications illustrated earlier. These applications were unique in that they were a bonded solution, meaning that the PP-based composite carrier was bonded to metal underbody structure and frame of the vehicle using Betamate™ low-energy surface adhesive (LESA) technology. This required the plastic design not only to meet the normal physical properties required of a composite thermoplastic solution, but also to be designed to optimize the adhesion requirements with the LESA technology in order to ultimately maximize the system properties of the module itself. The programs were being developed as a modular approach by Decoma Systems Integration Group, who assembled all of the individual components in the front-end (e.g. fan, wiring, windshield wiper fluid bottle, headlights, etc) and bonded the FEC to the steel underbody structure in a just-in-time delivery satellite plant to the DCX assembly plant.

It was the goal of the development team to demonstrate first, the polymer properties, as described above per the specification package requirements, and second, through part manufacture and trials with customer tooling to demonstrate mouldability and part functionality. The key metrics involved in the evaluation of the material were:

- ***Processability*** - Characteristics of this category include: defect rate, cycle time, releasability, compatibility with master set-up profile on machine, material handling, etc.
- ***Functional Performance*** - These characteristics involved the part itself with such attributes as surface aesthetics, stiffness, rivet acceptance, dimensional layout, vibration performance, bondability, etc.

Validation Summary – JK (Jeep Wrangler) FEC Program

The LGF-PP (40% glass- filled) part was run on a standard injection moulding machine. The material was processed using a standard set of injection parameter recommendations and ran very well. There were no issues with the post-moulding assembly equipment, which involved the insertion of bushings and rivets to the FEC frame.

The JK FEC tool is a P-20 steel tool with two cavities (left hand and right hand) a manual core section in each. The mould is water-cooled and set at about 125 F. It is an important characteristic of the tool that the temperatures remain reasonably consistent in order to prevent any localized warpage. The tool produces the substrate part shown in Figure 6.

The part is single gated near the centre, but is not a balanced fill. The C-channel is the last area to fill, and is the farthest point from the 4-way locator which makes this area susceptible to warp or dimensional variation. The unbalanced gate location was selected based upon design engineering work to optimize fibre orientation and maximize the strength of the part, and moving the gate to balance fill and minimize dimensional issues which would normally be the best option was not possible. It was also decided not to consider multiple gates, as it was desired that no knit lines or weak points be present on this part, which made for an increased flow length for the material.

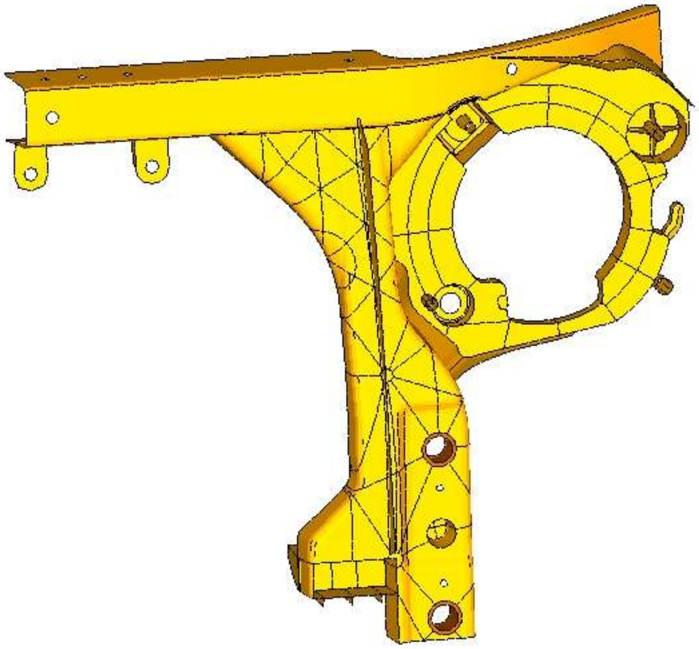


Figure 6. DaimlerChrysler Jeep JK LGF-PP Front-End Carrier (RH side shown).

The parts run were subjected to extensive functional validation testing which included on-car performance and bonding testing. Specific testing included harmonic resonance determination, deflection under load, rigidity, CMM and gauge dimensional testing, and on-vehicle performance testing. Stiffness of the product is a definite CTQ (critical to quality) item for the customer and the application for structural integrity, dimensional integrity and ride quality. All performance testing completed showed the material to be ideally suited to the module application.

Validation Summary – DCX KA FEC

A further validation of the same DLGF9411 40% LGF –PP material came about for the pre-production and eventually production build trials for the front-end carriers for the DaimlerChrysler 2007 KA program (Dodge Nitro) front end module. This module is also manufactured and assembled by Decoma. A diagram of the bonded FEC is shown in Figure 7.

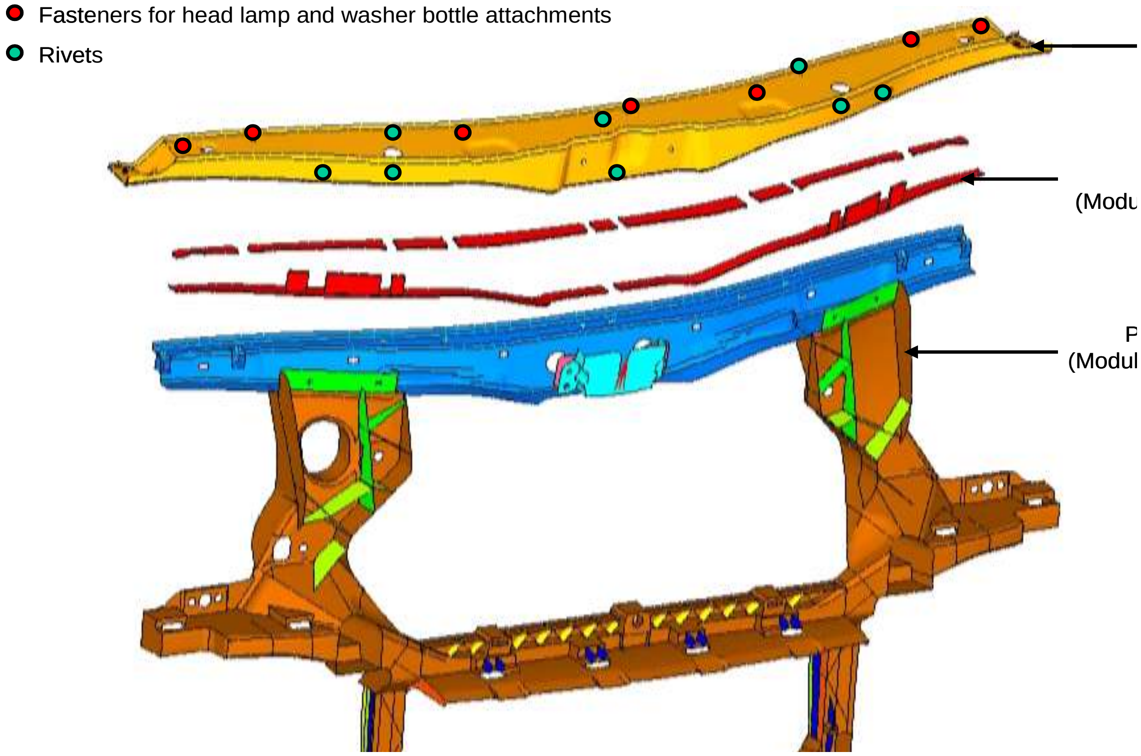


Figure 7: DCX KA (Dodge Nitro) Front-End Carrier Schematic.

The conclusions that were made from the validation trials were exactly the same as those for the JK program. The material processed very easily, and moulded a part that could be tuned to the build needs as the program development progressed. The KA was a much larger part, weighing approximately 3.6 kg with considerably longer flow lengths from the individual gates. For this reason a burn-out study was done. This study allowed for the characterization of the glass fibre matrix left behind after the polymer was pyrolyzed. A good burn-out result will show evenly distributed glass with a fibre length long enough to keep the structure more or less intact after the polymer has been pyrolyzed. This distribution is affected by many processing and tooling variables. This burn off study allows for the optimization of gating strategies, and comparison and optimization of injection mould process parameters. In one study the distribution of weight % glass was plotted across the part and compared against the distance from the gate. The samples were taken from 14 locations, ranging from 3cm to 90 cm from the gate location. The mean glass content was 40.9% with a standard deviation of 1.05%. This data is demonstrative of a good process set-up and gating conditions. The distribution of the glass across the part is consistent and little correlation was seen between the distance from the gate and the glass content. The qualitative study of the glass fibres after pyrolysis demonstrated a good underlying structure, and good fibre length retention.

Conclusions

This paper has demonstrated how two innovative material solutions, one in the development of a long-fibre thermoplastic composite (LGF-PP) and one in the area of adhesive bonding technology have been combined to create the opportunity to design an effective automotive solution. In particular, the incorporation of long-glass fibres into a formulated polypropylene-based polymer matrix has improved the structural, impact, and dimensional performance such that the lower cost, highly processable plastic can be used in difficult engineering applications. Opportunities for use of this material will abound in structural applications such as impingement shields, instrument panels, package shelves, load floors, door panels, and in front end carriers. The development of a unique adhesive solution to bond low energy surface, such as that of the PP matrix, to untreated metals has allowed the creation of robust multi-material engineering designs that are ideally suited for applications such as FEC's. The optimization of these materials in concert with a trend in engineering design towards modularity has generated the opportunity for implementation of the bonded hybrid FEC concept.

The performance validation data has demonstrated that such bonded hybrid composite FEC solutions can provide many benefits, such as reduced cost and weight, improved performance versus other fastener or overmoulded designs, and increased design flexibility, especially within the constraints of limited packaging space. The paper has outlined three case studies of this success available on commercial vehicles today.

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REFERENCES

1. Constable, R.C., "*Chemical Coupling agents for Filled and Glass-Reinforced Polypropylene Composites*", Handbook of Polypropylene and Polypropylene Composites, (ed. Karian), Marcel Dekker, 1999
2. Karian, H.G., "*Mega-Coupled Polypropylene Composites of Glass fibres*", Handbook of Polypropylene and Polypropylene Composites, (ed. Karian), Marcel Dekker, 1999
3. Van Poucke, J., James, A.J., "*Long Glass Fiber Polypropylene Technology for Automotive Applications*", SPE Automotive Composites Conference, Sept. 2006
4. Naughton, P. et al, "*Bonded Hybrid Automotive Front End Carriers*", IABC Conference 2005
5. Kotnis, A., Kauffmann, K., Teli, S., Goldhawk, M., *"Flexible Designs with Bonded Front-End Carriers*", APP Conference, Nashville, TN, 2007.
6. Automotive Engineering International Magazine, February 2007, p. 49.