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Multi-Process Tooling

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Multi-Process Tooling

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1. LISTS

1.1 List of Acronyms

BMC	Bulk molding compound
CF	Carbon fiber
CM	Compression molding
COM	Compression overmolding
CAD	Computer aided design
ECM	Extrusion compression molding
EOP	End of part
FCMF	Fibers and Composites Manufacturing Facility
GPa	Gigapascal
GF	Glass fiber
IM	Injection molding
ICM	Injection compression molding
IOM	Injection overmolding
IACMI	Institute for Advanced Composites Manufacturing Innovation
ILS	Interlaminar shear
kJ/m^2	Kilojoules per meter squared
LCF	Long carbon fiber
MPa	Megapascal
N	Newton
PA6	Polyamide (Nylon 6)
PA66	Polyamide (Nylon 66)ORNL Oak Ridge National Laboratory
PP	Polypropylene
PU	Polyurethane
RCF	Recycled carbon fiber
RFQ	Request for quote
SEM	Scanning electron microscopy
SMC	Sheet molding compound
SFT	Short fiber thermoplastics
SOP	Start of project
TCF	Textile carbon fiber
TPU	Thermoplastic polyurethane
UTK	University of Tennessee Knoxville

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1.4 Acknowledgements

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award DE-EE0006926.

Project acknowledgement: University of Tennessee, Oak Ridge National Laboratories, and Snider Mold

2. EXECUTIVE SUMMARY

Decisions made early in the automotive design process influence material selection, which in turn dictates process selection and tool design. Because of tool build time and cost of tooling, the original path is not easily altered, even if there is compelling evidence that another material or process would be beneficial. This project focused on tool design that is agile enough to allow its use in multiple processes—injection, injection compression, and extrusion-compression. This tool design allows for the manufacture of components with the most efficient process or materials, without building multiple, single-process tools.

The primary purpose of the Multi-Process Tool project was to physically demonstrate that a single, well-designed tool could be used to manufacture parts with a variety of materials that require different processes. A multi-process tool would be beneficial to providing data for any changes to the process since materials and processes can be interchanged without incurring additional tool cost(s). Battery tray parts, (representative of a multi-process tool, were successfully manufactured using various types of materials, such as fiber reinforced (carbon fiber and/or glass fibers, recycled carbon fibers), amorphous (PP, TPU), semi-crystalline (PA6, PA66), and crystalline (thermoset epoxy resin) polymers. Processing of the parts was achieved by injection molding, compression molding, compression overmolding, and injection overmolding. Specimens extracted from various locations on the battery tray parts were evaluated for mechanical properties (flexure and interlaminar shear strength properties). The results show that the tool can be used to produce parts from a wide range of materials and processes with no degradation of the physical or cosmetic properties.

3. INTRODUCTION

This project is about tool design that is agile enough to allow its use in multiple processes, including injection, injection compression, and extrusion-compression molding. The material forms include long- and short-fiber thermoplastics (LFT and SFT), tapes, preforms, sheet and bulk molding compounds (SMC and BMC, respectively), and material combinations. This tool design allows for the manufacture of components with the most efficient process or materials, without building multiple single-process tools. Each process and material has inherent benefits and drawbacks, such as fiber length attrition, fiber fracture, resin-to-fiber ratio, process waste, etc. All these aspects have an impact on a part's physical characteristics, cost, energy use, process waste, and material use. Present practices in tool design are determined very early in the engineering process. If design changes were to occur mid-stream in the tool build, it is cost prohibitive to build additional tools to accommodate a better processing method and/or material different from the original design. The original decision is not easily changed. New materials/composites are often difficult to integrate into current programs, particularly if the processing of the new material is different. Hence a multi-process tool can enable flexibility to incorporate different materials and processes if needed.

In injection molding, two tool halves of the mold are clamped together in a press. Hot material is then injected into the cavity and cooled. After cooling the part is removed by opening the press. Injection/compression is similar, but the tool is gapped open after the material is injected into the cavity, the press is closed, and the part is removed after cooling the tool. Compression molding is when material is placed into the cavity of a tool, and the press is closed. This can either be hot material and a cold tool or a hot tool and cold material. Extrusion compression is like compression with hot material. The material is passed through an extruder to make it hot enough to form. Each of these processes has inherent benefits and drawbacks. These can be material type, fiber-to-resin ratio, fiber length, speed of process and degradation/fouling of the polymers, and fiber length attrition.

Valley Enterprises has worked on a predictive manufacturing project (battery tray) with Honda, ORNL, UTK, MoldEx, and ACMA using long carbon fiber and thermoplastic in an injection molding process. Valley Enterprises invested $31,450 to modify an existing tool to simulate the geometry and material flow for long fiber thermoplastic composites produced via injection-compression and extrusion-compression processes. Using the tool as the model, the goal was to understand the impact of fiber loading, orifice size, screw design, and gate radii on fiber distribution and length. We investigated 13-mm-long carbon fiber in this preliminary effort. The data generated by this study provides a baseline for the Multi-Process Tooling project. Figure 1 shows the CAD model of the tool and representative parts fabricated via injection molding and extrusion compression molding with this tool. This mold was used to investigate the multi-process tool concept.

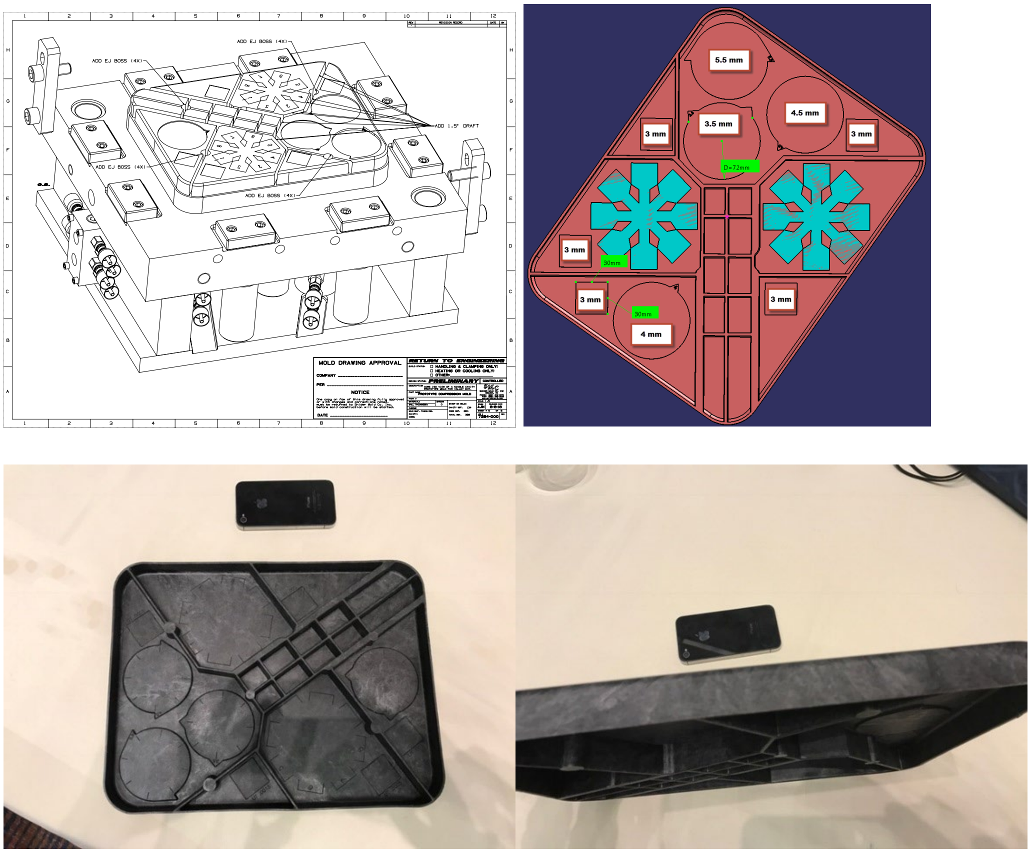

Figure 1. Tool design and parts; Representative multiple-process tool used to produce long fiber injection-compression and extrusion-compression part. The part features thick, thin ribs, thin/thick base areas, channel variations, and characteristics that provide understanding of material flow through the cavities.

The question is, how does this reduce energy consumption, or what is the relevance to the IACMI goals? There are two ways. First is to allow for new materials to break into the automotive business cycle. This is easily calculated as the embodied energy cost to manufacture raw materials to make a new tool for the new process/material and would also include the energy required to shape the tool materials, i.e., milling, grinding, heat treatment, etc. This is discussed in more depth later in this report. Second is the "forever cost" associated with accelerating a mass. If the new tool design allows for transition to a light material, then for the life of the vehicle, the energy to accelerate to speed is reduced.

Commercially implementing this concept is not difficult. It can be conveyed without elaborate drawings or directions, as any toolmaker skilled in the art of compression and injection tools will understand. There are a few simple rules: There is no metal-to-metal seal at the perimeter, the stops are external to core and cap, there is no vent (bypass is the vent), the bypass at the perimeter must be engaged before the material gets there in compression, and the bypass gap is .0254mm. In injection molding, the tool is fully closed before material is injected; for the other variations, a finite gap is maintained between the tool halves.

4. BACKGROUND

Decisions made early in the automotive design process influence material selection, which in turn dictates process selection and tool design. Because of the tool build time and cost of tooling, the original path is not easily altered, even if there is compelling evidence another material or process would be beneficial. For example, let's assume the original decision was to make a component with long glass fiber (50 mm) and PP, and the process chosen was compression molding with a part weight 1 kg. Injection molding the part with 13 mm CF (40%) and PP would offer a cost reduction of 25% and meet performance requirements, yet it would not be selected if the compression molding process was already locked in. In the initial materials and processes selection, tool production complexity and cost constraints influence this decision. Therefore, a multi-process tool would be beneficial to providing data for any changes to the process.

To see why multi-process tooling is useful, it is very important to understand the timeline for automotive life cycle, from design to end of part (EOP). A minimum of four years prior to SOP, design begins; at two years, RFQs are sent to suppliers, parts are awarded, and tooling kicks off (Figure 2). At -one year, first-offs are manufactured, and engineering modifications are made. Production begins and typically lasts five years, although programs can be extended up to five years, or components can be carried over for multiple generations. This could be 20 years for carryover components and 14 years for extended programs. This agile tool design is a path to bringing new materials to the automotive cycle without the current wait for the next product generation. It removes the barrier of cost and timing for a new tool as well as the energy required to make the new tool.

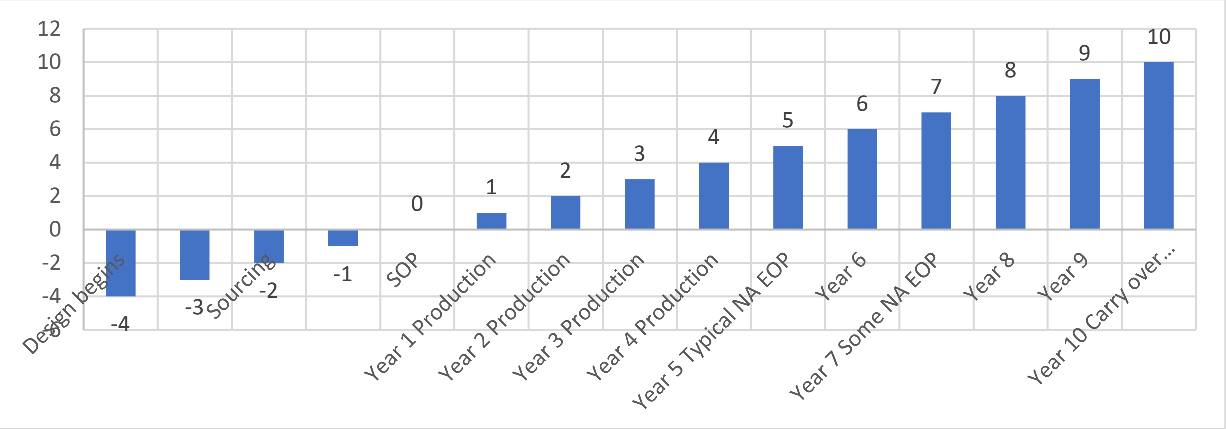

Figure 1. Automotive cycle

5. RESULTS AND DISCUSSION

Fundamental outcome of this project and associated trials is the concept of a single universal tool design that can be used effectively to both prototype and/or manufacture parts using different processes, namely injection, injection compression, compression, and extrusion compression molding. Depending upon the material used to build the tool, for e.g., aluminum versus tool steel, the tool can be categorized either as prototype (generally aluminum) or production (tool steel).

The bypass design of the outer perimeter of the tool is critical for proper venting without developing “flash,” or unwanted material squeezed out of the parting line. Temperature control is vital for this tool design. Excess heat in the core side of the tool will result in a crash condition with the cavity side. Excess heat on the cavity side will create excess gapping at the bypass, resulting in flash

To evaluate the mechanical performance of the battery parts manufactured using the multi-process tool, coupon level testing was conducted by extracting test specimens from the battery tray samples of all the variants (Table 1).

Table 1. Various material systems and respective processing conditions processed on the multi-process tool for mechanical and morphological characterization. Note: The RCF-epoxy and Dow Aksa CF-epoxy are thermoset resins, all others are thermoplastics

Materials and Methods	**Fiber sizing**	**Fiber length, mm**	**Fiber weightfraction %/ Type**	**Polymer matrix**	**Processing**
30% TCF- TPU (U2-01)	TPU	< 3	**30 CF**	TPU	IM
30% TCF- TPU (U2-04)	TPU	< 3	**30 CF**	TPU	IM
30% TCF-PA66	Epoxy	< 3	**30 CF**	PA66	IM
25% GF- 25% C-50 PA66	Thermoplastic	< 3	**25 GF, 25 CF**	PA66	IM
50% CF-50% PA66	Thermoplastic	< 3	**50 CF**	PA66	IM
RCF- PA66	N/A	< 12	**40 CF**	PA66	IM
RCF-PA66	Thermoplastic	<12	**50GF**	PA66	ECM
33% GF- PA66	Thermoplastic	3	**33 GF**	PA66	ECM
Hanwha Profuse 30	Thermoplastic	50	**30 GF**	PP	ECM
LCF 40%- PP	Thermoplastic	12	**40 CF**	PP	ECM
Polypro R6	Thermoplastic	3 to 6	**50 GF**	PP	ECM
RCF- Epoxy	Epoxy (Thermoset)	12	**60 CF**	Epoxy	ECM
Dow Aksa CF-Epoxy (-60°, 0°, +60°)	Epoxy (Thermoset)	25	**60 CF**	Epoxy	Comp Over-molding
Carbon Unidirectional tape	Thermoplastic	3	**30 GF**	PA6	IM Over-molding
Glass Unidirectional tape	Thermoplastic	3	**30 GF**	PA6	IM Over-molding

Materials and Methods

Battery tray parts were manufactured from various material variants at Valley Enterprises, Ubly, Michigan[1]. Injection moldable variants (short-fiber (< 6 mm) reinforced pellets) were processed by the injection molding (IM) process. Long-fiber thermoplastic (> 25.4-mm fiber length) variants, and CF-Epoxy variants were processed via compression molding (CM) process. Overmolding of continuous fiber on the IM and CM battery tray parts were processed in a single step process. In the overmolding process, discontinuous fiber matrix flows on the continuous fiber tape in a single step and conforms to the deep grid structure. On average, 10 to 15 parts were processed for each variant listed in Table 1. Test specimen extraction was carried out at University of Tennessee (UTK) Fibers and Composites Manufacturing Facility (FCMF), per ASTM requirements. Flexure (ASTM D790), ILSS (ASTM D2344), and Izod (ASTM D256) specimens were extracted along and across the fiber direction on IM, CM, injection overmolded (IOM), and compression overmolded (COM) battery tray parts manufactured on the multi-process tool (Figure 3). Mechanical characterization was carried out on TestResources load frame with 50 kN load cell at FCMF. Scanning electron microscopy (SEM) was conducted at the Advanced Microscopy and Imaging Center at UTK. SEM specimens were sputtered with gold and analyzed at 5 keV electron beam.

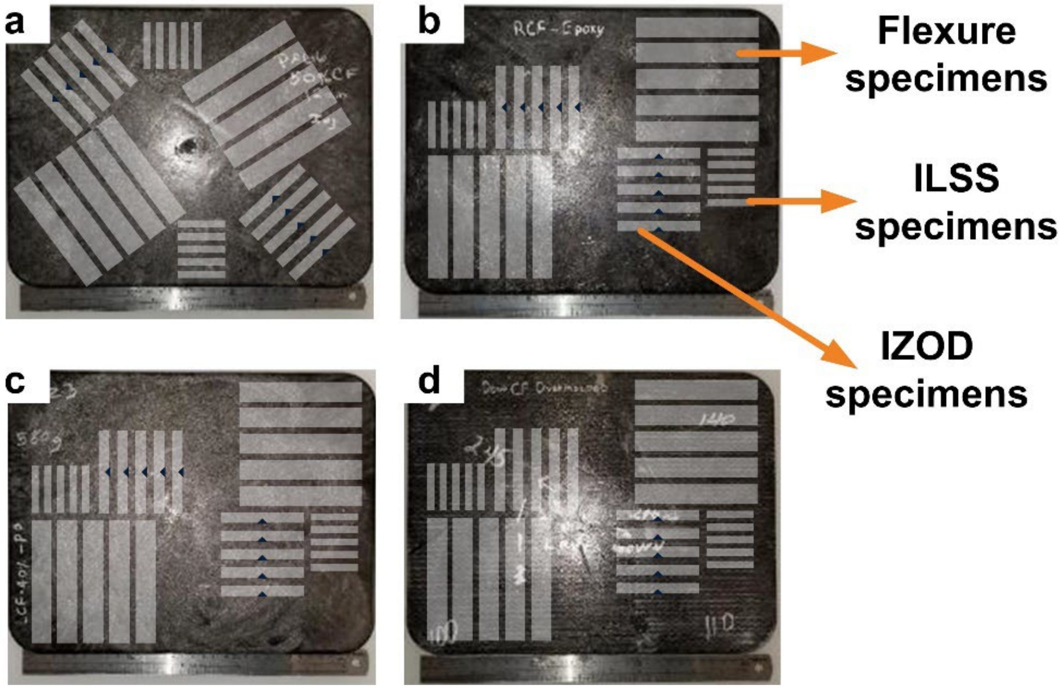

Figure 2. Test specimen extraction on battery tray parts. Specimens were extracted along and across the fiber orientation of (a) IM, (b) CM, (c) IOM, and (d) COM battery tray samples.

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[1] Multi-process tooling for discontinuous carbon and hybrid glass fiber thermoplastics
Uday Vaidya, Mark Robinson, Nitilaksha Hiremath, Pritesh Yeole, Merlin Theodore, Ahmed Hassen, John Unser., Materials and Manufacturing Processes Journal, in-review January 2022.

Results and Discussion

Various compositions were manufactured by different processing techniques, as shown in Table 1. Specimens were extracted out of the battery tray parts manufactured from IM, CM, IOM, and COM on multi-process tool. For IM samples, test specimens were extracted along (0°) and across (90°) the fiber flow direction. For COM samples, (0°) and (90°) test specimens were extracted with reference to the longer side of the tray (Figure 4).

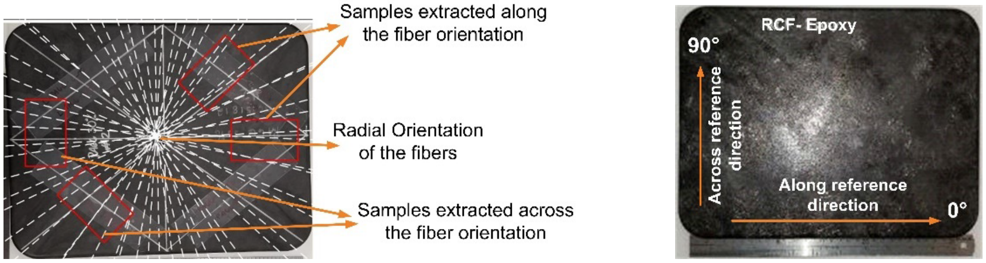

Figure 3. Representative images of IM and CM samples and reference direction

Flexure data of IM, CM, IOM, and COM battery trays of various variants processed on the multi-process tool are presented in Figures 5 and 6. Test specimens extracted in along and across fiber orientation were tested uniformly. IOM and COM clearly show higher flexure strength and modulus compared to IM and CM specimens. Though the fiber length varies between IM and CM specimens, and IM specimens have lesser voids and surface imperfections compared to CM specimens, longer fiber length always enhances the stiffness. Flexural strength and modulus of IOM and COM processed specimens are compared with IM and CM data in Figures 7 and 8 respectively. Overmolding enhanced strength and stiffness drastically. In the IOM variant, GF-Nylon is injection overmolded on GF unidirectional tape (thermoplastic variant). The flexure strength and stiffness of the IOM was enhanced by 130% and 85%, respectively compared to IM specimens. Similarly, in COM variant, RCF-Epoxy is compression overmolded on continuous Dow CF (thermoset variant), flexure strength, and stiffness of COM enhanced by 220% and 30%, respectively, compared to CM specimens. In hybrid variant, CF-GF-PA66 is injection overmolded on CF unidirectional tape (thermoplastic-hybrid variant), flexure strength, and stiffness of IOM enhanced by 120 % and 220 %, respectively, compared to IM specimens. Overmolding of continuous fibers on the tensile side of the flexure specimens absorbs most of the load to induce a crack front and traverses through the discontinuous fiber matrix, Figure 9. Hence, strength and stiffness enhancement are due to orthotropic load transfer with no significant weight increase in the specimens. Local overmolding can enhance stiffness where required, thereby eliminating the need for rib structures that otherwise increase the thickness and weight of the part[2]. Typical load vs. displacement curves of flexure testing for most of the variants are as shown in Figure 10. Failure mode analysis of flexure-tested specimens were as per ASTM D790 requirements. SEM images show typical failure mode, as shown in Figure 9.

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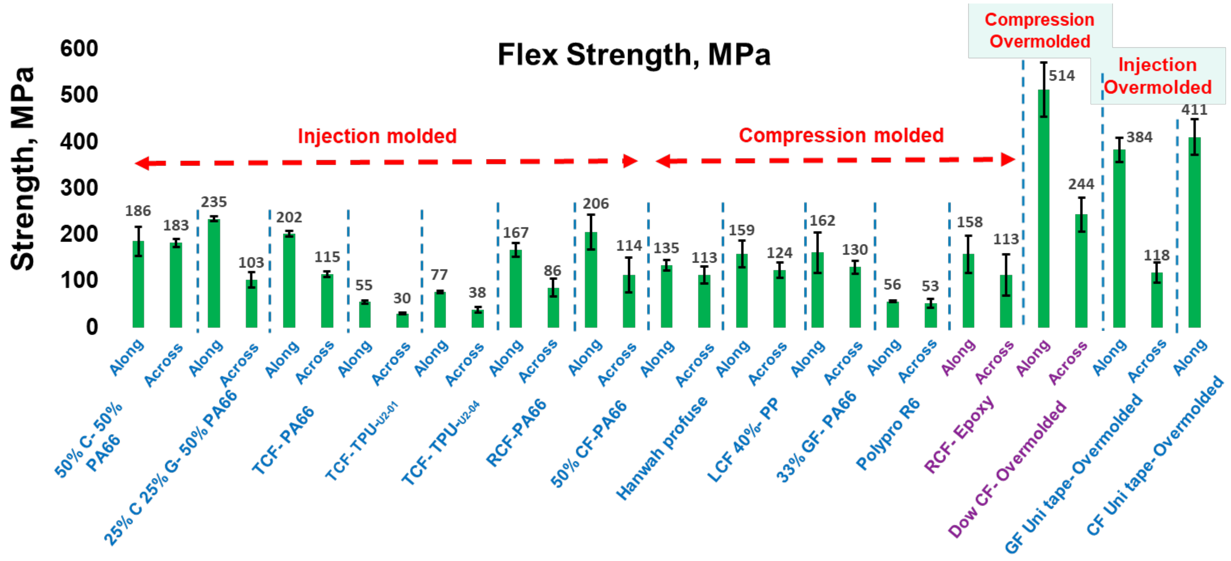
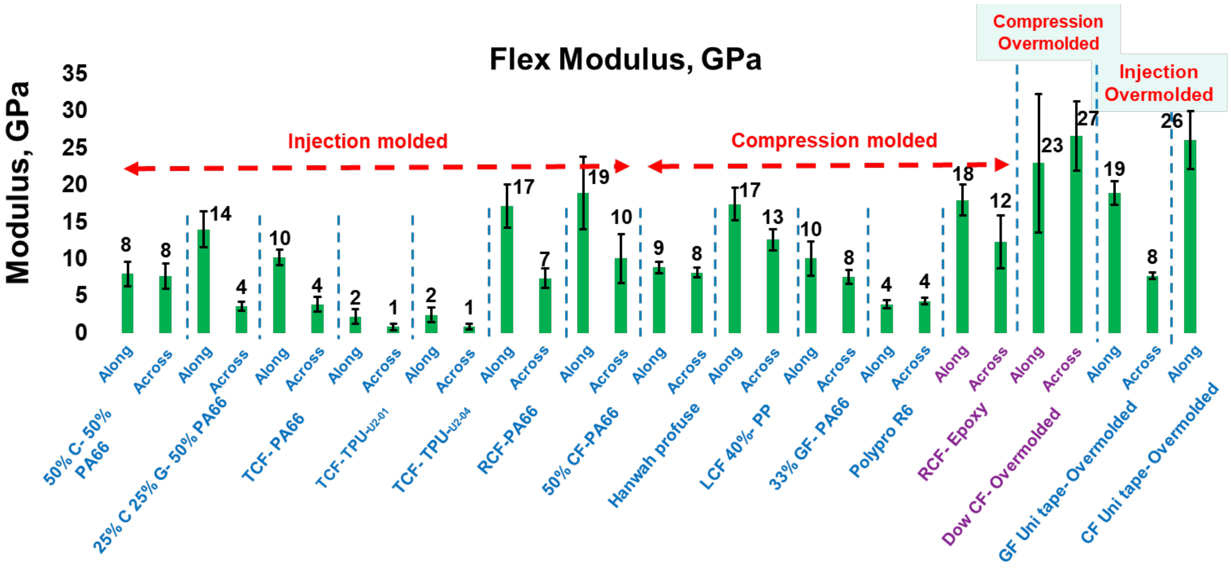
1) [2] Shailesh Alwekar, Ryan Ogle, Seokpum Kim, Uday Vaidya, Manufacturing and characterization of continuous fiber-reinforced thermoplastic tape over molded long fiber thermoplastic, Composites B:Engineering, February 2021. https://doi.org/10.1016/j.compositesb.2020.108597



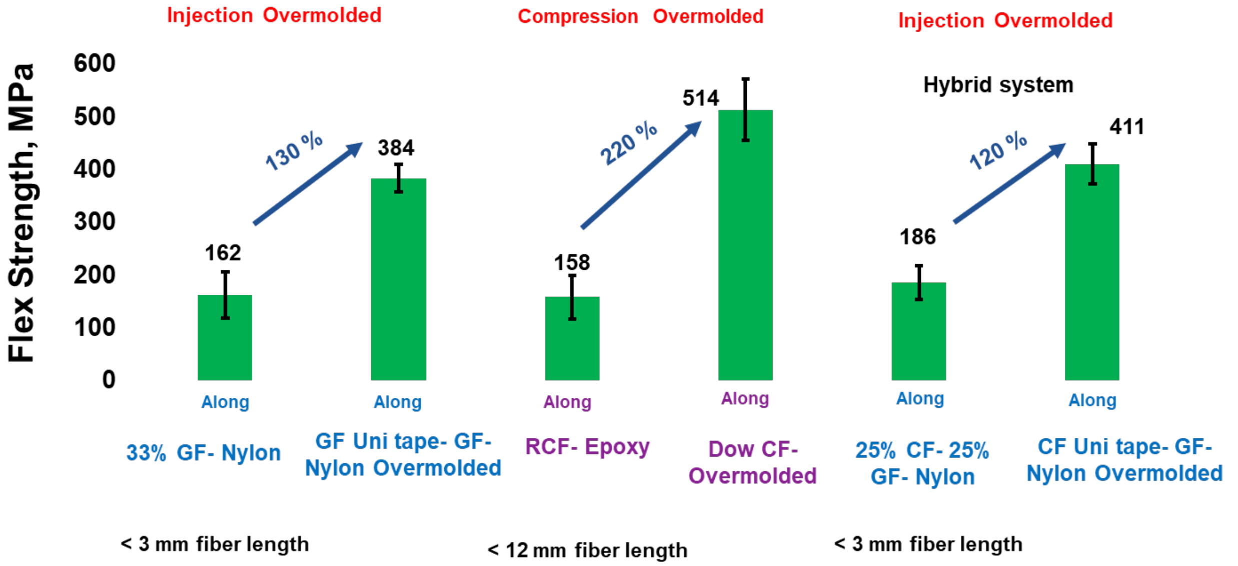
IOM and COM processed samples showed higher flexure strength compared to IM and CM processed variants.

Figure 4. Flexure strength of all the variants processed on the multi-process tool are presented. n=5



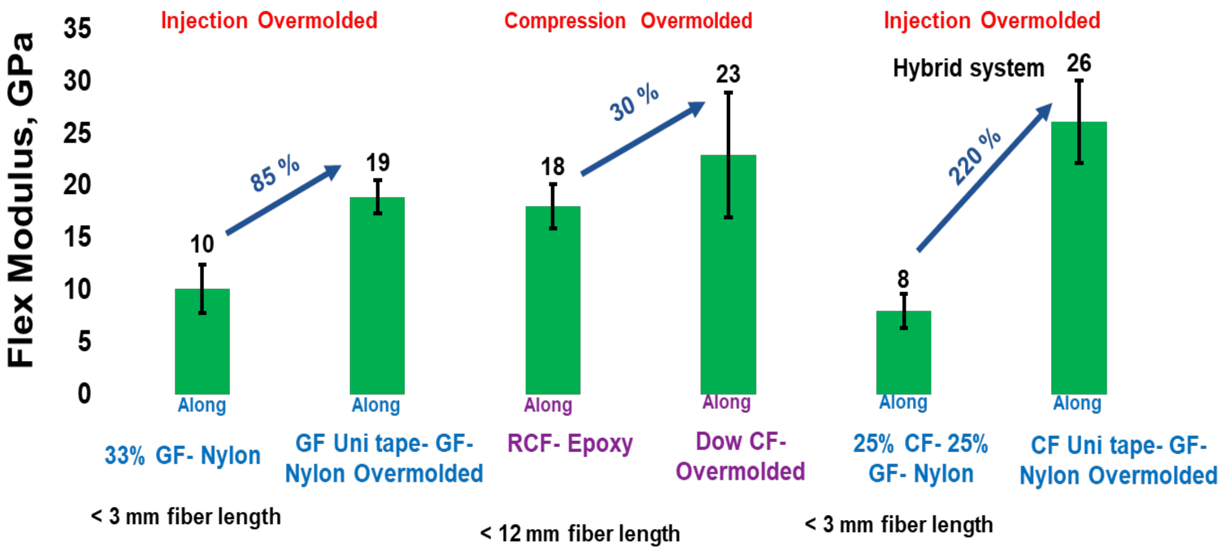
IOM and COM processed samples showed higher flexure modulus compared to IM and CM processed variants.

Figure 5. Flexure modulus of all the variants processed on the multi-process tool are presented. n=5



In thermoplastic variant, GF-Nylon is overmolded on GF unidirectional tape. In thermoset variant, discontinuous RCF-Epoxy is compression overmolded on continuous Dow CF-epoxy. In thermoplastic-hybrid variant CF-GF- Nylon is injection overmolded on CF unidirectional tape. Flexure strength enhanced drastically due to effective load transfer at the overmolding interface.

Figure 6. Flexure strength of IOM and COM compared with IM and CM specimens. n=5



In thermoplastic variant, GF-Nylon is overmolded on GF unidirectional tape. In thermoset variant, discontinuous RCF-Epoxy is compression overmolded on continuous Dow CF-epoxy. In thermoplastic- hybrid variant CF-GF- Nylon is injection overmolded on CF unidirectional tape. Modulus enhanced drastically due to effective load transfer at the overmolding interface.

Figure 7. Flexure modulus of IOM and COM compared with IM and CM specimens. n=5

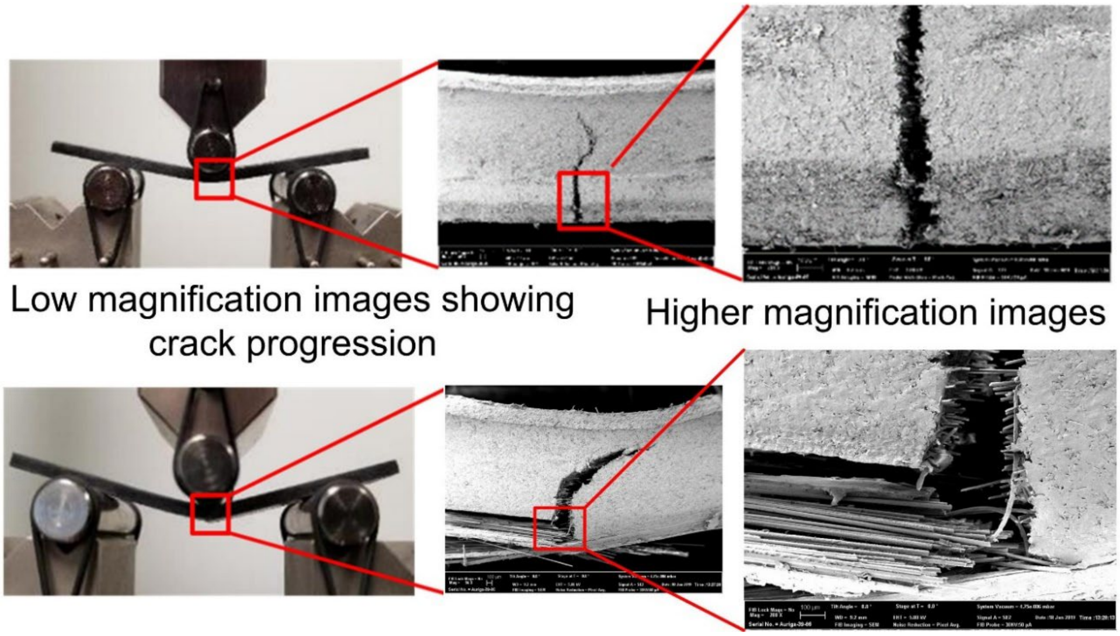


Figure 8. Typical failure analysis of flexure specimens observed with high resolution SEM at low and high magnification. Failure mode of the specimens was as per ASTM D790.

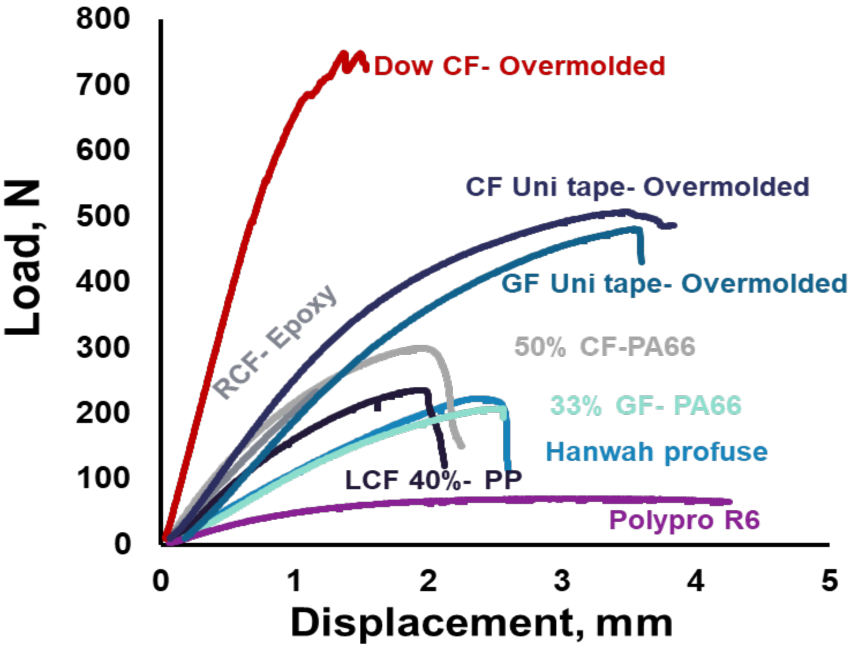
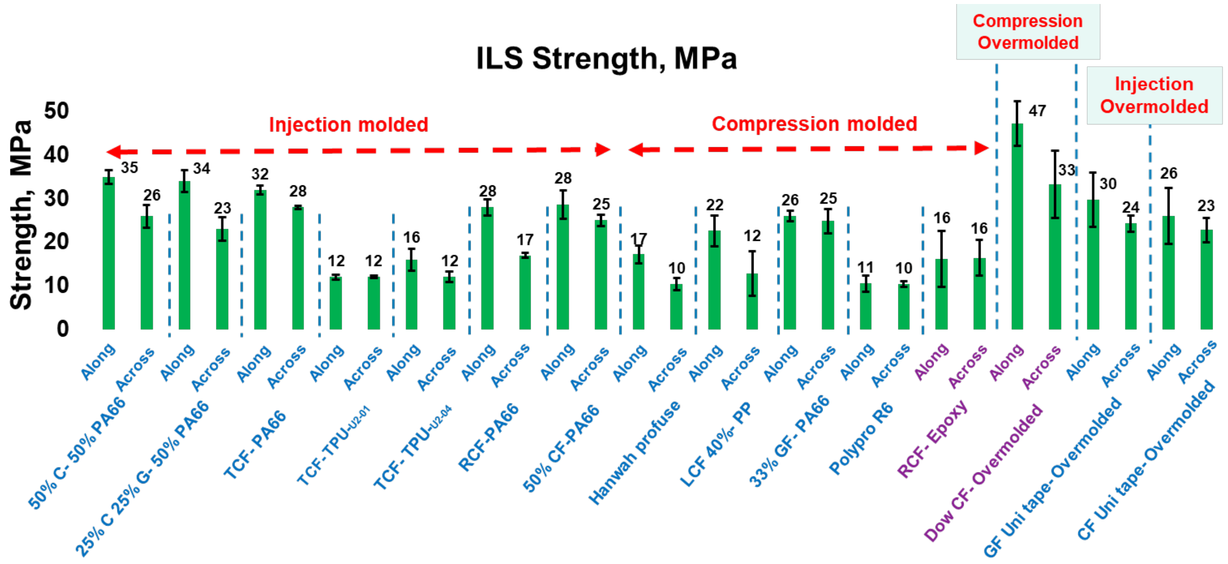


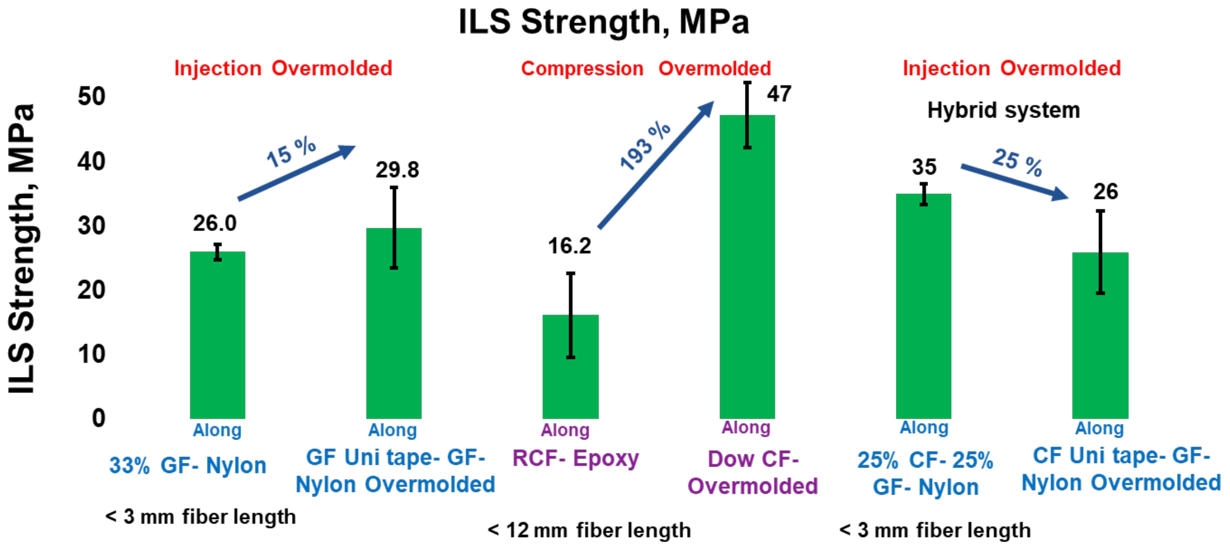
Figure 9. Representative load versus displacement curves of various variants are presented. Overmolded specimens failed at higher loads, compared to IM or CM specimens.

Interlaminar shear (ILS) strength data of IM, CM, IOM, and COM battery trays of various variants processed on the multi-process tool are presented in Figure 11. Test specimens extracted in along and across fiber orientation were tested uniformly on ILS test fixture, see Figure 12. IOM and COM clearly show higher ILS strength compared to IM and CM specimens. IOM and COM processed ILS test specimens are compared with IM and CM, respectively, see Figure 12. Overmolding enhanced strength drastically due to effective bonding and load transfer. In overmolded specimens, shearing of the continuous fibers absorbs most of the load and then the load transfers to the discontinuous fiber matrix, resulting in high shear strength. In IOM variant, GF-Nylon is injection overmolded on GF unidirectional tape (thermoplastic variant), ILS strength of IOM enhanced by 15 % compared to IM specimens. Similarly, in COM variant, RCF-Epoxy is compression overmolded on continuous Dow CF- epoxy (thermoset variant), ILS strength of COM enhanced by 193 % compared to CM specimens. However, in hybrid variant, CF-GF- Nylon is injection overmolded on CF unidirectional tape (thermoplastic- hybrid variant), ILS strength of IOM lowered by 26 % compared to IM specimens. This reduction could be due to weaker interface bonding during processing or due to anomaly in specimen extraction. As the ILS test specimens are of small size, micro-delamination can happen during machining process; also, there could be insufficient sizing compatibility. In thermoset variant, on the other hand, significant ILS strength enhancement was observed in COM specimens. This is due to sizing compatibility of CF with epoxy resin. Failure mode analysis of ILS tested specimens were observed as per ASTM D790 requirements. SEM images show typical ILS failure modes, as shown in Figure 13.



IOM and COM processed samples showed higher ILS strength compared to IM and CM processed variants. In hybrid variant there was reduction in the ILS strength compared to IM specimens

Figure 10. Interlaminar shear (ILS) strength of all the variants processed on the multi-process tool are presented.



In thermoplastic variant, GF-nylon is overmolded on GF unidirectional tape. In thermoset variant, discontinuous RCF-epoxy is compression overmolded on continuous Dow CF-epoxy. In thermoplastic- hybrid variant CF-GF-nylon is injection overmolded on CF unidirectional tape. ILS strength enhanced in thermoplastic and thermoset variants; however, in hybrid variant, probable micro-debonding might have reduced the load transfer and shear strength.

Figure 11. ILS strength of IOM and COM compared with IM and CM specimens.

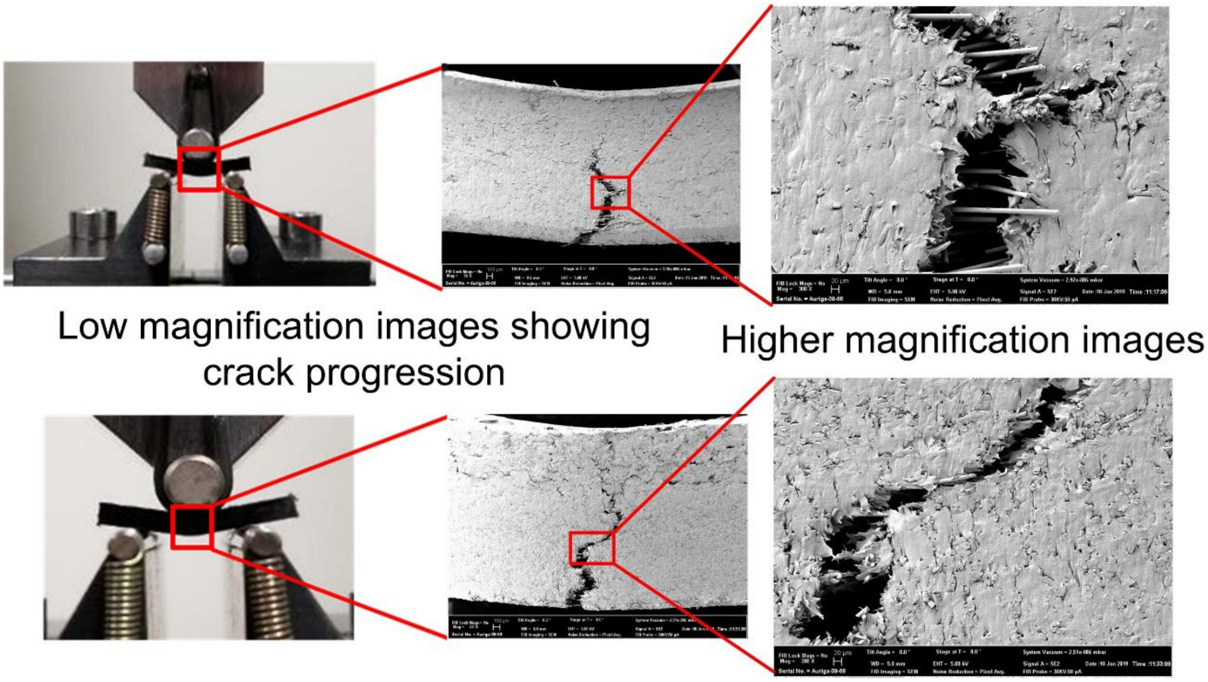
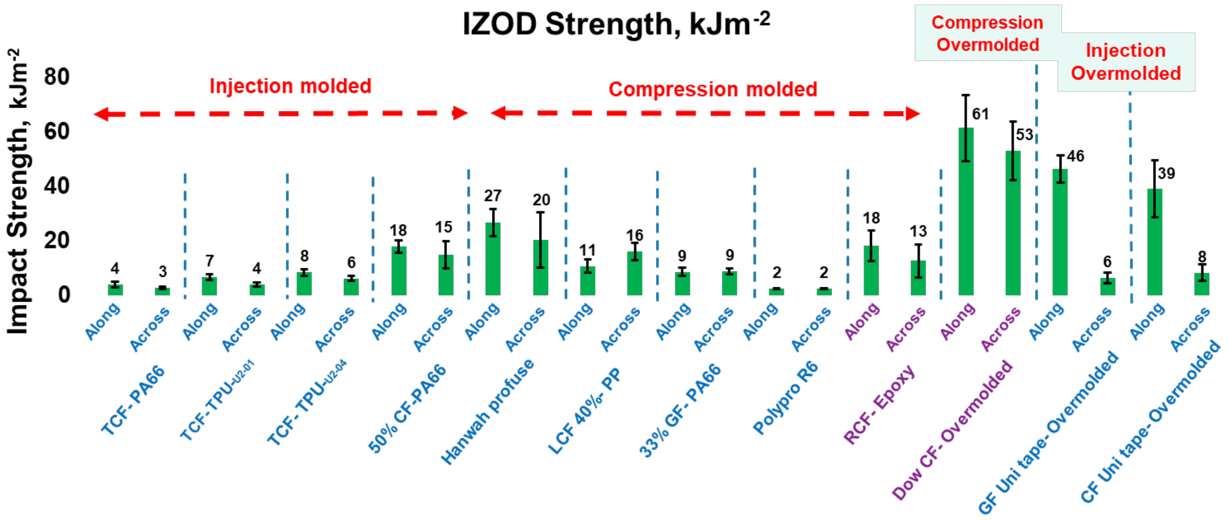


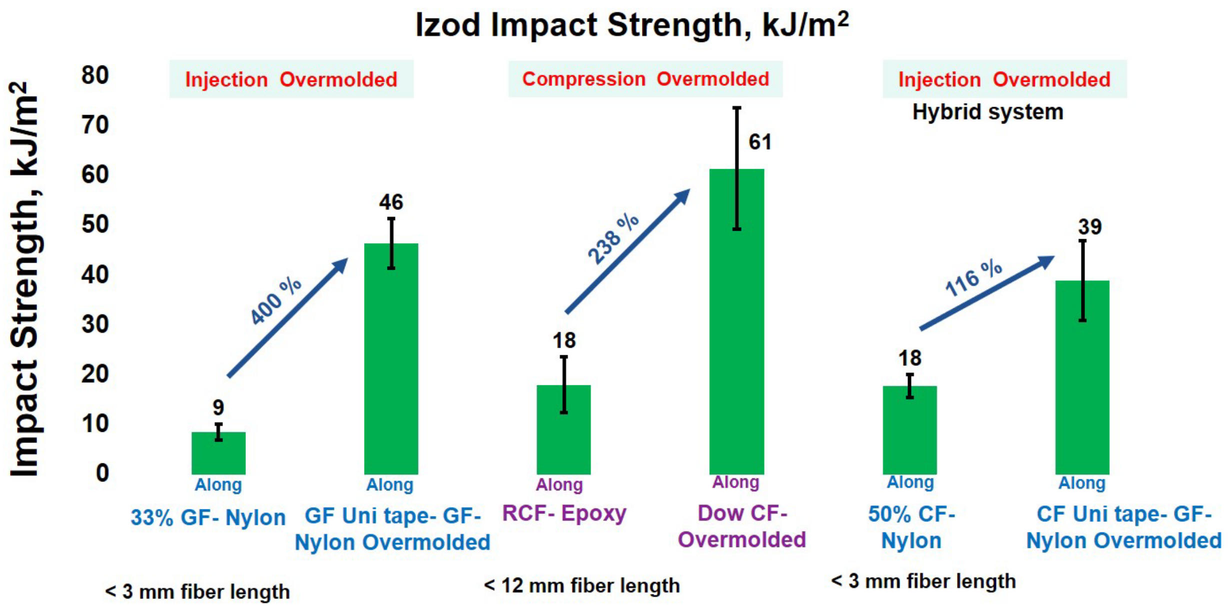
Figure 12. Typical failure modes of ILS specimens observed with high resolution SEM at low and high magnification. Failure mode of the specimens were as per ASTM D2344.

Izod impact strength data of IM, CM, IOM, and COM battery trays of most of the variants processed on the multi-process tool are presented in Figure 14. Test specimens extracted along and across fiber orientation were tested uniformly on impact tester. IOM and COM clearly show higher impact strength compared to IM and CM specimens. IOM and COM processed impact test specimens are compared with IM and CM, respectively, Figure 15. Evidently, overmolding enhanced impact strength drastically. In IOM variant, GF-nylon is injection overmolded on GF unidirectional tape (thermoplastic variant), the impact strength of IOM is enhanced by 400% compared to IM specimens. Similarly, in COM variant, RCF-epoxy is compression overmolded on continuous Dow CF (thermoset variant), impact strength of COM enhanced by 238% compared to CM specimens. In hybrid variant, CF-GF-nylon is injection overmolded on CF unidirectional tape (thermoplastic-hybrid variant), impact strength of IOM enhanced by 116% compared to IM specimens. Continuous fiber overmolding enhances energy absorption, and desired hinge break failure mode is observed. In IM and CM specimens alone, complete failure mode was observed and reduced energy absorption. SEM could not be conducted, as the test specimens were not able to mount in the SEM instrument.



IOM and COM processed samples showed higher impact strength compared to IM and CM processed variants. IM and CM specimens showed complete failure, and IOM and COM specimens showed hinge failure mode.

Figure 13. Izod impact strength of most of the variants processed on the multi-process tool are presented.



In thermoplastic variant, GF-nylon is overmolded on GF Unidirectional tape. In thermoset variant, discontinuous RCF-epoxy is compression overmolded on continuous Dow CF-epoxy. In thermoplastic-hybrid variant, CF-GF-nylon is injection overmolded on CF unidirectional tape. Overmolding enhanced impact energy absorption, and hinge failure was observed, as opposed to complete failure (not desired) in IM and CM specimens.

Figure 14. Impact strength of IOM and COM are compared with IM and CM specimens.

6. BENEFITS ASSESSMENT

Materials replacement: New materials are entering the marketplace at an ever-increasing rate, but barriers as discussed in the *Introduction and Background* section prohibit their timely entry into the automotive industry. Considering just one example based on the test results in Figure 5, a seatback manufactured using the Profuse (polypropylene + glass) material using compression molding weighing 2 kilograms could be replaced with an injected molded version using RCF PA66 (recycled carbon fiber + polyamide (nylon)) with a weight savings of 13.5%, or 270 grams per seatback. If there are four seatbacks per vehicle, this is a weight 1080g/vehicle. To prove these gains, the current practice would require an entirely new tool, associated long lead times to design and build one and then conduct trials with the new material option(s). This would greatly slow down the process of development and be expensive. The present work provides a pathway to save costs and accelerate the development since the tool is able to accommodate the new process(es) and materials without necessitating a new tool.

Tool Design: There is another inherent benefit in the tooling innovation as part of this work. The bypass shear edge in the tool with external stop designallows the tool to be closed to any point by simply adding or removing shim from the stops. In the example of the seat back rest, the part volume is 392 cubic centimeters. If 1 mm is removed from the stops, the part volume is reduced by 21.4%. Taking advantage of this capability would depend on the form, fit, and function associated with each individual part.

Lightweighting: Because of light weighting efforts over the years, the significant amount of weight savings have already been achieved. The present gains are more in terms of grams versus kilograms. The multi-process tool technology allows the removal of grams without waiting years for the next commercial opportunity. This has significant cost benefits, although this work did not address specific cost cases, but provides evidence of the benefits leading to cost savings.

7. COMMERCIALIZATION

One of the primary goals, other than those stated above, is to create the forward-thinking culture in the design phase of tooling. The question is'what can be done to a tool designed for a specific process to enable its use in another process'? It may be as simple as adding an insulating layer, allowing a cold tool designed for thermoplastics to be heated and used for thermosets, or adding a hole and channel for a gasket. Other than some creative engineering, dedicated machine time, and inexpensive components, there is no significant cost penalty.

The commercialization opportunities for this technology are multifold – (a) there is significant growth in hybrid manufacturing such as injection molding and compression molding. These technologies have been historically used in isolated fashion. This work can benefit tool makers in designing features within the tools from the prototype stage and be able to advance to small and medium volume production runs; (b) End-users can feature different material options without incurring additional tooling cost. For example, commodity to high-performance pricing for a part will only need different material options such as progressing from injection molded polycarbonate (PC) (used as example only) to compression molded glass reinforced PC to compression molded carbon reinforced PC to produce a housing fixture. Essentially the part is offered in different performance rating without needing additional tooling; and (c) new parts under development can be rapidly screened for multiple processes and materials; which can be costly and time consuming. The commercialization of the technology is within the tool makers network, automotive and industrial component, electrical and power transmission and related markets.

8. ACCOMPLISHMENTS

Other than proving this concept is viable by shortening the lead time for introduction of new materials into the automotive product cycle, which can lower the energy use as discussed earlier in this document, it has provided valuable information. Dr. Vaidya and his colleagues have used the information generated by this project to compare low-cost carbon fiber and textile grade carbon fiber to other materials and processes currently found in manufacturing.

9. CONCLUSIONS

Tool design can influence integration of new material technologies into the marketplace by denying access based on new tool cost and timing. The embodied energy cost required to change processes is a small part of the possible savings. The forever cost of accelerating each additional gram to highway speed is larger, particularly when viewed as all vehicles made with the new material, if the change can be made mid-cycle.

10. RECOMMENDATIONS

Because of the cost of tooling and the inherent risk aversion of most manufacturers, I believe the best recommendation for any manufacturer with inject and compression capability is to make the next prototype tool based on this design concept. This will provide the confidence required to move to a production tool.