

EPOXY COMPOSITES WITH SHORT FIBERS ARE LONG ON BENEFITS FOR AUTOMOTIVE APPLICATIONS

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Abstract

The automotive industry is no stranger to the use of polymers and composites. Some non-metallic materials currently being used in automotive applications include fiber reinforced nylon, polyphthalamide, polyamide-imide, and polyester in the form of bulk molding compound (BMC) or sheet molding compound (SMC). One significant reason for using these composites is to reduce weight and maximize fuel efficiency.

Long strand fiberglass for strengthening plastics such as nylon, PPA, PAI, and polyester, has been in use for decades. Carbon fiber can yield even greater strength, although it has been used mainly in aerospace, sporting goods, and in other high end applications such as race cars, super cars, and luxury vehicles due to cost. SolEpoxy has achieved good results by blending fibers of different types in order to optimize desired properties or minimize cost.

With this paper, SolEpoxy proposes to add another material to this list of common automotive composites: short-fiber reinforced epoxy. Epoxies feature high strength, resistance to high temperatures, chemical resistance, ease of molding vs. metal forming, and lower density which could yield dramatic weight savings. Epoxy composites reinforced with short fibers convey the additional important benefit of isotropic material properties. Unlike long-fiber reinforced composites, there is no need to orient or “lay-up” the reinforcing fibers. Short-fiber epoxy composites can be molded to near net shape and finished with machining just like die-cast metal.

We also offer some interesting observations. It is unsurprising that, in a given base epoxy, carbon fiber provides a boost in the flex and tensile strength. There is, however, a diminishing rate of return as fiber content is increased. Also, reinforcing fiber can have the effect of diminishing compressive strength and flex modulus. It is therefore important to observe two facts: first, epoxy composites offer advantages that could be very meaningful for fuel efficiency, cost and durability in an automobile. However, it is unlikely that a “one-size fits all” epoxy component could be specified for all automotive applications. This is not an impediment. Epoxy lends itself to custom formulations. The goal of this paper is to help the automotive industry understand the scope of the possible.

Background

Since its beginning, the automotive industry has been a creative user of a wide range of materials. Car bodies initially made of wood quickly pioneered the application of sheet metals. Ford demonstrated the plastic body “soybean car” in 1941. It was 1,000 pounds lighter than a comparable steel car¹.

As material technology evolved with the development of plastics, these new materials found their way into automobiles. The auto industry continues to push material scientists toward better, lighter, cheaper, easier-to-use composites that will improve automobile performance and safety.

With the ever increasing fuel economy requirements auto manufacturers are required to meet, one current focus of development has been on lightweight materials to reduce the overall vehicle weight. In 2015, Ford started making trucks with aluminum alloy body panels, reducing the F-150 truck weight by 700 pounds.² The automotive press enthusiastically announced that “GMC dropped a composite bombshell in the pickup truck world when it debuted the 2019 Sierra with a carbon fiber bed. They also offer their MultiPro tailgate, which has six-way functionality, and while it’s not a carbon fiber unit, it does incorporate a glass fiber composite construction. All combined, the new bed and tailgate drops 62 pounds versus a standard steel bed and tailgate”.³ These examples reveal the possibilities for weight reduction, improved performance, and the ability to employ easier and less costly manufacturing methods in the assembly process.

With the advancement of engineering grade thermoplastics like nylon (PA), polyphthalamide (PPA) or polyamide-imide (PAI), metallic components can be replaced in the most demanding automotive environment: under the hood. These polymers can be neat, or reinforced with mineral fillers or fibers to further improve their physical performance and durability. One material that has not gotten as much attention as these newer engineering polymers is epoxy in the form of epoxy molding compounds, EMC.

Perhaps it’s because this is not an apples to apples comparison; it’s more like comparing apples and broccoli. Epoxies are a thermosetting polymer technology as opposed to the thermoplastic nature of these other polymers. With pre-cured, one-part, b-staged epoxy compounds, you can melt them one time to fill a mold before the resin and hardener cross-link to cure. Once cured, epoxy can no longer be melted. In contrast, these thermoplastic resins can be re-used by blending them with virgin resin, helping improve the overall economics of processing with them.

All of these materials, both epoxies and thermoplastics, need to be molded into a form and then they require some post-mold “finishing” to achieve their best properties. For the epoxies and Torlon, a post-mold cure is required. For nylon, post-mold processing is also required to allow for moisture equilibrium before the optimum properties are realized.

The idea of using plastics in and around the automobile engine is not new. In the 1970’s, Matti Holtzberg and Polimotor LLC, began working on plastic parts to improve engine rpm and reduce weight. Starting with pistons and then moving on to the other components like connecting rods and valve covers, by the middle 1980’s the Polimotor Lola T616 racecar featured a mostly plastic engine where the engine block was made of epoxy composite. We are working with Mr. Holtzberg now, and we hope to push his vision of plastic engines further.

Description of Equipment and Processes

All of the epoxy molding compounds described in this paper were produced and tested at SolEpoxy. Our manufacturing process combines epoxy resin, hardener, performance additives, and inorganic materials through a high-shear, twin screw extruder. Here, the resin – hardener reaction process is initiated but quickly quenched and then held suspended by refrigerated storage of molding compound until the material is melted that one more time during the molding process which restarts the cross-link and cure reaction.

SolEpoxy composite molding compounds are blended and homogenized several times during our manufacturing process so there is no further blending or lay-up process required on the part of our customers. They can utilize our compounds in compression molding, transfer molding, high-productivity auto-molding, or injection molding.

Perhaps unique to our company, we employ short fibers in our fiber-reinforced molding compounds. This enables our molding compounds to be molded to net shape with fine features. It also conveys isotropic material properties to molded components because the reinforcing fibers remain randomly aligned even though the molding compound viscosity drops very low when the material is melted and transferred into the component mold. In spite of using short reinforcing fibers, we are able to maximize strength of material by employing additives and processing knowhow to ensure that fibers become intimately bonded within the epoxy substrate.

Our molding compounds are provided to our customers refrigerated, and in granular or pellet form. Customers who use injection molding or compression molding processes typically utilize *granular* material. Those who use manual transfer molding machines or “auto-molds”, which perform transfer molding with automated mold compound feeding systems, typically employ *pellets* of molding compound.

If a process calls for large pellets – of diameter 25mm or above (there are customers who employ 170mm pellets), we recommend pre-heating prior to charging the molding press. The preheat step softens the pellet to the consistency of marshmallow and it ensures uniform melting and flowing of mold compound from the molding machines transfer pot into the mold chamber. Molds and molding compound pellets are co-designed such that there remains a mold compound cull in the transfer pot and all of the runners, mold cavities and vents exhibit complete fill with molding compound at the end the transfer step. The last step in this process is called in-mold curing. The mold remains closed against transfer pressure for two to five minutes, depending upon part and mold compound requirements, in order for the molded part to cure sufficiently that it can be removed from the mold without damage.

After molding, epoxy parts are hot and hard to the touch but they are soft enough that rough handling could leave dents or even defects. This is why de-molding is done with care and parts are marshalled before post-mold curing ovens in order to advance the cross-linking of molecules and complete the cure. Post cure conditions will effect final properties which bear upon chemical resistance and temperature durability so this step must be controlled just as are the molding parameters.

The specimens developed and tested for presentation herein were transfer molded by our experienced technicians using a single molding press, a single set of specimen molds and a single set of molding parameters. Working in this way, we have minimized the sources of potential variation in order to isolate the formulation changes that we explored in our effort to reveal the impact of using different reinforcing fibers and in using these fibers in varying concentrations.

Our primary focus was to compare flexural strength among a collection of molding compound

formulations where we substituted different types and different concentrations of reinforcing fibers within a common epoxy base material. We tested many properties such as tensile strength, compression strength, and Izod impact resistance but we are reporting just flex strength here because this data provides the best basis for comparison. All of these tests are destructive and as such, it is impossible to re-test a specimen if results are an outlier. And, with some of these test, including, in particular, tensile strength testing and izod impact testing, results are highly dependent upon fixturing. Finally, we believe that the flex strength and modulus is likely to be the most important material property in most automotive applications that we contemplate. Focusing on this result enables one to draw generalized conclusions about which fibers and which fiber concentrations will impart the collection of properties needed in a subject application.

The flex strength test is 3-point bending test across a 4” span, the specimens being stressed to failure. We utilize an Instron Model 4205 with a 20,000 lb. load cell and this test is quite reliable. The only “variables” are the material being tested, and the test specimen part quality.

To ensure test specimen quality, “Flex bars” are transfer molded by experienced technicians who clean and prepare the molds in a consistent, repeatable fashion. Each “flex mold” yields four specimens. To acquire the data herein we typically mold 12, post cure and then break 12 specimens. Standard deviations and outliers are presented with the data.

Material Data and Discussion

Table I shows uncured material properties of thermoplastic polymers, and the base epoxy material that will be modified and examined further. Trade names of these materials are not included and specific part numbers have been changed to create more generic comparisons.

Table I. Uncured Material Properties

Uncured Material Properties							
Property	Unit	PAI ⁴			PPA ⁵	PA ⁶	SolEpoxy EMC-1(FG)
		P-N	P-30FG	P-30CF	A-33FG	N-33FG	
Melt Viscosity		high	high	high	high	high	low
Melt Temp.	°C	~340	~340	~340	321	280	110*
Filled	%	unfilled	30 FG	30 CF	33 FG	33 FG	75 Si, 5 FG
Dry Time (pre-process)	hrs	3	3	3	4	3	NA
Post Cure time	hrs	336+	336+	336+	24-48	24-72	2--4

FG – fiberglass CF – carbon fiber Si – silica

* This is the molding compound melt temperature which initiates the thermoset curing reaction. Molding temperatures are typically in the range of 150°C to 180°C. After the epoxy composite has cured, it cannot be re-melted.

The first property to discuss is the melt viscosity. All of the thermoplastics have a very high viscosity compared to the epoxy. While the epoxy has a melt viscosity in the 50-150 Pa-s range, the thermoplastics typically have a melt viscosity in the 100,000 Pa-s range and higher. As a frame of reference, EMCs will flow like tomato paste while filling a mold. Thermoplastics flow like caulk which makes it more difficult to mold net-shape, fine features. The temperature required to melt these thermoplastic polymers is also much higher than that required to melt the epoxy.

All of these chemistries may be processed as neat (unfilled/unreinforced) materials, and all can have reinforcing materials added to them. For thermoplastics, these materials are generally fibers, although other fillers can be added that improve flame suppression, chemical resistance, heat stability, etc. Many of these same additives can be added to an epoxy system to achieve the same results. With epoxies, the total amount of reinforcement can be higher without compromising the moldability of fine features. Many epoxy mold compounds have a filler content that can reach 70% or higher. For instance, the EMC-1 contains 75% silica filler and 5% fiberglass added as reinforcement. The silica will improve chemical resistance, reduce shrinkage and increase stiffness. The fiberglass will help with improve tensile and flexural strength.

In many respects, epoxy molding compounds are actually easier to process than these thermoplastics – which is a non-intuitive claim because thermoplastic injection molding is such a common process. The reason is that all of these materials require special pre-handling and post-processing in order to achieve optimal properties. It turns out that the thermoplastics require more care and processing than do epoxy molding compounds.

For instance, the thermoplastic resins need to be dried before processing. If the moisture content is too high, it will create molding problems. While epoxies are also sensitive to moisture, SolEpoxy's manufacturing process is entirely climate-controlled. Moisture content is measured and minimized; finished goods are packaged and refrigerated until used. With proper handling – which is easy to master, epoxy molding compounds can be used in all seasons and in non-climate controlled molding shops.

The larger processing difference is seen during molding and post-molding. In the case of epoxy, the process is relatively simple. Parts are typically molded at 150°C to 180°C where the total cycle time including the transfer of material into the mold plus in-mold curing under transfer pressure takes from 2-5 minutes. The molds are then opened and parts removed. When a sufficient number of parts are racked and ready, they are placed in an oven for 2 hours at 177°C, removed and left to cool in ambient.

For these high-performance thermoplastics, post-curing and post-conditioning is much more involved. Table II below shows a typical post cure schedule for a thin-walled PAI part. It should be noted that the thicker the part cross section, the longer the post cure process takes to complete. And, the oven temperature is not constant. Each part could require a special, pre-programmed ramp schedule, thus necessitating multiple and sequenced batch runs. In sum, the schedule to post-cure PAI runs multiple weeks!

Table II. Post cure schedule for thin parts⁴

<i>Post Cure Schedule for PAI parts</i>		
<i>Part size</i>	<i>Days</i>	<i>Temperature, °C</i>
	1	149
<i>Parts with a maximum</i>	1	191
<i>Cross section of 7.6 mm</i>	1	204
	1	218
	1	232
	1	243
	1	252
	10	260

By comparison, epoxy is easier. Thin-walled PAI parts take 100 times longer to cure than any size epoxy part, regardless of thickness. At 260°C, the temperature to cure PAI is about 50% hotter than an epoxy post curing oven. These facts suggest that the cost to manufacture a finished part is far higher for one of these thermoplastics than for an epoxy but that's not all. Epoxy molding compounds are actually affordable materials – more comparable in cost to aluminum than these exotic thermoplastics. We offer this table of magnitude prices as a frame of reference.

Table III. Price range of raw materials⁷

<i>Material Pricing</i>		
<i>Material</i>	<i>Cost - \$/kg</i>	<i>Cost - \$/cm3</i>
<i>PPA (neat)</i>	1.65 - 4.00	0.006
<i>PA 6/6</i>	3.01 - 4.58	0.006
<i>PAI</i>	40 - 57	0.085
<i>Epoxy (EMC)</i>	4 - 10	0.019
<i>Aluminum⁸</i>	0.90 - 1.32	0.004

The epoxy is neither the lowest cost material nor the most expensive. It is very competitive with the nylon-type materials and is a fraction of the cost of the PAI-type resins. Factoring in the extended processing time of thermoplastic resins, or the expense of producing metal parts, epoxies offer an appealing combination of relatively low material and processing costs and comparatively fast part production.

All of this doesn't matter if the epoxy doesn't have the properties to survive and perform in the intended environment. Table IV below lists many of the cured physical properties important to successful survival under harsh conditions.

Let's examine the carbon fiber systems. We took a base formulation, EMC-1, which is 75% (wt.) filled with silica and also contains 5% (wt.) fiberglass. We made carbon fiber versions of this material and compared the properties. The carbon fiber versions contained 3.4, 5, 10, and 15% carbon fiber and will be referred to as EMC-3.4, EMC-5, EMC-10 and EMC-15. The 3.4% carbon fiber system was formulated to have the same amount of fiber as 5% fiberglass, taking the density difference of the fibers into account. The 5, 10, and 15% CF were then made to evaluate higher fiber loadings. The data included here is limited to one set of data points from one batch of material for each different version. No attempts have yet been made to optimize the formula or the processing of these materials. There was also no attempt to optimize the molding process. A standard "best practice" was used to mold all the test parts covered in this paper.

Table IV. Cured Properties

Cured Properties							
Property	Unit	PAI			PPA	PA	SolEpoxy EMC-1
		P-N ⁹	P-30CF ¹⁰	P-30FG ¹¹	A-33FG ¹²	N-33FG ⁵	
Tensile Strength	MPa	152	221	221	221	185	118
Tensile Elongation	%	7.6	2.3	1.5	2.5	3.5	3.3
Tensile Modulus	Gpa	4.5	14.6	16.5	13.1	10.1	7.2
Flex Strength, 23°C	Mpa	244	333	355	317	260	165
Flex Modulus	Gpa	5	11.7	19.9	11.4	8.2	6.6
Compressive Strength	Mpa	220	260	250	185		315
Compressive Modulus	Gpa	4	7.9	9.9			5.7
HDT, 1.82MPa	°C	278	282	282	280	255	250
CTE1	ppm/°C	30.6	16.2	9	24	39	18
Shrinkage	%	0.6-0.85	0.1-0.25	0-0.15	0.4-0.8	0.4-1.0	0.25
Tc	W/m-°K	0.26	0.37	0.53		0.28	0.8+
UL94		V-0	V-0	V-0	HB	HB	V-0
SpG	g/cc	1.42	1.61	1.47	1.44	1.39	1.91
Dielectric Strength	kV/mm	23	33	23	21	27	50

Some properties like spiral flow and hot plate gel time will not be discussed in much detail. While these properties are important to a material processor, the focus of this paper is on the physical performance properties of the materials.

Flex strength is the mechanical property we look at first, and most often. One mold shot of material will produce 4 test specimens. For comparison, an equal material charge will only produce 2 tensile bar specimens. The other reason flex is used as a reference test is the test itself. The flex test is a 3-point bending test across a 4" span, and the bar is stressed until the part fails. The test is quite reliable and there is very little chance of a compromised run. The only "variables" are the material and the test specimen part quality. In contrast, the tensile strength test can potentially have issues with specimen testing. The test specimen, often referred to as a dog bone, can slip while clamped in the test grips, compromising that run. Additionally, the dog bone can break outside of the testing length of the part, either in the grip area of the part or in the shoulder to the testing span, again adding questions to the reliability of a given data point. Lastly, due to the isotropic nature of the material, if we see an increase in the flex strength, we would expect to see some increase in the tensile strength as well.

If we look at Figure 1, we see a trend that we would expect, increasing strength with increasing fiber content. What is most impressive is the strength increase from the EMC-1 sample to the EMC-3.4 sample. EMC-1 is reinforced with fiberglass while EMC-3.4 is reinforced with carbon fiber. The fiber volume of these two samples is equivalent, so it appears that the carbon fiber offers better performance, 16% better at this loading level. The carbon fiber part would also be 2.5% lighter than the fiberglass part.

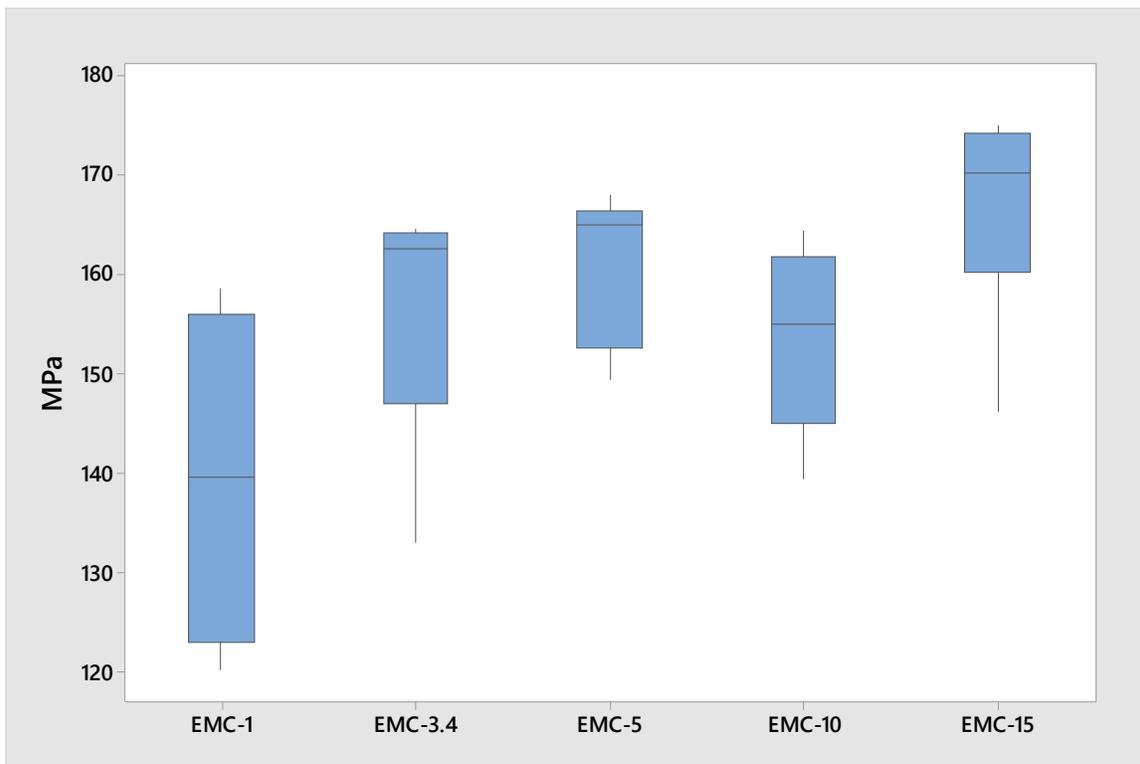


Figure 1. Flex strength

Figure 2 displays the tensile strength of our material set. Similar to flexural strength, the tensile strength also shows a trend toward higher performance with a higher fiber loading. EMC-15 displays a significant jump in strength but is only based on two data points as we ran out of material and no more parts could be made.

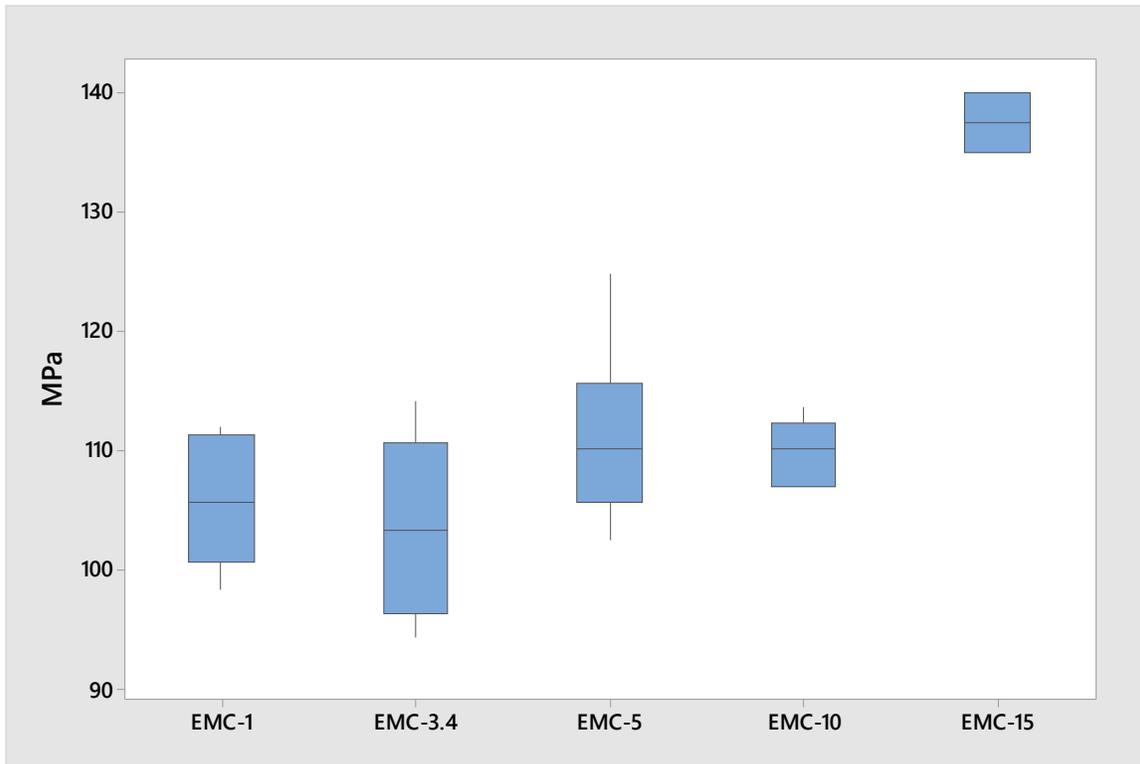


Figure 2. Tensile strength

Figure 3 shows the compressive strength comparison for this series of materials. The first two samples, EMC-1 and EMC-3.4, being similarly reinforced, perform in a similar manner. This was an expected result. What was not expected was the drop-off in compressive strength with increasing fiber content. The prevailing thought is that with more fiber comes more strength. While this seems to be true for the tensile and flexural properties, the opposite appears to be true for compressive strength. Imagine trying to push a rope, and it starts to make a little sense.

Since one of the target application areas is the engine compartment, heat resistance is an important part of material performance. Underhood parts cannot sag or warp when the temperature increases, so a heat distortion test (HDT) provides valuable information on material creep at elevated temperatures. Figure 4 presents a summary of HDT values for these materials.

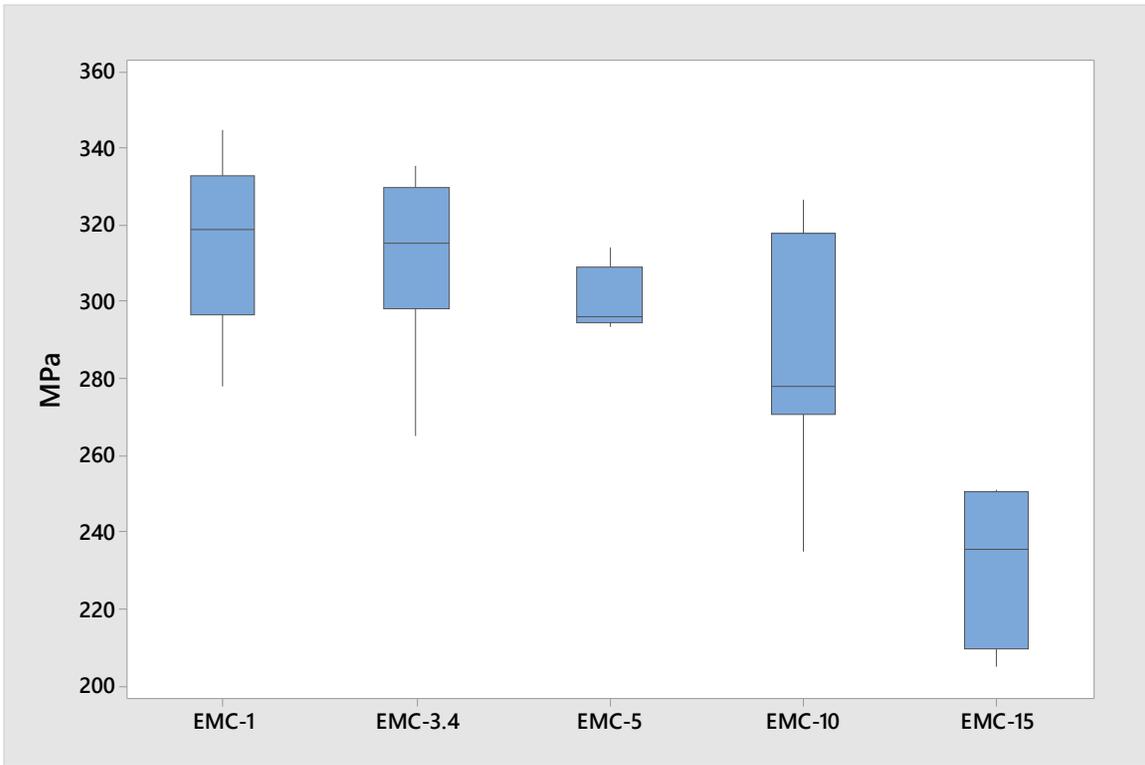


Figure 3. Compressive Strength of EMCs

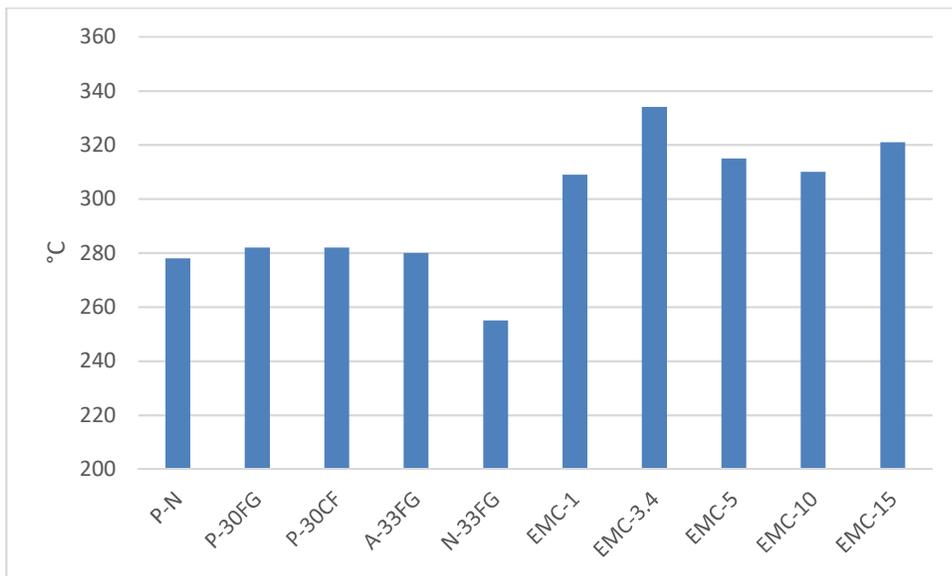


Figure 4. HDT of various material systems

It is interesting to note that while the thermoplastics have higher flexural and strength properties due to the long fiber reinforcement, the HDT values of the all the EMC materials exceed the properties of the thermoplastics. This is in no small part due to the thermosetting nature of

the resin system, with additional contributions from the high percentage of inorganic fillers. With HDT values over 300 °C, the epoxy materials can provide superior high temperature performance necessary to operate in under the hood applications. We also believe that EMC use can be expanded into underhood applications because we have a material that is already performing in this environment, as part of the fuel injector (Image 1 below) on industrial heavy equipment.



Image 1. Fuel injector with EMC (yellow) encapsulated solenoid.

We also decided to test the tensile and flexural strength of the EMC at elevated temperatures. The material comparison of these properties was a little more challenging because different material suppliers tested their products under different conditions or did not present such test data. Flexural strength was reported at 100 °C for the PPA, but the PAI flexural data was generated at 135 °C. Tensile strength data was only found for the PPA product and that was also at 100 °C. As an initial benchmark, we chose to test the flex and tensile properties of the EMCs at 100 °C.

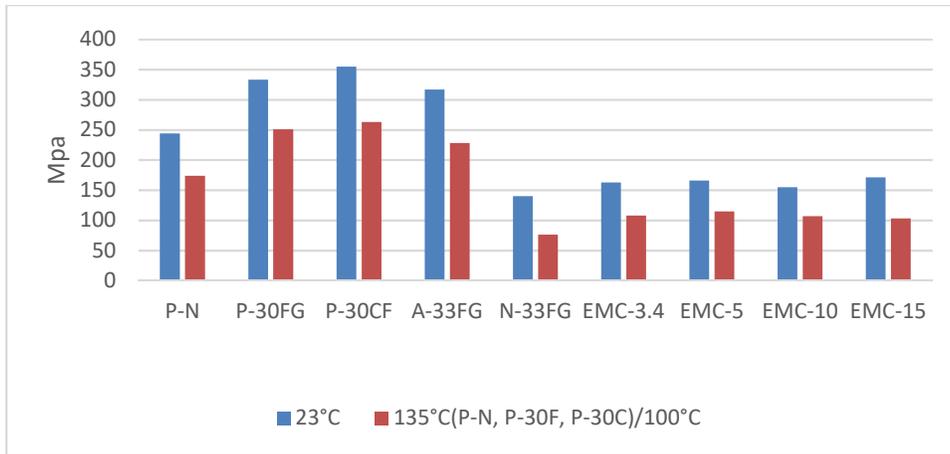


Figure 5. Flex strength comparison at multiple temperatures

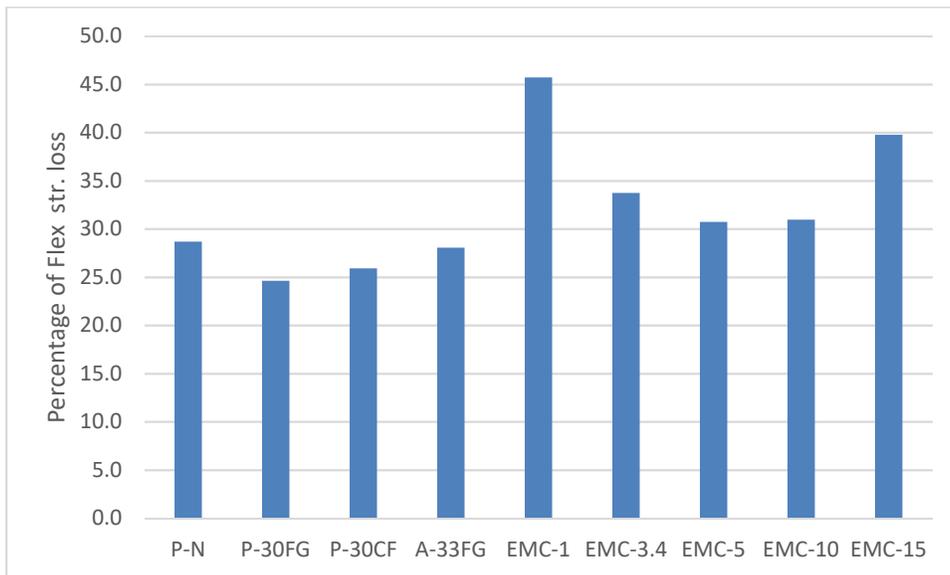


Figure 6. Percentage of Flex strength loss

Figure 5 demonstrates the flex strength of most of the materials at 23°C and a higher temperature. The PAI were tested at 135°C and the remaining materials were all tested at 100°C. The short-fiber EMC is lower in flex strength but with the exception of the fiberglass reinforced EMC-1, the decrease in strength is comparable to the thermoplastics, on a percentage basis, as show in Figure 6.

There are some material performance properties that will not be discussed in detail in this paper, but they are properties where the EMC appears to have a definite advantage over the thermoplastics. One such property is thermal conductivity. EMC-1 was not designed with any thermal conductivity target. It is filled with silica and fiberglass to approximately 80% loading by weight. Its thermal conductivity is 0.8 W/m-°K -- significantly higher than the 0.53 W/m-°K achieved by the PAI P-30C, the highest value observed among the thermoplastics discussed here. With Tc as a design target, and currently in development, materials with a Tc of 2.5 - 5

W/m-°K are being developed. This is achievable because the EMC contains a much higher percentage of inorganic fillers. As vehicles move toward electric motors and electric propulsion, thermally conductive and electrically insulating EMC materials could become important materials in future automotive designs.

EMC based materials can also potentially outperform the thermoplastics in dielectric strength. The dielectric strength is a measure of the electrical resistance or insulation a material will provide. The performance value of the EMC-1, at 50 kV/mm, is almost double the insulation value of the closest thermoplastic. This value is actually typical for most EMC materials, and this performance can be improved on as well if necessary. Systems have been developed that have a dielectric strength of 100 kV/mm.

Summary and Next Steps

In this paper, we compared the physical properties of engineering thermoplastics and carbon fiber reinforced epoxy molding compounds for their potential use in demanding automotive applications. While the thermoplastics have been touted for their performance at elevated temperatures and their use in demanding applications have grown, epoxy mold compounds have been left behind, particularly in automotive applications. This is in spite of the fact that these epoxies have exhibited good high-temperature performance. Additionally, the process economics might be lower for epoxies than for the thermoplastics. These epoxy materials can also be processed on similar equipment, specifically injection molding machines that enable higher volume production. The short fibers and unique processing produce materials with isotropic properties capable of performing in very demanding environments.

Additional high temperature testing needs to be performed on the EMC systems. The superior performance of the EMCs in the HDT testing reveals the potential for these materials in very high temperature applications like automotive engine compartments. Where elevated temperature tensile and flex strength data was available, the EMCs performed in a similar manner to the thermoplastics. Still, a more complete comparative analysis of properties could be informative.

No effort has been made to optimize these CF epoxy mold compounds or the molding process for them. The next work to be conducted will be increasing the fiber content to see how much fiber can be added. Additionally, we will be choosing one formulation to optimize for further parts evaluation work. Specific properties we hope to optimize are T_g – glass transition temperature, and the tensile and flexural strength. This could require modifications to the formula or changes to the processing of the material.

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