ADVANCED SMC RESINS FOR ELECTRIC- VEHICLE BATTERY-ENCLOSURE APPLICATIONS

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ABSTRACT

The fast-growing electronic and hybrid vehicle industry demands safe and reliable battery enclosure systems that can survive harsh conditions. In designing these structures, engineers need materials that are fire- and heat- resistant, have high strengths, high stiffness, and low mass. The preferred materials also need to be fabricated into complicated shapes with short cycle times.

Compression-molded fiberglass composite materials meet the requirements of the design engineers. Sheet Molding Compound (SMC) composite materials offer a cost-effective molding process and flexible structure design capabilities. Besides, the composite material can be tailored to meet the specific part design requirements. The SMC resin formulation can be formulated with different filler and additive packages for optimized strength, density, flame resistance, and flow characteristics. The overall benefit of using SMC composite materials is an equal or better performance compared with metals, at a lower cost.

The technology presented is based on a proprietary low molecular weight resin, which expands the product development capability of highly filled SMC resin systems. The critical properties of SMC resin made with the said resin systems are studied, and the formulation impact on the properties is discussed.

1. INTRODUCTION

Improving battery efficiency and safety performance is one of the technical challenges for electric vehicles (EV) to compete with traditional cars made of internal combustion engines (ICE). In order to improve EV cars performance, engineers dedicate tremendous efforts to design battery systems in which batteries can perform more safely and efficiently. Different OEMs and battery manufactures have varied proprietary designs to fit their own needs. These various designs usually lead to diverse enclosure structures for molders to produce. A cost-effective EV battery box production is a combination of a minimum investment in the tooling system, a maximized production capacity, and the flexibility of producing parts of versatile shapes.

The selection of materials for the battery structure has a considerable impact on the effectiveness of battery enclosure production. Traditionally, EV battery enclosure materials are comprised of steel and aluminum, owing to their high impact strength, excellent mechanical shock resistance, and good thermal properties. With the evolvement of new designs and requirements mentioned above in the EV industry, the disadvantages of metals are apparent. Primarily, manufacturers need to invest in expensive metal stamping equipment to make different battery enclosure structures. Thus, replacing materials that require less tooling investment to produce the new designs becomes more interesting to molders. The light-weighting trend in the EV industry also encourages engineers to use materials with lower specific gravity than metals while still maintain the other essential properties and performance.

Sheet mold compounding (SMC) material is a potential replacement of metals in making EV battery enclosure structures because of multiple benefits.[1] Firstly, the SMC process has the advantages of short production cycle times and the capabilities to fit various part designs. Secondly, SMC materials possess a variable range of mechanical properties, density, thermal properties, surpassing metals in many applications in the auto industry for decades. Lastly, several characteristics associated with SMC are specifically beneficial for the battery enclosure application. Like most of FRP materials, SMC has excellent thermal insulation and electrical properties. Advanced low-density SMC technologies offer solutions to OEM’s light-weighting requirements. Using SMC material can lower approximately 20 to 50% of the total mass compared to the use of metals, without sacrificing strength and stiffness performance. Furthermore, SMC processing can accommodate deep-draw designs and integrate sophisticated features such as attachments, seal locators, ports, and plugs. Thus, the overall production tooling cost of the SMC process is estimated to be 25 % to 75 % lower than metal tooling cost, therefore significantly reducing the total part cost per vehicle.

The outlook of using SMC for the battery enclosure application is determined by how well these materials meet the critical performance needs. There are many property requirements for battery enclosure parts, depending on the specific designs. The essential properties are mechanical properties, flame retardant performance, and density. The flame retardance performance is impacted by the level of flame-retardant filler in the SMC paste resin. The mechanical properties are related to the level of fiberglass incorporated in the final part. Glass microspheres are added to the formulations for light-weighting purposes. All these ingredients impact the flow of the SMC sheet, a crucial characteristic of a successful SMC process. Therefore, the proper balance of these ingredients in the SMC resin formulation is critical. In this paper, we explored ta hybrid resin's performance as a base resin for battery box SMC formulations. The resin technology has a lower initial viscosity compared with traditional UPR/VER resin at the same styrene content, enlarging the formulating window by allowing the incorporation of more glass fiber and fillers in the finished part. This article is to discuss the formulating boundary of this resin-based system and the optimized properties as a result of the study.

2. EXPERIMENTATION

2.1 Materials

The hybrid resin was blended with low profile additives, mold release agent, alumina anhydride (ATH), and initiator to form SMC A pastes. Microsphere was added when a low-density A paste and SMC material was required. The SMC B paste was a mixture of isocyanate and MgO at a specific ratio that was used to thicken all formulations studied in the paper.

SMC sheets were made on an SMC machine with controllable fiberglass feeds and blade gaps for the desired levels of fiberglass loading. The SMC sheets were matured at room temperature for eight days. Before each SMC sheet being mold on the eighth day, an acceptable fiberglass wetting was confirmed to ensure a representative panel was made. The molding process lasted 2 minutes at a temperature of 320 F with a molding pressure of 12.76 MPa. The dimension of the finished panel was 30.48 cm by 30.48 cm, with a thickness of 2.5 mm.

2.2 Testing

2.2.1 Viscosity

Ingredients of SMC A pastes were blended by a mixer at a speed of 600 rpm. The A paste mixtures were equilibrated at room temperature for one hour, and then the viscosity measurement was taken on a Brookfield viscometer. The testing spindles and speeds were varied depending on A pastes viscosity values.

2.2.2 Specific gravity

A molded panel was weighed on a balance with a 0.1 mg readability and then submerged in a water tank with an outlet to gather the water expelled from the tank. The volume of the sheet was calculated by the weight of the expelled water and the density of water. The panel specific gravity was calculated by dividing the sheet weight and its volume. The average value of two repeats was reported in this paper.

2.2.3 Spiral flow

A spiral flow tool was used to measure the flowability of thickened SMC sheets. SMC sheets were cut into 14 cm by 14 cm pieces and then stacked in six layers. The pre-weighed stack of SMC sheets was placed in the center of the spiral flow tool. As the heated tool pressed the SMC sheets, the material was forced to flow in a spiral mode until it was cured and lost flowability. The flow length was measured afterward and an average of two measurements was reported.

2.2.4 UL 94 5VA

UL 94 5VA is a vertical burning test for small bar plastic samples. The test was operated on a Bunsen burner with protocols specified in the UL 94 test method (reference). For the sample to pass the test, the material should be self-extinguishing ≤ 60 seconds after flame time plus afterglow for all 5 individual samples. Five replicates were measured for panels made from each SMC formulation. The averaged after flame plus afterglow times were reported.

2.2.5 Cone calorimetry

Cone calorimetry testing is a method for measuring fire resistance properties of condensed materials in small sample sizes. The measurement was operated by a third-party lab following ASTM E1354. SMC panels were cut into samples in 10.16 cm by 10.16 cm and tested at a heat flux of 50 kW/m^2. Two repeats were tested for each SMC panel. The averaged value of the peak rate of heat release (HRR) and average specific extinction areas (Avg SEA) was reported in the paper.

2.2.6 Tensile properties

The tensile properties of the SMC panels were measured according to the protocol specified in ASTM 638. Five replicates were measured for panels made from each SMC formulation. The averaged peak tensile strengths and tensile moduli were reported.

3. RESULTS

The experiments conducted to understand the potential usage of the new proprietary resin for battery enclosure applications included three main sections. As mentioned in the introduction session, the motivation of the study was to prove the concept idea that the low initial viscosity resin can accommodate large amounts of none liquid components in the SMC parts. This benefit, if being understood thoroughly, may expand the SMC A paste formulating scope and provide the automotive industry with more SMC material options. The study started with a design of experiment (DOE) to learn the impact of each of the design factors on A paste viscosity. As a result of the learning, a liquid base resin was defined for making a series of SMC A pastes, which was further used to prepare SMC panels for this study. The properties of these SMC panels were measured, reported and analyzed in the second part of this session. In the last section, we summarized the overall properties of each SMC panel and discussed how each might fit potential needs in the battery enclosure application.

3.1 Liquid resin optimization

A DOE was initiated to study different factors' impact on the A paste viscosity. The details of the DOE design are listed in Table 1. Base resin A listed was the hybrid resin to study, and base resin B was a UPR/VER blend used for making general auto parts. Two types of low-profile additives, LPA X and LPA Y, were used. Other than these two categorical factors, four continuous factors, the percent of LPA solid content, the percent of total styrene, the percent of ATH, and the percent of microsphere were included. These components were formulated into an A paste according to the DOE and the viscosity of each paste was measured and reported. JMP software was used to fit the viscosity into a model, as illustrated in Figure 1, with a calculated Rsq of 0.9903 and a P value less than 0.0001, indicating that the model represents the correlation between the factors and the results effectively. Based on the fit model, the impact of each factor was ranked in Table 2, with 1 as the most impactive factor and 5 as the least. Not surprisingly, the amount of ATH and microsphere were the two factors that influenced A paste viscosity the most. Within the group of liquid ingredients, LPA type was the most impactive factor, and the styrene content was the least.

For the battery enclosure application, it was anticipated that the SMC A pastes were densely loaded with ATH to boost the flame-retardant performance and possible microspheres for light-weighting purposes. A resin with a low viscosity was preferred as a starting point for the A paste formulating. Therefore, the most impactive liquid factors based on the JMP analysis were selected to form the optimized liquid resin. This resin is the first formulation in Table 2, which contained base resin A, LPA X, and 52 wt% of total styrene. Additional mold release, initiator, was added to form the SMC liquid resin component.

Table 1. Liquid resin optimization DOE design and results

Resin	LPA	LPA solid %	Total Styrene %	Huber A 100	Spheres	A paste Viscosity cps
A	X	10	52	200	0	2568
B	X	12	47	200	0	11640
A	Y	11	49.5	125	12.5	7120
A	X	12	52	50	25	1904
A	Y	11	52	50	25	6120
A	Y	10	47	200	25	138400
B	X	12	47	125	25	49200
A	X	12	47	50	0	384
B	X	10	47	125	0	4740
A	X	12	52	200	12.5	8200
A	Y	10	52	200	25	99360
A	X	10	47	50	25	3216
A	X	10	52	50	0	206
B	Y	12	47	50	0	2516
B	Y	10	52	200	0	16800
B	X	10	49.5	200	25	94400
B	X	10	52	50	12.5	3280
B	Y	11	47	200	0	31640
B	X	12	49.5	50	25	4312
A	X	12	47	200	25	32800
A	Y	12	52	200	0	13320
B	Y	11	52	50	25	14000
B	Y	12	49.5	200	12.5	117600
A	Y	10	47	50	0	477
A	X	10	47	200	12.5	9960
B	Y	11	47	200	25	418400
B	Y	10	49.5	50	0	1576
A	Y	12	47	50	25	12000
B	Y	10	47	50	25	21440
B	X	11	52	50	0	1040
B	Y	12	52	200	25	393600
A	X	10	52	125	25	5536
B	X	11	47	50	12.5	2880
A	Y	12	52	50	0	684
B	X	12	52	125	0	2388
A	Y	12	47	200	0	33200

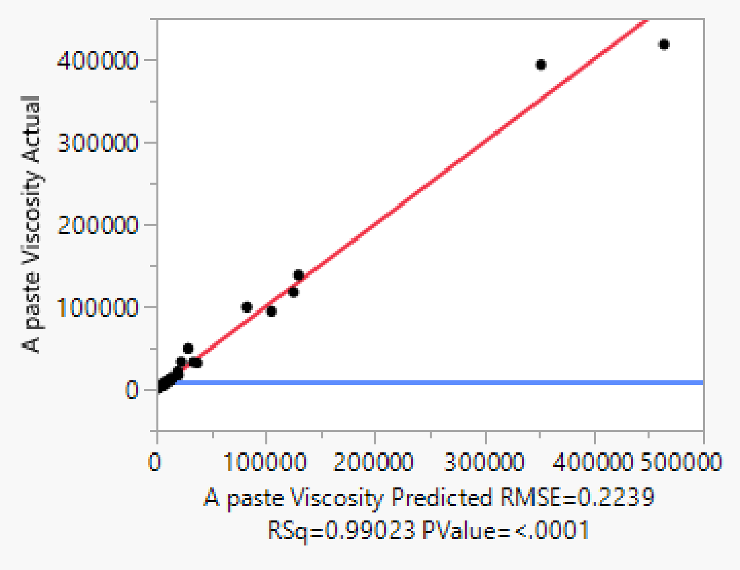

Figure 1. DOE JMP model of liquid resin optimization

Table 2. Liquid resin optimization DOE design and results

Factor	Impact on A paste viscosity
Level of ATH	1
Level of Glass bubble	2
LPA type	3
Resin type	4
Styrene level	5

3.2 SMC formulations, flowability, and mechanical properties

We report five SMC A pastes using the new base resin defined in section 3.1. These A pastes included various types of ATH at different loadings and one contained microsphere. Five SMC sheets were made by combining the A pastes at various loading of fiberglass and then molded into SMC panels. With the varying amounts of ATH, microspheres, and fiberglass contents, the resulting panels were expected to exhibit a broad range of mechanical, flame retardant, and light-weighting properties.

The studied SMC A paste formulations are listed in Table 3. Formulation A and B were filled with ATH type 1 at 125 parts and 200 parts per 100 parts of the liquid base resin, respectively. Formulation C is formulation A with an additional 15 parts of microspheres. In the liquid resin optimization study, it is found that with 125 parts of AHT in the A paste, a 15 part is approximately the maximum loading of microsphere for the SMC A paste to be in a processible viscosity range. Formulation D and E were made with 200 parts of ATH type 2 and ATH type 3, respectively. The viscosity results listed in Table 2 showed that within the group of formulation with 200 parts of ATH, formulation B had the lowest viscosity of 25,000 cps. The viscosity of the formulation D and E were both higher than that of formulation B. This observation was attributed to possible variations in the particle size distribution of different types of ATH. With 125 parts of ATH type 1, formulation A had the lowest viscosity of 2,245 cps. Adding 15 parts of microspheres to this formulation increased the viscosity to 8,345 cps.

Table 3. SMC A paste formulation and viscosity

	A	B	C	D	E
Hybrid SMC resin (part)	100	100	100	100	100
ATH type 1 (part)	125	200	125		
ATH type 2 (part)				200	
ATH type 3 (part)					200
Microsphere (part)			15		
A paste viscosity (cps)	2,245	25,000	8,345	38,000	29,000

Each SMC A paste was combined with the desired fiberglass contents and thickened to SMC sheets to be tested for flow lengths and mold into SMC panels. The flow lengths and properties of these panels are shown in Table 4. The target property requirements included in the table are based on market feedback. The flow testing results showed that all panels achieved at least 26 inches of flow length for the material to be moldable for making the battery enclosure part. Panel A contained a fiberglass content as high as 38 wt%, leading a tensile strength of 124 Mpa and a tensile modulus of 12 GPa. In panel B, the fiberglass content was reduced to 32 wt% since the amount of ATH in the SMC paste was increased to 250 parts compared with the 125 parts in Panel A. At this fiberglass level, panel B's yielded a tensile strength of 105 MPa, lower than the tensile strength of Panel A. The modulus of panel B was 11 GPa, slightly lower than the modulus of panel A. The flow lengths of panel B SMC sheet remained at about 26 inches. The fiberglass content of panel C was 36 wt%, close to the 38 wt% of panel A. However, the tensile strength of panel C notably decreased to 83 MPa, indicating the additional microsphere had a significant impact on the tensile strength of SMC panel. The density of panel C was 1.64 g/ cm ^{3}, considerably lower than the densities of other panels. Panel D and panel E were similar to panel B, except that each contained different types of ATH. The flow lengths of these two SMC sheets were about 30 inches, and the tensile strengths were approximately 85 MPa. By comparing these values with the properties of B formulation, it seems that using alternative ATHs improved the flow and decreased the material's strength. Noticing that slightly lower fiberglass contents in these two formulations may partially contribute to these differences, it is also suspected that the variations in the particle size distribution of ATHs may also cause the properties deviations. Another observation was that the modulus of all panels in this study remained around 11 GPa, seemingly independent of the amount of ATH, microsphere, and fiberglass. The hypothesis is that the SMC moduli are related to the base resin and its curing chemistry in the range of the studied SMC formulations.

Table 4. SMC panel properties

	Test method	Property requirement	A	B	C	D	E
% glass	Internal method	-	38	32	36	30	30
Flow (inch)	FACTS	>26	27	26	26	32	31
Density (g/cm ^{3})	Internal method	-	1.92	1.95	1.64	1.9	1.94
Tensile strength (MPa)	ASTM D 638	>80	124	105	83	85	86
Tensile modulus (GPa)		>10	12	11	11	12	12

3.3 Flame retardancy properties

The flame retardancy properties of the studied panels were measured by the UL 94 5V and the cone calorimetry methods to observe different fire responses characteristics of the materials.[2] the testing results are not alwycomparable are summarized in Table 5. Because the industry has not agreed on the fire resistance property requirements for battery enclosure applications, the fire property requirements listed in Table 5 were recommended by the cone calorimetry testing laboratory. Panel B, D, E are in the group of panels made of SMC A paste containing 200 parts of ATH. These panels exhibited an after flame plus afterglow times close to zero seconds. The peak HRR of panel B, however, was 257 (kW/m^2), much higher than the results of panel D and E, which were about 170 (kW/m^2). A similar trend was observed in the Avg SEA results. Panel B performed at an Avg SEA of 376 m^2/kg, whereas the other two panels' Avg SEA were around 300 m^2/kg. Although the 5V testing results did not seem to be dependent on the type of ATH, the cone calorimetry results indicate at the same loading, the ATH type has some impact on the panel fire properties. Panel A containing 125 part of ATH type 1 had a peak HRR of 239 kW/m2 and an Avg SEA of 450 m2/kg. The 5V testing result of panel A was close to zero seconds. With added microsphere to the formulation of panel A, panel C's peak HRR and Avg SEA were slightly reduced compared with panel A. However, the 5V testing result of panel C increased to 9.8 seconds.

All panels passed the UL 94 5VA testing and demonstrated excellent fire retardancy properties. Since the UL 94 5VA test method is often used in the auto industry, we believed these panels are potential materials for producing battery enclosure parts. With the criteria listed for cone calorimetry testing, only Panel D and E passed the testing while panel B was close to passing. Since the criteria set for the cone calorimetry test are not specific for the battery enclosure applications, it is difficult to draw a conclusion from these data. As a matter of fact, research has shown that there is little correlation between the cone calorimetry test and UL 94 testing.[3] However, the cone calorimetry testing provided differentiable results, which can be used to learn how panels perform differently from each other. Therefore, instead of focusing on meeting criteria or not, we use the cone calorimetry results to compare panels' fire properties and facilitate the discussion in the next section.

Table 5. SMC panel flame retardance properties

	Property requirement	A	B	C	D	E
UL 94 5 V test (s)	< 60	0.2	0	9.8	3.4	0
Peak Rate of heat release (kW/m^2)	< 250	239	257	206	176	166
Avg Specific Extinction Area (m^2/kg)	< 350	450	376	426	311	303

3.4 Discussion

This report's primary purpose was to understand what the new resin can offer to the battery enclosure application. With each panel's properties being compared in sections 3.2 and 3.3, it is necessary to have a discussion of the overall performance of the panels. To facilitate the disccusion, each property was normalized by its requirement as displayed in Figure 2. All formulations met the flow length requirement for making a battery enclosure part. This processing property is critical for molders to be able to manufacture acceptable parts at a reasonable speed without scraps. As being mentioned, good flow in a highly filled SMC resin usually meant less formulation space for either ATH or microspheres, which consequently impacts the flame retardancy properties or light-weighting characteristics. The main question to answer in this study was whether the new resin system can be used to make panels with properties and performance meeting specific requirements with the limitation of flow property. The other question was that if the hybrid resin can generate SMC materials suitable for battery enclosure applications and what best-desired properties the new resin system can offer, namely light-weighting, tensile strengths, or fire retardancy performance. Figure 2 provides a visualized comparison of panel properties versus each requirement aiming to answer the two questions. One can see from Figure 2 that panel C was the one with the lowest specific gravity in the study. Its mechanical properties met the minimum requirements, and its flame retardancy performance was reasonably good. This panel formulation is the best light-weighting choice that the new resin system can offer. Similarly, if the user desires the highest mechanical properties, Panel A can be a suitable candidate. Although its Avg SEA was high, it passed UL 94 5VA testing, as shown in section 3.3. The panels with best fire retardancy performance were panels D and E. Since the alternative ATH may directly involve additional investment in raw materials, the molder has the option to chose panel B, which has well balanced mechanical properties and excellent flame retardancy performance as its 5VA testing results were 0 seconds for all 5 repeats.

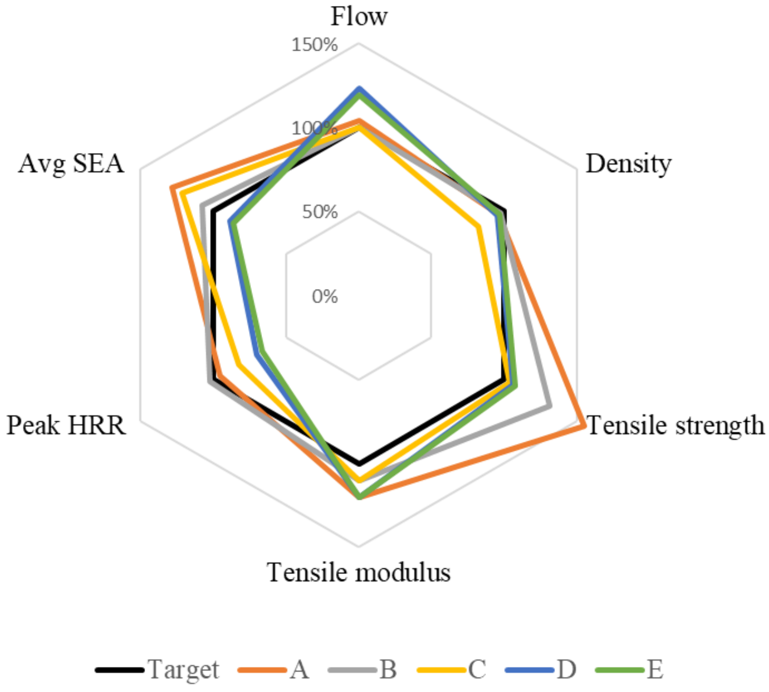

Figure 2. A comparison of peformance of all panels

4. SUMMARY

In this paper, we investigated a new hybrid resin potentially suitable for making SMC parts for the battery enclosure application. The resin was used to formulate five SMC pastes, and panels made with these pastes were tested for various properties. The overall performance of each panel was summarized and compared. The results proved the concept that the new low viscosity hybrid resin could be applied to formulate densely filled SMC resin for battery enclosure application. By analyzing the flow lengths of SMC sheets, specific gravity, tensile properties, and the flame retardancy properties of panels made with selective SMC formulations, the formulating boundary of each ingredient and the impact on properties were established.

5. REFERENCES

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