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High-performance epoxy/carbon fibre SMC

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Sheet moulding compound (SMC) is a major, industrially relevant manufacturing process. Epoxy/carbon fibre SMC is a new material that achieves the highest mechanical performance. To fully impregnate carbon fibre, however, poses a processing challenge due to its high surface area. This paper describes a systematic approach used to improve the mechanical performance of epoxy/carbon fibre SMC.

Sheet moulding compound (SMC) has long been used with polyester and vinyl ester resins to achieve good overall performance and gain commercial acceptance in a range of applications. Material systems using chemistries compatible with the SMC processing technique, such as epoxy, were recently developed to increase mechanical performance [1]. Epoxy, specifically, is suitable for numerous structural applications due to its low-viscosity, which can best wet carbon fibre. In terms of safety, it is low in volatile organic compounds and eliminates styrene monomer exposure. To illustrate its range of performance, several of the process-property relationships of epoxy/carbon fibre SMC are presented for semi-structural and structural applications and benchmarked against epoxy/glass SMC.

Epoxy: the key ingredient in high-performance SMC

Epoxy sheet moulding compound (EP SMC) was manufactured on Dieffenbacher equipment at the Fraunhofer Project Centre in London, Ontario, Canada. This industrial-scale line is suitable for both standard and direct SMC processing. In this instance, the direct process was ignored so as to replicate the standard conditions with which many SMC producers are already familiar. A schematic of this equipment is shown in Figure 1 with some of the heating components highlighted. Though room temperature processing of epoxy/carbon fibre is viable, it is common to lightly heat the paste to further reduce its viscosity.

Since the material is often made in small batches, a Bowers stand mixer with a low-shear dispersion blade was used instead of continuous dosing equipment such as a meter-mix-dispense system or an extruder. The low-viscosity SMC epoxy from Hexion – EPIKOTE™ resin TRAC 06605 and EPIKURE™ curing agent TRAC 06608 – was provided with an internal mould release – HELOXY™ additive 06805. The resin was mixed according to the data sheet, excluding the optionally recommended BYK A-560 degassing agent. The epoxy was carefully mixed for 5 minutes to keep the batches consistent.

The selected carbon fibre was the Zoltek Panex 35 50K-T13. This standard-modulus fibre has a low amount of epoxy-compatible sizing, easily spreading during the compounding and moulding operations.

The quality of the compound is directly related to the selected processing parameters. From previous work, several key parameters were selected as the main optimization targets included the sheet basis weight, compaction pressure, and zone temperatures. The target fibre volume content was set to 45%; the baseline parameters are documented in Table 1.

Panels made from carbon fibre with different filament counts were also fabricated as previously described: 3K, 12K, 15K, and 50K. While the fibres were of different manufacturing origin, they were all epoxy sized at similar concentrations.

Tailored (also called co-cured) epoxy SMC with epoxy prepreg was created in

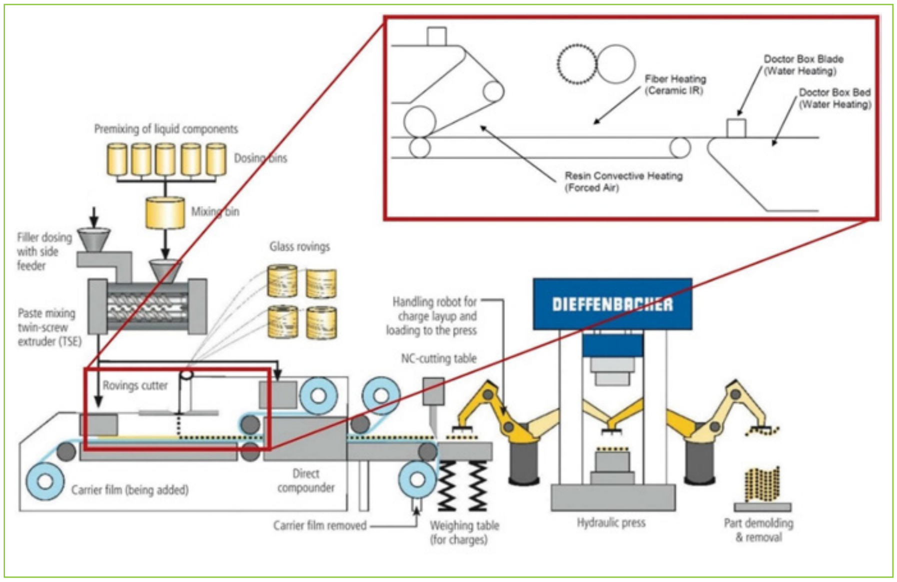

Fig. 1: Schematic SMC equipment at the Fraunhofer Project Centre with heating callout

Tab.1: Epoxy SMC compounding parameters

Parameter	Setting	Notes
Fibre length	25 mm	
Resin temperature	25°C	
Resin film thickness	1.5 mm	Lower film thickness resulted in better fibre wet-out
Basis weight	3500 g/m2	Lower basis weights resulted in better fibre wet-out
Line speed	1.5 m/min	The maximum speed is 1.5 m/min for operator safety
Fibre volume	45%	
Line heating	Off	Line heat at 40°C resulted in improved fibre wet-out
Compaction "pressure"	75 mm	Roller offset value; roughly equivalent to 0.25 bar

Tab.2: Epoxy SMC moulding parameters

Parameter	Setting	Notes
Core/cavity temperature	135/145°C	
Vacuum	On	Until resin gel point (~40 s)
Load profile	75 bar	Constant
Speed profile (slow)	1 mm/s	Only from SMC charge height
Mould coverage	50%	Centre placed
Cure time	3 min	~60 s/mm

a sandwich-panel style SMC charge such that both materials were simultaneously cured when moulded together. Here, the carbon fibre was identical in both the SMC and prepreg materials and the respective resin contents similar. The prepreg did use a different Hexion epoxy system, but one selected for its similar chemistry, thereby preventing differential curing and the resultant micro-cracking and delamination at the SMC/prepreg interface. The prepreg was added in several weight fractions as unidirectional material aligned with the SMC machine direction.

A fibre spreading device was installed in the SMC line to better open the fibre bundles prior to compaction. The approach used to spread the fibre is proprietary to Dieffenbacher and is designed specifically for high-tow carbon fibre. Using this method, the carbon fibre is not fully filamentized, making the reduced fibre bundle sizes easier to disperse and impregnate during compaction.

The epoxy SMC was matured according to the recommended guidelines at room temperature for at least one week prior to moulding. Square panels of 2-3 mm thickness were compression moulded in a chromed tool previously seasoned with the LOCTITE™ FREKOTETM 770NC mould release agent available from Henkel Adhesives North America. Panels were moulded such that the SMC charges maintained the "machine direction", the partial alignment of fibre parallel to the compounding belt direction.

The SMC moulding parameters were generally held constant with incremental adjustments trial-to-trial to improve the quality of the panels. Among the major settings captured in Table 2, one of the critical parameters was found to be the mould filling speed (controlled by the press closing speed), whereby a slower speed during the final few millimetres prevented certain moulding defects.

Figure 2 shows several sample panels as-moulded from the baseline formulation, the spread tow, a co-cured sandwich panel, and the test coupon pattern. These panels generally exhibited a clean, blister-free surface, but were not fabricated for the purpose of achieving class-A quality.

The moulded panels were sectioned into testing specimens following European standards: tensile samples according to ISO 527-4 and flexural samples according to ISO 14125. For reference, the disks and tensile gauges (post-test) were subjected to ignition loss testing according to ISO 7822 to map out the panel fibre volume content and variability. Some dynamic mechanical analysis samples were also taken from each sample panel for separate study.

Excellent mechanical properties for structural design

The tensile results for two selected carbon fibre formulations and one glass fibre formulation are presented in Table 3. These raw results are averages for all the tested coupons in both the machine direction

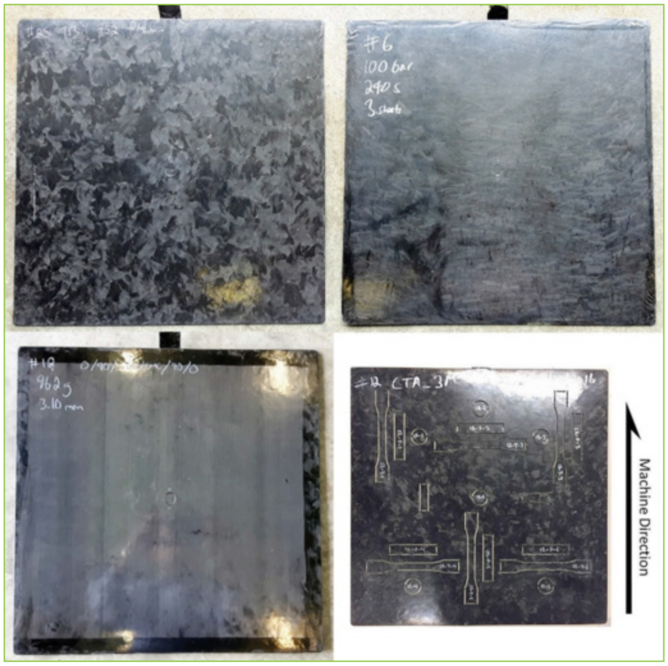

Fig. 2: Sample SMC panels: a) baseline, b) spread tow, c) co-cured sandwich, d) sample pattern

Tab.3: Selected epoxy SMC properties

Parameter	Setting	Notes	Notes
Density [g/cm3]	1.44 ±0.04	1.47 ±0.04	1.94 ±0.05
Volume fraction [%]	44.6 ±5.3	49.0 ±3.6	53.5 ±3.2
Tensile modulus [GPa]	21.8 ±3.3	32.0 ±2.5	20.9 ±1.6
Tensile strength [MPa]	87.0 ±17.9	142.6 ±15.7	304.8 ±18.3
Failure strain [%]	0.44 ± 0.09	0.50 ±0.06	2.46 ±0.32

and counter-machine direction.

The glass/epoxy SMC comparator has excellent properties with high modulus and strength, albeit with a penalty to the material density. The baseline carbon/epoxy SMC represents a first effort with a new SMC matrix and exhibited sub-optimal fibre wetting, resulting in the low observed properties. The improved II epoxy/carbon SMC takes advantage of a lower basis weight, using line heating at 40°C to lower the paste viscosity, and slightly higher compaction pressure. These improvements helped to increase the carbon fibre wet-out as well as reduce variability in the SMC sheet and subsequent moulded panels.
To best compare all the results, the properties were normalized with respect to a given fibre volume fraction. The linear normalization (Equation 1) is generally accepted as accurate for small volume fraction differences of <5%. The normalized property is the ratio of the target fibre volume to the measured fibre volume content multiplied by the measured property. This equation is also used to scale the standard deviation.

$$X^* = \frac{v_f^*}{v_f} X \qquad (1)$$

The normalized results for the 50K carbon/epoxy SMC are shown together in Figure 4. Small improvements were observed by adjusting the compounding and moulding settings. Major improvements were seen by employing spread-tow material. The best properties were achieved by co-curing the epoxy SMC with 20 wt.% of epoxy prepreg in a sandwich-type material.

Plotting the different co-cured materials (Figure 5) with respect to the baseline SMC material revealed a linear trend between the pure SMC and pure prepreg panel properties. This observation is especially important since it implies that epoxy SMC, a lower-value product, can replace prepreg, a high-value product, in some current designs without impacting weight. For example, a panel primarily in flexure could maintain its bending stiffness using a sandwich panel with epoxy SMC as the core material rather than a pure prepreg alternative.

Finally, SMC materials with different carbon fibre tow sizes are compared in Figure 6. As the tow size is decreased, both the stiffness and strength of the resulting epoxy SMC increase. Smaller fibre bundles are more easily wetted during compounding and more easily dispersed during moulding, resulting in more effective fibre load transfer. Standard deviations were also observed to decrease with lower bundle filament counts.

Summary and outlook

A wide range of epoxy/carbon fibre SMC panels were fabricated and tested in a series of industrial-scale trials suitable for any high-volume application. Several approaches were taken to improve the performance of epoxy/carbon SMC including process settings, hybridization, and carbon fibre type. It was shown that a 50K spread-tow material can perform at a similar

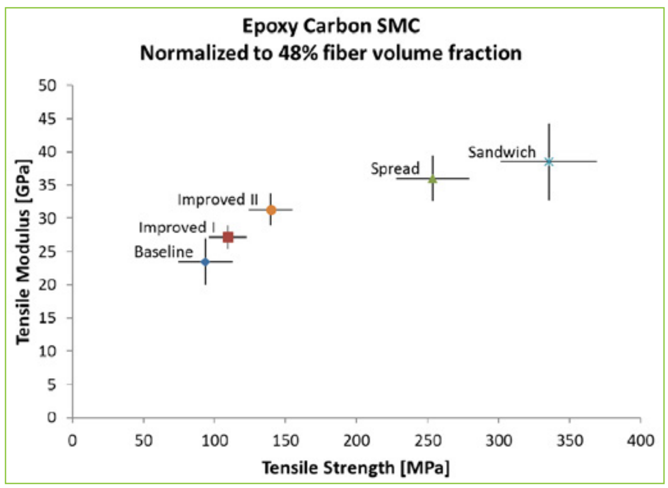

Fig. 4: Tensile properties of various epoxy/carbon SMC products and production settings

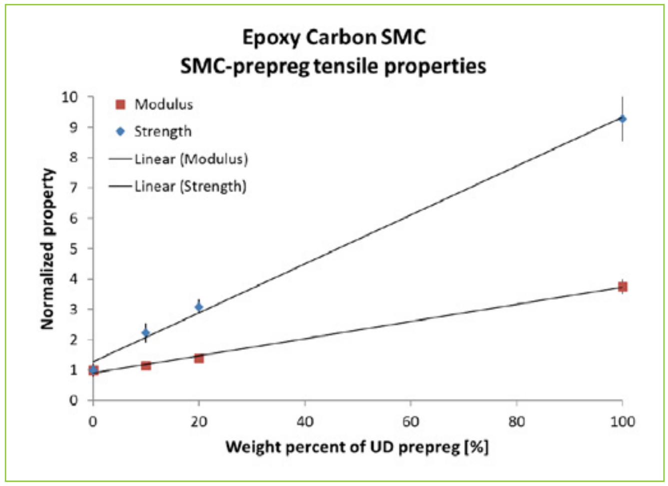

Fig. 5: Tensile property trends of co-cured prepreg with epoxy/carbon SMC

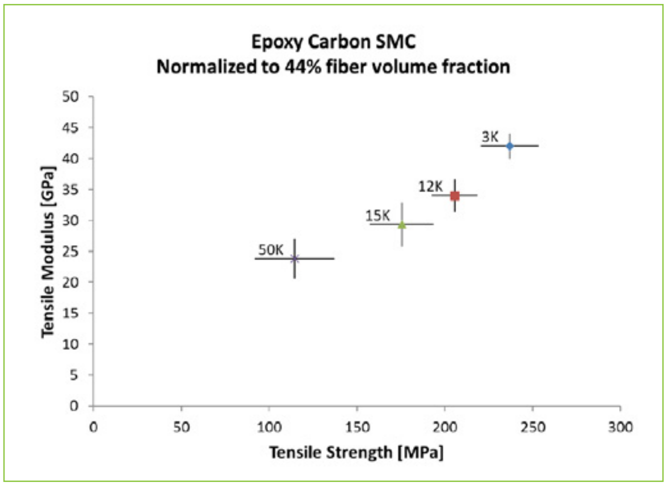

Fig. 6: Epoxy/carbon SMC performance based on fibre tow size

Main features

- Low VOC; eliminates styrene monomer exposure
- Cost-effective, reduces labour and material scrap
- Uses the same equipment, easy to switch from traditional unsaturated polyester and vinylester systems
- Achieves high-volume, low-density parts with superior performance
- Suitable for numerous semi-structural and structural applications

level to a 12K standard-tow material and that compatible prepreg and epoxy/carbon SMC impart the best mechanical performance. Thus, future developments should focus on process optimization with fibre spreading technology and the combination of continuous fibres. It is the combination of material, process, and know-how that best enables high-performance epoxy composite structures. □

More information:
www.hexion.com/automotive
www.hexion.com/contacts

Reference

[1] Swentek I. (2017) New epoxy systems enabling styrene-free high-performance SMC manufacturing. JEC world: presentation, Paris, France, 14-16 March 2017.