New solutions for e-mobility: thermally conductive thermoset plastics

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Abstract
The number of electric cars is expected to increase sixfold by 2030. In order to meet growing requirements in the field of electrical engineering and electronics, new developments and materials are constantly gaining in importance. Epoxy resins (EP) play a major role in this, since applications of plastics for use in the automotive industry require high temperature resistance, good chemical resistance and hybridization possibilities on different materials and substrates.
Due to high cost pressure, efficient and economical processing is also a prerequisite for successful use.
These diverse and demanding requirements are met by thermoset molding compounds based on epoxy resins. This paper shows ways of using these materials for the automotive sector and also the electrified powertrain. The focus is in particular on the possibilities of and opportunities for thermally conductive and at the same time electrically insulating compounds based on epoxy resin.

1. Introduction: thermosetting materials and their applications
Thermoset molding compounds are a group of plastics that crosslink from oligomeric resins during a chemical reaction in conjunction with a thermal input to form a macromolecule. The three-dimensional structure of the macromolecules prevents these material classes from melting, which means that they have a very good safety reserve even at extremely high temperatures above 250°C.
The crosslinking reaction takes place in the epoxy-resin-based thermoset compounds treated here during processing at temperatures of 150–180°C.

Fig. 1: Polyaddition of the oligomers to form the 3D macromolecule
The EP molding compounds are created by polyaddition, in which the active EP groups react stoichiometrically with hardener groups. No gaseous fission products are formed thereby, which makes for simple processing. This has the advantage that no gases need to be removed from the molds, thereby rendering the use of complex degassing concepts obsolete. EP molding compounds consist of an EP resin/hardener resin binder system to which 70–85 wt% fillers and reinforcing materials are added.

A targeted selection of fillers and reinforcing materials, which are coordinated in terms of type and quantity for the application in question, makes it possible to develop certain characteristics. Here the mechanical properties, isotropic/anisotropic behavior and electrical insulation properties can be set within a very broad framework. In applications involving the encapsulation of components, however, it is necessary to adjust the coefficient of linear expansion of the EP molding compound to the materials and substrates to be encased. The coefficient of linear expansion can thus be set to values of 15–25 ppm, which remain largely unchanged in the range extending from 60°C to the glass transition temperature, which is 165-180°C. But even in higher ranges up to temperatures beyond 250°C, these values remain very low. This is necessary to avoid any delamination occurring between the two substrates and to ensure the functionality of the components. In addition, the thermal conductivity can be adjusted and set individually by using the appropriate fillers.

EP molding compounds are generally used to coat sensitive electrical and/or electronic components. This coating or encapsulation ultimately serves to protect against harsh environmental conditions, such as are particularly prevalent in the automotive sector. Applications can be found here in the areas of the powertrain, transmission and elsewhere, in which the components must be hermetically encapsulated to protect them against aggressive automotive fluids so that they can permanently withstand temperatures from -60 to 200°C. These specific properties are required by, for example, speed and position sensors, media pumps based on BLDC technology as well as by control boards and are already established practice.
2. Realizable thermal conductivities and their limits

For many applications in the automotive sector and especially for the electrified powertrain, good thermal management is essential to protect parts and components from too high a temperature and to dissipate heat from the system. In the case of control boards, for example, heat such as that generated by MOSFETs and choke coils must be dissipated. Due to their compact design and high performance requirements, modern electric motors are particularly dependent on effective heat dissipation. The use of thermally conductive molding compounds therefore makes it possible to significantly improve their efficiency and thus the efficiency of the motor.

In comparison with known standard thermoplastics such as PA 66, PA 6, PBT, PPS etc. with a typical thermal conductivity of 0.2–0.3 W/m*K, standard, EP molding compounds with 0.4–0.6 W/m*K, whose thermal conductivity has not been modified, already show a thermal conductivity twice as high. If these are specifically prepared with various thermally conductive fillers, it is possible to increase the thermal conductivity of thermoset molding compounds up to 10 W/m*K without any problems. The compounds are electrically insulating and have dielectric strengths of 40–60 KV/mm. The materials are processed either by the classic injec-
tion-molding process or by the transfer press process. However, the method reaches its limits when a particularly large or extremely pressure-sensitive electrical or electronic components are encased with very highly thermally conductive, thermoset molding compounds. Here flow length decreases with increasing thermal conductivity and the injection pressure or cavity pressure required for filling increases.

A good compromise between the thermal conductivity achieved and good processing performance is found with materials of 2.5–4.0 W/m*K. For many applications, however, thermal conductivities of 1.0–2.5 W/m*K are sufficient, since a very small wall or insulation thickness of 0.2–1.0 mm does not demand higher thermal conductivities.

3. Low-pressure processing: injection molding or transfer molding
EP molding compounds are mainly processed by injection molding or transfer molding. Both of these methods are standard technologies that make a fully automated process possible. The processing takes place partly using molds with very high number of cavities – up to 32. Depending on the component, they are heated to temperatures of 150-180°C with corresponding curing times of 30–90 seconds. This fully automated processing technology with a large number of cavities and short cycle times has the decisive advantage that it makes extremely cost-effective processes possible.

EP molding compounds are often used to coat particularly pressure-sensitive components, since the use of extremely easy-flowing materials makes an internal mold pressure of <50 bar possible – and with the corresponding optimizations even <10 bar can be achieved. This does however call for the use of a cavity pressure sensor. In addition, the tool and cavity geometries must be designed rheologically using a filling simulation.

The processing sequence can basically be divided into three process phases:

- Injection
- Repacking
- Curing (and plasticizing for the next processing cycle)

It is recommended to switch from the injection profile to the holding pressure profile with the aid of a cavity pressure sensor. This process is also known as 'cavity-pressure-dependent switch-over'.
4. Applications of thermally conductive molding compounds: circuit board encapsulation and electric motors

Thermally conductive molding compounds have two main fields of application in the automotive sector:

1. Overmolding of control boards

With this method, the thermally conductive molding compounds are used for media-tight encapsulation of printed circuit boards. Here it is important to ensure that the boards are gently overmolded/encapsulated so that the components are not damaged during processing. Examples include electronic components such as MOSFETs, controllers, electrolytic capacitors, LEDs and HALL-effect cells. The EP molding compounds help prevent overheating of the components by dissipating temperature peaks to the heat sources, thereby protecting the entire component from being destroyed by overheating. In many cases the heat sources are only selectively very thin-walled with a coating thickness of 0.2–0.5 mm. In this case, thermally conductive EP molding compounds make the use of expensive additional processes such as thermally conductive pastes or metallic cooling-grid structures superfluous. Thermal conductivities of 1.0–3.0 W/m*K are used predominantly here. Another possibility is to heat the heat-generating components directly during encapsulation by using a thermoset cooling-grid structure molded in the injection-molding process.

Fig. 5: Raschig GmbH / INMAR Solutions

The boards correspond approximately in size to a DIN A4 sheet. In addition to the complete and all-round overmolding of the boards, overmolding on one side alone is also possible. Due to the good connection of the EP molding compounds to the FR4 circuit board material, to the applied solder mask and to the aluminum structures, media tightness is also secured here.
2. Use in electric motors

In the course of increasing electromobility, electric motors play a very important role in the automotive sector. In addition to media pumps such as oil and cooling water pumps, electrification in the powertrain means that EP molding compounds are also used for hybrid engines and the fully electric vehicle. Likewise there are applications here for rotors as well as for stators in classic commutator motors and also in brushless motors.

In rotor encapsulation, the application lies, for example, in the positionally accurate fixation and media-tight embedding of the permanent magnets. EP molding compounds are used for stators to deliver the basic insulation as a single yoke tooth, but also for complete encapsulations of the entire stator package. After winding, these stators are in some cases finally overmolded with thermoset EP molding compounds in order to fix the windings and winding heads. The more fully the individual winding layers are impregnated, the greater ultimately will be the heat dissipation and robustness of the motors.

With the stator encapsulation, the motor control board is also integrated, whereby the plug and the cable harnesses are encapsulated in a media-tight manner. In all of these processes, the best possible cooling of the engine components is sought.

The great advantage of thermally conductive EP-based thermoset molding compounds is found particularly in the following applications:

- Impregnation of the coils and windings
- Improvement of efficiency through high thermal conductivities
- Thin-walled overmoldings of the basic insulation, which increases heat dissipation
- The high temperature resistance permits applications for UL 1446 Class H (180°C)

In collaboration with PVS-Kunststofftechnik GmbH & Co KG Niedernhall, a demonstrator has been constructed for PIAE 2020 to illustrate the influence of molding compounds with different thermal conductivities and of the insulation thicknesses. This particular component is a stator's single tooth with a length of 105mm. It was encapsulated by the injection-molding process at Arburg GmbH and Co. KG Lossburg.
The following influencing factors were examined:

Different thermal conductivities of the EP molding compounds

- 0.5 W/m*K
- 1.2 W/m*K
- 2.5 W/m*K
- 4.0 W/m*K

The insulation thickness of the yoke tooth overmolding was

- 0.8 mm
- 0.5 mm
- 0.25 mm

The first step was to investigate the possibility of processing the different molding compounds with the different insulation thicknesses.

The overmolded yoke teeth were then wrapped and thermally examined by the Department of Plastics Technology in Erlangen. The first results show a significant influence of the examined parameters on the cooling behavior of the stator tooth. The detailed results will be presented at the PIAE conference on March 25th and 26th 2020 in Mannheim.

Summary

The investigation shows that thermoset molding compounds based on EP resins have a wide range of possibilities for use in the automotive sector and thereby deliver clear advantages:

1. Due to the enormous adaptability of the formulations resulting from the different compositions of the fillers and reinforcing materials, excellent properties can be achieved for specific requirements.
2. Modern processes and a rheological design through simulations ensure cost-efficient processing.
3. Multi-cavity molds and short cycle times also improve profitability.
   a. From the available results it is clear that thermally conductive molding compounds enable innovative solutions for control boards and motors, especially for the electrified powertrain.