Monitoring of properties of epoxy molding compounds used in electronics for protection and hermetic sealing of microcircuits

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Abstract. It is known that epoxy molding compounds have a significant impact on productivity, service life and reliability of electronic microcircuit components. Wrong choice of a molding mixture can lead to mechanical stresses, deformation, cracking or lamination of the protective packaging followed by microcircuit breakage. The study summarizes information on composition, main operating characteristics and application methods of epoxy molding compounds as well as their impact on microcircuit shape distortion. Main methods for control of physical and mechanical properties of epoxy molding compounds with the most significant impact on microcircuit hermetic sealing and on formation of different kinds of defects in the protective packing.

1. Introduction
For correct and long service of electronic microcircuit components in automobile, aviation, ship, rocket and space equipment it is often required to protect the components from the environment, including mechanical (shocks, vibrations), chemical (moisture, heat, UV) and electrical impact. A solution to this problem is to apply various sealing coatings (glass, ceramic, silicone, epoxy, etc.) which provide for protection and heat dissipation as well as simplified installation of electronic components on a printed circuit board. The most popular type of protective sealing coatings are epoxy molding compounds (EMC) because of their affordability and advantages related to the productivity of the hermetic sealing process.

Literature analysis showed that by now a huge amount of theoretical and empirical data has been accumulated on peculiarities of electronic microcircuit components hermetic sealing with epoxy molding compounds [1, 2]. Though in practice manufacturers often observe certain problems during the hermetic sealing process, e.g. deformation, cracking or lamination of protective packing surface, formation of defects, cavities and discontinuities [1-5]. Understanding the impact of the EMC composition and properties on mechanical stresses and deformation of protective packing and substrate at the final stage of microcircuit manufacturing process is one of the most important problems for microelectronics.

This study is devoted to generalization of data on EMC composition and properties and on reasons for defects formation and protective sealing shape distortion during hermetic sealing process. In this study results of research on EMC composition, properties and application procedures are described with a purpose to solve this problem.

2. Basic information about EMC

2.1 Ingredient composition of EMC and its role
Nowadays there are plenty of MC of different shapes, weight, color and properties developed, manufactured and used for hermetic sealing of electronic components of devices in micro- and nanoelectronics. The main manufacturers of EMC are the following: Henkel Electronic Materials LLC, Hitachi Chemical Co.Ltd., Kyocera Corporation, Nepes AMC, Skymart Technologies PTE LTD, Sumitomo Bakelite Co. Ltd, Eler, KCC Corporation. Every company has a product range consisting of several dozens of EMC types. This variety is caused by a wide spectrum of tasks solved by a manufacturer.

EMC are thermoactive composite materials consisting of epoxy resins, hardeners, a filler (SiO$_2$ or Al$_2$O$_3$), catalysts, coloring agents, coupling and releasing agents (see figure 1a) [1]. During manufacture primary components of EMC are mixed at room temperature then transferred to a kneader, heated up to some particular temperature and then mixed until obtaining a homogeneous mixture. After mixing the material is rolled in sheets and cooled. Obtained sheet are crushed into powder, then the powder is pelleted (see figure 1b), the pellets are used for hermetic sealing of microcircuits [6].

![Figure 1](image)

(a) Typical ingredient composition of EMC (a), samples of EMC in pellet forms (b)

The main component of any molding mixture is a resin or a mixture of resins. The epoxy resin is the most popular one, since it has well-balanced physical and chemical properties (high adhesion strength, chemical strength, thermal resistance and moisture resistance, low viscosity and shrinkage ratio), low cost and good aesthetic properties. Besides use of the epoxy resin is preferable with regard to the hermetic sealing process, because it has a low glass transition temperature and short gel time [1, 6].

Phenolformaldehyde resins, anhydrides, amines or aliphatic alcohols can be used as a hardener. Anhydrides are usually used to produce heat-proof EMC and phenolic compounds increase moisture resistance of a coating. Every hardener has its own advantages and disadvantages, e.g. price or productivity, this is why it is chosen according to properties of the hardened coating [6].

Catalysts are used as a part of EMC to speed up the hardening process. Wrong choice of a catalyst can make EMC less stable and decrease the service life.

Use of different hardeners, catalysts and variation of the quantitative ratio of them and epoxy resins allows to control mechanical and adhesion strength, flow characteristics, thermal expansion coefficient, moisture resistance, glass transition temperature, specific resistivity, dielectric properties and service life of EMC.

Filler type also has a significant impact on final properties of EMC. For example, if Al$_2$O$_3$ is used as a part of EMC it increases thermal conductivity and changes magnetic properties and if addition of
SiO₂ increases strength and electric insulation properties. Correct choice of a filler and its content in EMC allows to solve most of the problems occurring during hermetic sealing. It is critical that the filler and sealed substrate, which usually consists of several inhomogeneous materials - a printed circuit board, glue, a semiconductor element, had close values of thermal expansion coefficient. It allows to prevent substrate deformation and EMC delamination from it. Such filler parameters as shape, diameter, size distribution and specific surface area of particles have impact on the packing density, a well a on flow characteristics or EMC ability to fill cavities. When EMC is in a molten state the filler with particles of spherical shape (amorphous SiO₂) has lower viscosity and flows better. On the other hand a filler with particles of plate-like shape (crystalline SiO₂, Al₂O₃ or Si₃N₄) has higher viscosity because of bigger particles and is used to manufacture EMC with high thermal conductivity coefficient. This is why size and shape of filler particles are among the most important parameters for choosing EMC [1, 2, 6].

Another components affecting EMC properties are silane coupling agents and colorants. The former are used to strengthen the bonding between an inorganic filler and an organic resin matrix as well as to improve EMC adhesion with the substrate and semiconductor elements, the latter serve indication purposes and simplify the laser marking process. [6].

Thus, components contained in EMC provide for required physical and chemical properties, adhesion strength and mold-ability. Percentage ratio of components and the chemical composition of EMC itself can differ depending on required operating properties of a protective sealing, type of the substrate used and application method.

2.2 Main EMC properties and their influences on packaging

All EMC manufactured are characterized by a set of properties and parameters which define their potential fields of application. All EMC properties can be divided into four groups: (1) industrial, (2) hygro-thermomechanical, (3) electrical and (4) chemical properties. Several industrial and hygro-thermomechanical properties are crucial for selection of EMC. They define EMC applicability for particular processes: (1) which hermetic sealing method shall be used, (2) which electronic microcircuit elements can be sealed, (3) shape and dimensions of obtained protective packaging. These properties include the following: spiral flow, mold shrinkage, thermal expansion coefficient, glass transition temperature and gelation time [2].

The spiral flow is one of the most important EMC characteristics, since it has a direct impact on the behavior of the molten molding mixture in a mold die. This parameter is used to compare different materials, to evaluate EMC quality and to determine compatibility of EMC with a particular mold die. The spiral flow on its own is not a measure of viscosity even though it can be used for its evaluation implicitly. The spiral flow is a characteristic of a flow and shows the distance which molten EMC will pass in a mold die under certain temperature and pressure [2, 7].

The mold shrinkage is a value indicating the difference in linear dimensions of a mold and a sample extracted from it at room temperature [2, 7]. It depends directly on the composition (type of resin, filler, reinforcing elements, etc.) and thermal expansion coefficient of EMC, which can be chosen in such a way that the size difference is minimum. Modern EMC have shrinkage ratio of 0.01 to 0.3%. EMC shall be elected in such a way that its shrinkage ratio corresponds to the shrinkage ratio of the substrate material. It ensures stability of size and shape of materials after hermetic sealing and prevents occurring of different types of stresses leading to deformation of the substrate with EMC.

The glass transition temperature (T₉) is another important property of any epoxy resin. It is the temperature at which thermoactive EMC transit from a solid (glass state) state into a softer one (elastic) [2, 7]. The transition of EMC from glass to elastic (rubberlike) state leads to a sharp increase (by 2-3 times) of the thermal expansion coefficient and decrease of hardness and modulus of elasticity. The glass transition temperature shall not be confused with the melting point. It must be pointed out that actually T₉ is not a particular temperature, but a temperature range where the mobility of polymeric chains increases significantly which allows EMC to flow along the mold die filling cavities. The T₉ value can vary depending on EMC degree of cure, this is why in is crucial to maintain storage
temperature at all times. Besides the glass transition temperature \( T_g \) of EMC can vary because of moisture adsorption, which also shall be taken into account.

The thermal expansion coefficient (TEC) is a parameter characterizing relative change of volume or linear dimensions of EMC in case of temperature increase by 1°C at constant pressure [2, 7]. Has a dimension of reciprocal temperature. In practice EMC are characterized by two different TEC values, which are usually called \( \alpha_1 \) and \( \alpha_2 \). Value \( \alpha_1 \) is TEC below the glass transition temperature and \( \alpha_2 \) - above \( T_g \). If only one TEC value is given in EMC specification, then most probably it is \( \alpha_1 \). Since different materials expand differently at the same heating rate, then for hermetic sealing one shall choose EMC with a TEC closest in value to TEC of the substrate. It allows to reduce the risk of protective packaging shape distortion and EMC lamination.

The gelation time is the time required by EMC for transition from a liquid state to a solid (gel-like) state at the hermetic sealing temperature [2, 7]. When this time expires EMC stops flowing and the process of mold die filling stops. Decrease in the gelation time leads to reduction of time required to fill the mold die, which requires pressure and EMC flow rate increase. EMC flow rate increase can result in damaging microcircuit sealing elements, e.g. displacement or tearing of wire contacts. Otherwise if low flow rate is used for EMC with short gelation time, it can result in the formation of cavities and incomplete sealing of the microcircuit. The gelation time can also be a reason for cracks formation and weak adhesion of EMC to the substrate material.

Thus EMC properties are crucial when choosing the method and parameters for hermetic sealing, protective packaging structure and field of application in electronics.

3. Epoxy molding compounds application methods

The following two methods are commonly used for sealing of microcircuits: transfer or pressurized casting method and compression method [1, 2, 7].

The pressurized casting method is a process when molten EMC is brought into a closed mold die at particular temperature and pressure (see figure 2a). The compression method is a method when particular amount of molten EMC is put into the bottom part of a heated mold die. After that the mold die is closed with the top movable part to which a microcircuit is fixed. In the course of closing the mold die is pressurized, which results in EMC filling all cavities and getting in contact with the microcircuit (see figure 2b). During hermetic sealing temperature and pressure are maintained at a constant level until full cure of EMC.

Recently the compression method with EMC powder gradually displaces the transfer method from the market, even though the latter had been the main hermetic sealing method for several decades.

![Transfer molding](a)

![Compression molding](b)

**Figure 2.** Schematic diagram of microcircuit hermetic sealing process by means of transfer method (a) and compression method (b)
This may be explained by the fact that in case the transfer method is used there is a high probability of defects, loss of integrity and deformation of the protective packaging because of many impact factors (pressure, temperature, EMC composition and properties) affecting the process of filling the mold die cavities and subsequent EMC curing. Also the compression method has several advantages:

1. During hermetic sealing process one can control the pressure value which allows to reduce the number of cavities in the protective packaging. The possibility to decrease the pressure during hermetic sealing allows to apply this method for hermetic sealing of devices sensitive to pressure, e.g., MEMS devices.
2. Low equipment maintenance costs. A special film is used for mold die protection, which allows to perform continuous hermetic sealing process and increase the mold die service life.
3. Allows to change protective packaging thickness. Can be applied to obtain very thin protective coatings, hermetic sealing of multi-chip modules and hybrid microcircuits.
4. Cost effectiveness. It is possible to control EMC expenditure during hermetic sealing process.
5. Short length of the EMC path in the mold die, which reduces the probability of filler segregation.

Based on the above said the compression method has obvious advantages and allows to solve more industrial tasks when compared to the transfer method. But it is necessary to pay due regard to EMC composition and properties when using this method.

4. Results and Discussion

It has been established that the main physical and mechanical EMC properties with an impact on generation of various types of defects in the protective packing during molding are the following: spiral flow, mold shrinkage, thermal expansion coefficient, glass transition temperature and gelation time [1-3, 7-9]. Right choice of molding mixture allows to prevent problems related to production effectiveness, stress and deformation of the protective sealing, cracking and lamination of EMC surface (see figure 3). Though it is not always possible in practice. The main problem is that molding compounds’ manufacturers often specify only approximate values of the EMC parameters or do not give them at all. One can assume that the most probable reasons for that are the following: (a) - change of EMC properties in time even when storage conditions are fulfilled [9]; (b) - measuring conditions used by EMC manufacturers, e.g. for spiral flow, can be different from microcircuit sealing conditions at particular manufacturing site; (c) - a manufacturer can use some internal standards to determine EMC properties and these standards can differ from commonly used.

|Figure 3. Photos of deformed substrate - (a) and EMC defects (faults) appearing in the course of the sealing process - (b).|

It was established that at the present time there are several ways to solve this problem: (1) using EMC with higher glass transition temperature ($T_g$) for microcircuit hermetic sealing [1], which
improves stability of substrate size at different temperatures. Although using EMC with high $T_g$ puts serious restrictions on using particular equipment, choice of substrate material and hermetic sealing parameters; (2) repetitive optimization of the manufacturing process by selection of hermetic sealing parameters (temperature, pressure, etc.). But in practice this is a very expensive (heavy expenditure of microcircuits and EMC) and time-consuming process; (3) preliminary modeling of hermetic sealing process using special software for casting process simulation, such as ANSYS or Moldex3D [10].

A distinguishing feature of computer modeling is accuracy and efficiency of optimization of the hermetic sealing process in the context of selection of temperature, pressure and mold die filling rate, protective packaging deformation reduction and EMC shrinkage. But to get correct modeling results one shall know exact value of spiral flow, mold shrinkage coefficient, thermal expansion coefficient, glass transition temperature and gelation time of EMC. The study conducted identified a set of methods and standards for measuring and control of EMC physical and mechanical properties required to model the microcircuit sealing process (table 1).

| Parameter                      | Measuring units | Method                        | Standard                        |
|--------------------------------|-----------------|-------------------------------|--------------------------------|
| Spiral flow                   | inch            | Measuring the spiral flow     | ASTM D3123 [11], SEMI G11-88 [12] |
| Mold shrinkage                | %               | Thermomechanical analysis     | ASTM D955-08 [15], ISO 2577 [16] |
| Thermal expansion coefficient | $10^{-5}/^\circ$C | Thermomechanical analysis     | ASTM D696 [13], SEMI G13-88 [14] |
| Glass transition temperature  | $^\circ$C       | Thermomechanical analysis     | ASTM D696 [13], SEMI G13-88 [14] |
| Gelation time                  | s               | Change of EMC polymerization rate | SEMI G11-88 [12] |

It is worth mentioning that EMC properties control shall better be performed at the production floor. In practice most companies are forced to deviate from the standards specified in Table 1 or to develop their own methods for EMC properties assessment. The reason for this is the necessity of adapting testing conditions to conditions and requirements of a particular production site. The critical factor of EMC properties production control is testing which allows to obtain relevant information which can be useful for production department and modeling department.

5. Conclusion
The study shows that the incoming inspection of EMC properties is the most efficient and cost-effective way to minimize the risks related to mechanical stresses, deformation or loss of integrity of protective packing in course of hermetic sealing of electronic microcircuit components. The results obtained can be used by both scientists and engineers of companies involved in electronic microcircuit components manufacture for correct selection of EMC, optimization of manufacturing processes, studying and understanding of causes for various types of deformation and stresses during hermetic sealing.

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Acknowledgments
The authors acknowledge the Ministry of Science and Higher Education of the Russian Federation for the financial support under the project no. 05.577.21.0293, unique identifier RFMEFI57718X0293.