Process Control to Enable High Yield Rates and Tailored Motor Performance in Thermoplastic Encapsulation

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I. Introduction

Thermoplastic encapsulation has been increasingly used over the last twenty years in order to bring cost and performance improvements to traditional motor construction. Dramatic cost reductions and performance improvements are enabled via thermoplastic encapsulation. Manufacturing steps are eliminated while component count and cycle times are slashed. The adoption of this technology is likely to accelerate even more with the increased emphasis on energy efficiency and manufacturing cost reduction.

Due to the high value of the electro-magnetic assembly and the difficulty in re-working, anything but a high yield system can mean high COPQ (Cost of Poor Quality). It is therefore critical to enable high yield manufacturing systems, while working with the high pressures and temperatures inherent in the process.

This paper will detail the manner in which process control methodologies can assure high yield rates. It will also discuss the use of process control to enhance certain performance related characteristics of the encapsulated assembly – e.g., mechanical robustness, vibratory characteristics, and thermal transfer characteristics, as well as dimensional and air gap control. The dimensional control section of this paper will discuss both control of expansion rates and the matching of expansion rates between the thermoplastic encapsulant and the encapsulated motor components.

Figure 1. Encapsulated Electro-Magnetic Devices

II. Materials Utilized

In general, one utilizes the lowest cost combination of thermoplastic base polymer and filler, ground insulation, and magnet wire to meet application requirements. These application requirements include defined environment (e.g., temperature and chemicals), structural requirements, and thermal requirements of the device. Thermoplastic materials used range from commodity resins such as polypropylene to high performance resins such as LCP (Liquid Crystal Polymer), PPS (Polyphenylene Sulfide) and polysulfone. These polymers exhibit melt processing temperatures of 350° to 750° F.

Fillers and modifiers allow enhanced performance, but also increase the technical challenges of achieving high yields. Glass fiber is most common for increasing strength, stiffness, and dimensional stability. Enhanced thermal transfer can be achieved with a range of ceramic fillers, some of which are highly abrasive. Carbon fiber is also used to enable high thermal conductivity and superior structural properties. The inherent electrical conductivity of the carbon fillers poses special challenges.

In order to enable high yield rates with this range of materials, one must prevent even minor damage to the thin insulating layer on each magnet wire. This discussion will be relevant to the full range of base polymers and fillers. Optimizing part design, tool design, and process control enables even high temperature polymers with aggressive filler systems to encapsulate lower temperature insulating components.

III. The Encapsulation Process

The thermoplastic encapsulation process is a high speed, high pressure, and high temperature process.

Higher filler levels generally yield increased performance, yet they also drive up material viscosity, which in turn makes the molten thermoplastic difficult to push in the mold cavity. As an example, thermally conductive fillers generally require 55% to 80% filler loadings, depending on the desired conductivity. This high material viscosity increases the risk of magnet wire damage.

Thermoplastics, however, exhibit non-Newtonian fluid behavior; this means that the viscosity of the material is variable and is dependent on the shear rate applied to the fluid at any instant of time. High shear rates, induced by high speed filling of the mold cavity, reduce resin viscosities and enable easier and more forgiving fill over the magnet wire.

High velocity fill is more difficult to control precisely then is low speed fill, similar to the difficulty in maneuvering a car at 90 m.p.h. as opposed to 10 m.p.h. While the mold cavity is filling, cavity pressures tend to slowly rise until the point is reached where the cavity is full, at which point a sudden and significant increase in cavity pressure occurs. A small variation, such as but not limited to a short cycle interruption, can cause significant pressure spikes in the mold cavity. This "water hammer" type pressure wave can damage the electro-magnetic assembly. It should be noted that this phenomenon may or may not be visually apparent on the part, and cannot be seen on any normal injection molding machine output. To resolve this challenge, a process control system must be used which enables precise monitoring and control of the speeds, pressures, and material viscosities at any point in time

High velocity fill is thus used to reduce material viscosity to a specific value, and to maintain that value. The control system then triggers the molding machine to halt the fill process just prior to the point where a pressure wave would result. The instantaneous feedback is critical due to volumetric variations typical in motor and transformer applications. Changes in the number of turns, wire gauge, and winding pattern can lead to significant differences in the available volume for the plastic. Process feedback allows one to adjust the process settings on a part-by-part basis in order to insure each part sees the same process conditions. Figure 2 shows a set of molds with encapsulant volume variations of greater then 50%, and the Wire Guardian process control system which reacts to these volumetric differences and to resin viscosity differences.

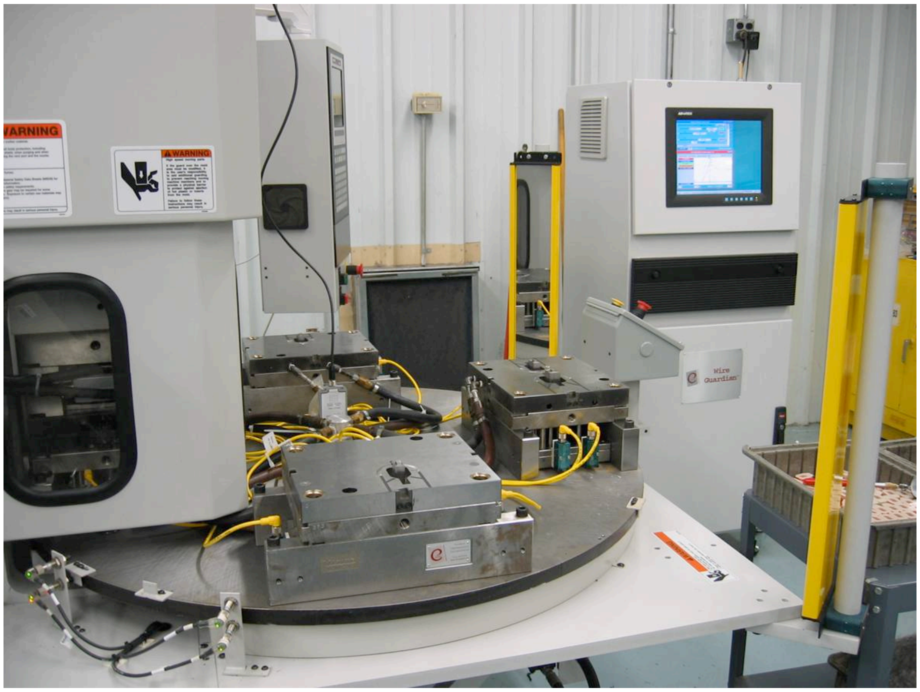

Figure 2. Process Control System to adjust for 50% variation in encapsulant volume

Higher pressures during the molding process have a positive impact on part performance, but can have an adverse effect on yield rates. Maximum structural properties and dimensional control are generally achieved at higher pressures. Higher pressures also aid the resin in penetrating end turn bundles and filling interstitial voids in the magnet wire. The more precise the process can be controlled, the higher the pressure which can be used and the better the ability to maximize mechanical properties and encapsulant penetration.

An approach we have found effective is to perform a series of DOE trials in order to establish a set of process boundary conditions which enable desired yield rates. These boundary conditions will be unique for each assembly, based upon variables such as part geometry, tool geometry, encapsulant material, filler orientation requirements, insulating components, magnet wire, and assembly performance requirements. The process control system is then set to maintain conditions within the process boundaries.

IV. Process Control to Enhance Performance

The ability to tightly control the molding process also enables one to positively impact the assembly in areas of dimensional control, vibration damping, and management of temperature related expansion / contraction of the encapsulant.

One of the advantages of component integration and part count reduction is the positive impact on **stack up tolerances**. An example of this is shown below, for locating a bearing off of the stator. The assembly interfaces, signified by arrows, are reduced from four to one.

Traditional Motor Construction
Stator ID → Stator OD → Outer shell → End Bell → Bearing

Thermoplastic Encapsulated Construction
Stator ID / Encapsulant → Bearing

Figure 3. Stack Up Tolerances to Locate Bearings

In tight tolerance parts such as stepper motors, locating the bearing directly off the stator encapsulant helps allow the 63 micron (0.0025") air gap required. In motors with large diameter stators and end bells, the advantage can be even more pronounced.

While reduction of assembly interfaces allows a reduction in stack up tolerances, turning this benefit into reality requires maintaining the dimensional tolerances of the encapsulant. Material shrinkage and hence dimensional control is dependent upon a number of variables, including temperatures, shear rates, filler alignment, pressure integral throughout the cycle, and cooling rate. The precise process control described earlier allows one to control the critical mold fill variables as well as the integral or sum total of all pressure applied throughout a cycle.

In regards to **vibration and audible noise**, thermoplastic encapsulation unitizes the structure and enables damping of the overall vibrations. By modifying process conditions and material formulation, vibration characteristics of an assembly can be shifted away from resonant frequencies. This can translate into reduced vibration and reduced audible noise.

An example of this is seen in a previous study of the impact of the effects of processing parameters on computer hard drive Voice Coil Motors (VCMs). Parts were molded in a range of materials and over a range of process conditions. The molded parts were then tested using a Laser Doppler Vibrometer (LDVM).

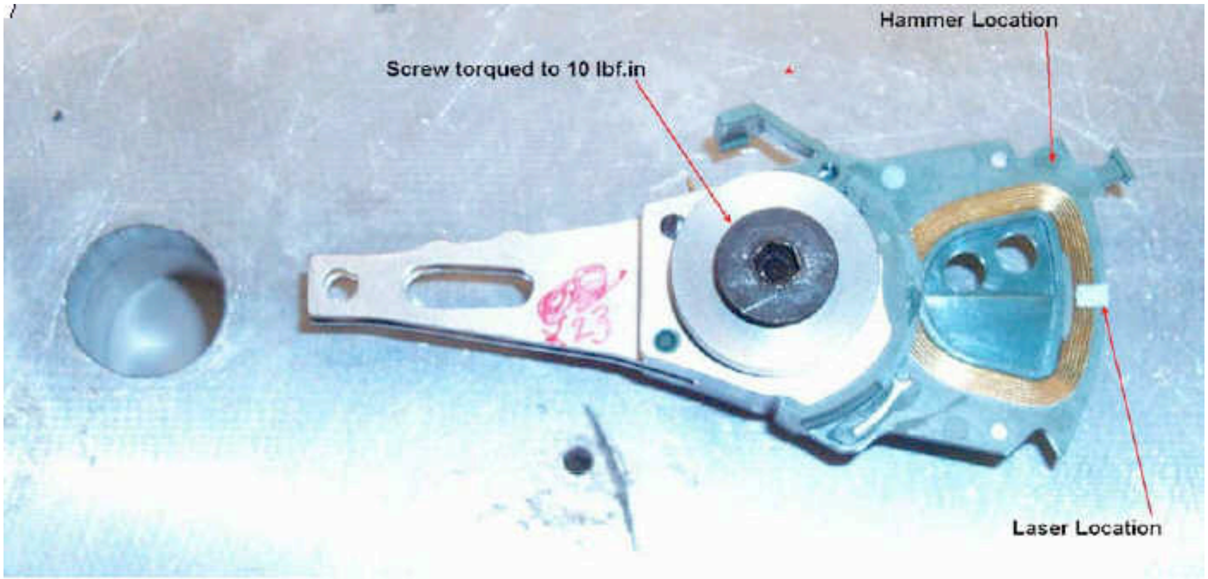

Figure 4. Sample VCM part clamped into the LDVM test fixture.

One of the major conclusions to come out of this study was the influence of cavity pressure on vibratory characteristics of the assembly. Both absolute cavity pressure and the pressure gradient across the individual part play a key role. Chart 1. compares the first resonant frequency of the Voice Coil Motor vs. cavity pressure in a 40% glass reinforced Polyphenylene Sulfide (PPS) resin. This data indicates a strong correlation between cavity pressure and resonant frequency (correlation coefficient of 0.535). The results are more pronounced for the second order harmonic as is evidenced in Chart 2. Again, 40% glass reinforced PPS is shown here, however this same phenomenon was shown to occur in other glass reinforced and/or ceramic reinforced formulations.

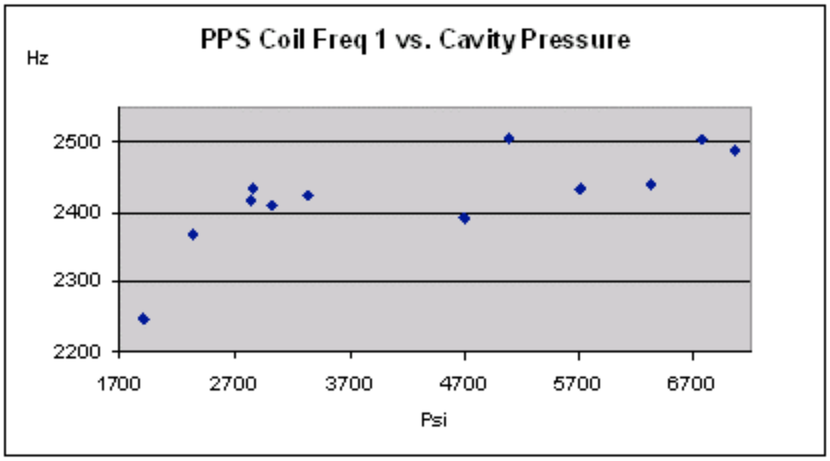

Chart 1. 1^{st} Resonant Frequency vs. Cavity Pressure, VCM

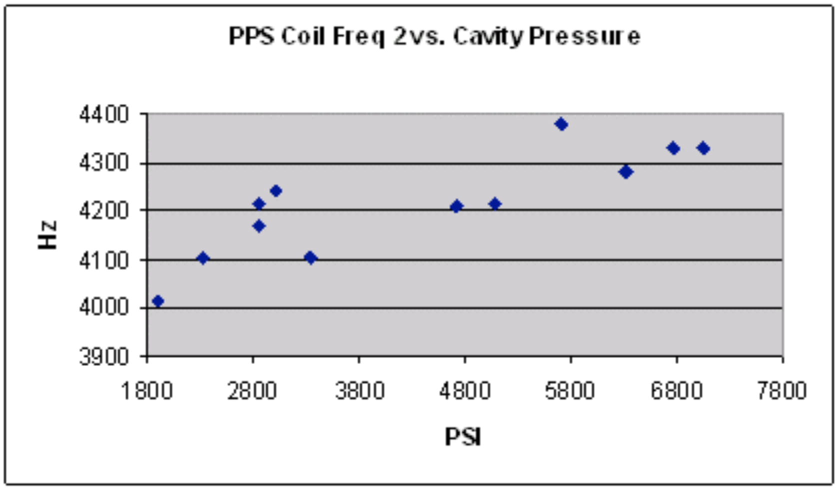

Chart 2. **2^{nd} Resonant Frequency vs. Cavity Pressure, VCM**

Because of the strong correlation between cavity pressure and resonant frequencies, robust molding process control is necessary to prevent unintended variations in resonant frequency. Control of the molding process can also be used to "tune" resonant frequency.

An additional benefit of thermoplastic encapsulation is the ability to **manage expansion and contraction rates, as well as thermal conductivity**. As a reference, traditional potting compounds are sometimes used to provide thermal transfer or environmental protection for the magnet wire. One of the problems which occurs is that the relatively long cure times of potting compounds allow the fillers to settle out due to gravity. As the dense fillers settle to the bottom, the assembly progressively loses the desired material characteristics near the top of the assembly. Design and performance issues can result due to the non-uniformity in thermal transfer and expansion / contraction rates. Thermoplastics have nearly uniform filler dispersion through out the part. The plastic is completely solidified within 5 to 30 seconds of injection into the cavity.

Experiments have been performed to assess the actual CTE (coefficient of thermal expansion) of large stator components encapsulated with plastic. Stators were molded and then test samples were cut out of the encapsulated stators and were ground and polished to be completely flat and parallel. These samples were cut to achieve numerous combinations of encapsulant flow direction and magnet wire / end turn orientation. Next, parts were repeatedly thermal cycled and measured to determine expansion / contraction rates.

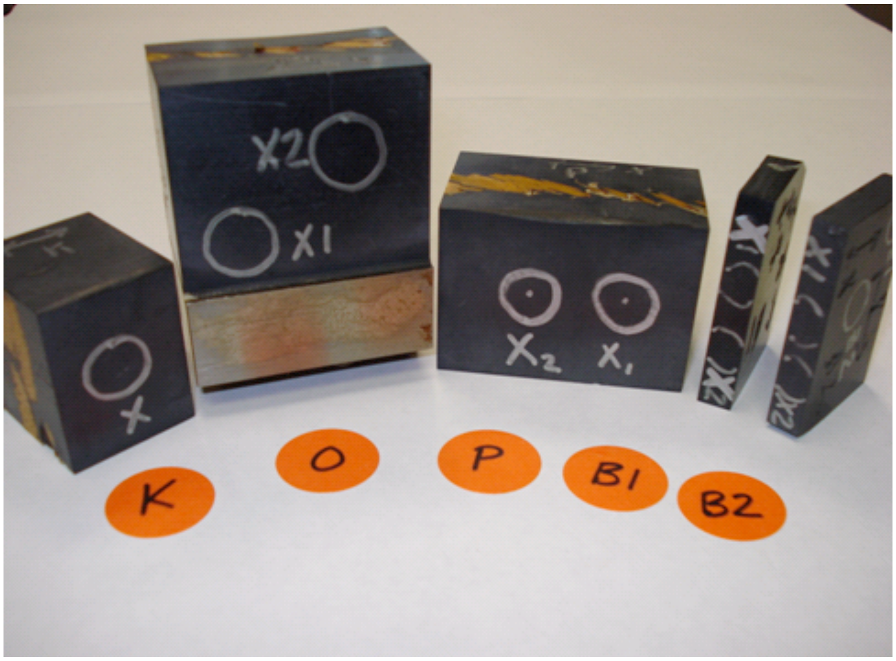

Figure XX. Large Stator CTE Test Samples

While it had been expected that net CTE values would be a composite of the individual encapsulant and end turn CTE, results instead showed that the CTE had more complex variation, being dependent on a number of different factors:

- Measurement in the X vs. Y vs. Z planes.
- Magnet wire orientation and wire gauge size
- Base encapsulant composition and flow direction
- End turn / encapsulant ratio in a specific direction
- Magnet wire / encapsulant interface

There are several design, processing and material options to adjust for these CTE variations. One approach which has been valuable is the use of thermoplastic materials with a lower CTE value tailored to the underlying copper, aluminum, and steel components.

Precise process control is even more critical when molding thermoplastic materials which are designed for high thermal conductivity and / or low CTE. These materials generally have high filler levels, which causes the plastic to lose some of the inherent compressibility of the material while it is in the liquid state. This poses a challenge because the melt compressibility helps to cushion and reduce the "water hammer" effect discussed earlier. If molding process control does not provide a highly repeatable velocity or pressure transfer, small variations in the process are amplified in the mold, leading to variations in electrical yields, dimensions, and other important characteristics.

V. Conclusions

Thermoplastic encapsulation brings many advantages to the cost and performance of electro-magnetic devices. The high cost of scrap necessitates world class yield rates. This involves knowledge in assembly design, materials of construction, and tooling design. The critical piece that ties this all together at the manufacturing stage is an extremely precise and responsive process control system. The closed loop feedback is insures that each part is exposed to identical conditions during the fill, pressurization, and cooling stages of the molding cycle.

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