MANAGING COIL EPOXY VACUUM IMPREGNATION SYSTEMS AT THE MANUFACTURING FLOOR LEVEL TO ACHIEVE ULTIMATE PROPERTIES IN STATE-OF-THE-ART MAGNET ASSEMBLIES

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ABSTRACT

Liquid epoxy resin impregnation systems remain a state-of-the-art polymer material for vacuum and vacuum/pressure impregnation applications in the manufacture of both advanced and conventional coil winding configurations. Epoxy resins inherent latitude in processing parameters accounts for their continued popularity in engineering applications, but also for the tendency to overlook or misinterpret the requisite processing parameters on the manufacturing floor. Resin system impregnation must be managed in detail in order to achieve device life cycle reliability. This closer look reveals how manufacturing floor level management of material acceptance, handling and storage, pre- and post-impregnation processing and cure can be built into a manufacturing plan to increase manufacturing yield, lower unit cost and ensure optimum life cycle performance of the coil.

INTRODUCTION

The overall balance of electrical, physical and chemical properties of epoxies for coil winding applications has been well documented back to the early 1960's. These early formulations recognized the relationship between high temperature properties (continuous service ≥ 200ºC) and radiation resistance by employing Bis A and Bis F resins with a wide range of acid and acid-anhydride curing agents and catalysts in one and two component systems.

These early systems required processing with high temperature cure schedules in one, two and three stages to achieve ultimate properties. With these high temperature systems; the corresponding mismatched coefficients of thermal expansion (CTE's), between the dielectric insulation system and the copper conductors, resulted in interlaminar stress cracks in the impregnated coil winding assemblies. Stress cracking led to further formulation development using a wide variety of flexible resins, curing agents and minority components. While the flexibilizers eliminated the stress cracking; they also contributed to degradation in the desired high temperature and radiation resistance properties. It became necessary to modify the formulations to achieve the right balance between ultimate properties and cure management processing dictated by assembly methodology. [1]

These modifications account for a large number of successful formulations still being used. Advances in chemistry and lessons learned from these modifications have led to both improved formulations. We now have a better understanding of the role that process management plays in achieving ultimate properties and predicting life cycle reliability of a magnet assembly. [2]

KEY ELEMENTS AT THE TASK LEVEL

The central issue for managing dielectric insulation materials at the task level is to ensure that: 1.) they are within their respective manufacturer's finished product specification and shelf life at the time of application, and 2.) they are processed to meet requisite parameters dictated by material chemistry. A closer look at key elements in a manufacturing plan reveals how this can be accomplished.

Material Acceptance

Copper conductor, both bare and enameled, should be inspected for surface defects and foreign contamination. While established cleaning technologies are available, they should not be employed to correct deficiencies in the as received conductor; because they are not universally compatible with magnet wire enamels. Reliance on the impregnating resin to "heal" defects in wire enamel insulation should be minimized because each such "heal" point is a compromise of a layer of redundancy of the insulation system.

Film tape, fiberglass tape and cloth should be visually inspected for the integrity of their respective packaging. Any signs of damaged packaging, particulate and/or moisture contamination should result in rejection. Using clean material has a very large benefit to cost ratio when impregnating large coils.

Impregnating resins with their inherent complex chemistries should be tested for viscosity, reactivity (ability to cure) and ability to attain acceptable cured properties. These tests ensure that the "Working Life Viscosity" of the resin system is within specification, can be maintained through the impregnation process and will deliver ultimate cured properties.

Use a viscometer. Viscosity testing recognizes that the "Batch Viscosity" of an impregnation resin, as manufactured, is the baseline from which "Tank Life" and "Working Life" Viscosity ranges will evolve. While formulators employ various resin and curing agent

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chemistries to achieve property values and maintain the low initial viscosities and long work life associated with epoxy vacuum impregnation systems; these system formulations share a common processing sensitivity to rate of rise in viscosity over time at temperature exposure. This sensitivity is cumulative from the date of manufacture and it is imperative to ensure that transit exposures do not result in an increase in viscosity which would shorten the anticipated Working and Tank Life of the resin. Shipping and shelf history can degrade the resin and viscosity is your "tell-tale". A suitable viscometer should be employed to confirm that the viscosity of the material, as received from the vendor, is within the range specified by the vendor's batch certification. There are a number of ASTM test methods which can be referenced to develop an acceptance standard. (Note: Where high or low temperature climates are a factor, do not hesitate to specify temperature monitoring of the container packages during shipment through the procurement process.)

Find out before impregnation that the resin will cure. Reactivity testing typically uses a "gel test" (ASTM D 2471) or an in-house "sunshine/stroke gel test" on a hot plate to assess reactivity.

Will the resin have the expected strength? Measure cured property attainment using Durometer Hardness Testing (ASTM D 2240) or a similar in-house test in a small sample before impregnation.

Handling and Storage

Don't contaminate the conductor with the oil and water from your compressed air system. Copper conductor surface preparations frequently employ blow drying and it is essential that either dry nitrogen or clean filtered air be used to avoid the deposition of oil and water vapor from the compressed air lines on the cleaned surfaces. .

In those insulation systems where wrapped film tapes act as a primary insulation, the tapes can attract foreign particulate to their edge while in storage and during in-process handling. These contaminates can entrain during the lapping process and lead to cut-thru or air entrapment. During the lapping process, tolerances and tensions must be maintained. Improper tensioning will lead to stretching and wrinkling of the tape. Stretched tape will attempt to relieve and reposition itself during conductor forming operations; while loosely wound tape will wrinkle; entrapping air that will mobilize during vacuum operations. Both conditions will account for film movement and produce an exposed conductor surface. Furthermore, hot flowing resin can act as a carrier; lifting and repositioning loosely wound film tape and expose conductor. With any such exposure, the impregnating resin may not provide an equivalent dielectric insulation value to compensate for the displaced film tape. [3]

Fiberglass tape and cloth will attract both foreign particulate and moisture during storage and processing under ambient plant conditions. Moisture resident in fiberglass insulation can hydrolyze anhydride curing agents; and thus decrease cured physical property values. The hydrolyzed curing agent reduces molecular functionality and the rate and extent of cross-linking that occurs during a given time at temperature cure schedule. Moisture can also mobilize during vacuum processing; outgassing to create open pathways through the cured resin system and agglomerating to create voids in the dielectric insulation system.

Impregnating resins have common distinctions in Process Properties which are derived from formulation chemistry. These include viscosity, rate of reactivity, peak exothermic temperature, thermal stability, vapor pressure and shrinkage. How these properties are controlled by formulation dictates the extent of shop practice government required to achieve ultimate properties in the cured dielectric insulation. Shop practice must recognize these key process parameter distinctions for in-process "Handling". Control of the resins must also extend to "Storage" practices centered on minimizing the potential for thermal and moisture contamination.

Impregnation Processing

Temperature, vacuum and pressure are the primary in-process parameters governing impregnation processing. They are interactive with the magnet design configuration and assembly methodology and must be effectively managed at the shop level.

The general method of using temperature to govern the impregnation process is to decrease the viscosity of the resin by raising its temperature during the impregnation; to a lower "Working Life Viscosity". This viscosity permits saturation of the dielectric insulation constituent materials to zero tolerance interstices, prior to gellation. Working viscosity depends on the thermal mass of the system, the ability to heat the system and the ability to distribute the epoxy to the entire coil during this time window needs careful planning and execution.

To achieve this Working Viscosity, the overall conditions of the impregnation system have to be managed and this is called "Tank life Viscosity" range. This is a range over time at temperature in which the epoxy impregnation system can be moved and reflects the use of temperature, along with solvent, vacuum and pressure to first retain a lower viscosity and then move the system. Improper viscosity management practices result in incomplete saturation of the dielectric insulation system, interlaminar stress cracking of the cured epoxy resin; coupled with an overall reduction in the ultimate properties. Under haphazard management, the same

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formulation can produce different sets of ultimate properties with correspondingly different levels of saturation density in the dielectric insulation system.

Vacuum cycling, for both pre-impregnation and impregnation processing will ensure that residual air and moisture, entrained during assembly, will be removed prior to saturation. It will also eliminate the opportunity for hydrolytic contamination of the impregnating resin during saturation. During this process, the oil fog from the vacuum pump should not exhaust into the plant atmosphere and contaminate in-process inventory. Employ a good de-mister/filter or eject the exhaust out of the plant. Monitoring the times to and at vacuum during the various vacuum cycles is essential to both complete saturation and maintaining the stoichiometric balance of the resin system during impregnation. Excessive exposure to vacuum will deplete the low molecular weight components of the resin system. The cumulative vacuum exposure given to the resin system should be recorded.

Cure Management

The epoxy impregnation system cure schedule is defined as the cumulative time to and at temperature exposure through the various process phases of drying, preheat, cure and post cure. The cure phase may be single or multiple stages depending on the complexity and size of the magnet device design configuration, the temperature sensitivity of the constituent magnet materials and the upper temperature limit required to mobilize the epoxy system reactants.

The objective of the cure schedule is to achieve the optimum crosslinking of the epoxy resin system while minimizing the mismatched coefficients of thermal expansion of the materials employed in the magnet. These two objectives must be balanced in defining the appropriate cure schedule for an epoxy impregnation system to avoid incomplete saturation of the dielectric insulation, interlaminar stress cracking through the cured epoxy and lower levels of crosslinking; all of which will lower the optimum cured property values of the system.

To achieve this balance, the rate of cure must be established so that saturation of the dielectric insulation is complete and the copper conductor is stabilized at the proper cure temperature prior to gellation. The time to reach temperature for preheating of the material and the device along with the time at temperature should be carefully planned to permit saturation and thermal stabilization of the magnet device prior to gellation. The upper limit for the cure temperature should be derived from the minimum temperature required to attain the highest degree of crosslinking. In setting upper temperature limits and times at temperature for the cure schedule; it should be noted that as gellation increases, the mobility of the epoxy resin system reactants is reduced and reaching optimum system functionality may require additional time at temperature. It is essential to recognize that while time to get to temperature is a critical element of the cure schedule in managing the mismatched coefficients of thermal expansion; time *at* temperature determines the optimum functionality of the epoxy system. It is equally important to control the time to and at temperature during post cure processing of the cured magnet device from the upper temperature limit of its cure cycle to ambient room temperature.

Cure management starts with understanding the resin system's properties. The next step is to know the heat capacity of the mold and coil and to match the thermal and vacuum control system to the planned Working Life Viscosity and Cure Cycle. The authors recommend a Traveler document to be filled out during the cure with specific time lines reflecting the resin induction and cure plan and the necessary instrument readings to be taken. [4]

CONCLUSION

A well designed production Traveler can provide shop floor task management by acknowledging the interactive dependency between the key elements of "Receiving and Inspection", "Handling and Storage", "Pre-Process Quality Control", "Process Conditioning", "Fixtures and Tooling", "Temperature", "Vacuum", "Pressure", "Cure Management" and "Post Process Quality Control".

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