VPI Processes and Resin Evaluations for CPA Electrical Windings

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Abstract - High energy density requirements for fieldable electric gun applications has led to the air-core compensated pulsed alternator (CPA) or compulsator as the generator of choice to provide pulse power. The air-core nature of the machines combined with ambitious power density requirements has led to the minimizing of metallic supporting structures which places additional structural requirements on the electrical windings within the generators.

A very important material used in forming air-core winding structures is the epoxy which is carefully applied to the coils using a vacuum pressure impregnation (VPI) process which has been utilized by UT-CEM over the past two decades. The two epoxy systems which UT-CEM presently uses have been successful and proved adequate for the compulsator performance requirements to date. However, newer compulsator design requirements and epoxy/composite materials have extended the ability of compulsators to deliver more energy in a smaller size. This has resulted in a research effort at UT-CEM to identify epoxy systems which can operate at higher strains and temperatures demanded by future compulsator applications.

This paper presents results of the research performed on epoxy material systems suitable for use in compulsator windings as well as procedures developed to transfer the resin into winding structures with minimal void formation.

PART ONE: RESIN EVALUATIONS

Epoxy Specifications

New UT-CEM compulsator epoxy systems require a minimum heat deflection temperature (HDT) of 110°C, a strain-to-failure greater than 1.3%, and a working time (gel time after mixing all the ingredients) of at least four hours. In addition, it must have mixed properties and characteristics compatible with UT-CEM's VPI equipment and characteristics that result in successful void-free encapsulations. Final qualification tests of potted sample coils are used to determine if the use of the new epoxy system results in high-strain, high-temperature VPI potted coils which meet the electrical, mechanical, and thermal requirements.

Epoxy Selection Methodology

The search for new epoxy systems which can meet the new UT-CEM requirements began in June 1996 with a literature search at The University of Texas Engineering Library. Two books were identified which would be of immense use in understanding epoxy resins, hardeners, fillers, diluents, and catalysts and their effects on final properties.[1]

Another aspect of the selection method was to work with the epoxy manufacturers, particularly Dow Chemical and with the hardener manufacturers, particularly Lonza and Albermarle Corporations. Their help has been invaluable in the formulation of improved epoxy systems.

The process for evaluating a candidate epoxy system is as follows:

Identify the Ingredients

Resin, hardener, fillers, diluents, and catalyst. A system would be found with typical properties published from either the resin or hardener manufacturer. Some systems were recommended by UT-CEM's sponsors and by other UT-CEM engineers. In all cases, each system had to meet the epoxy specifications outlined above.

Perform Level One Testing - Evaluation of Mixed Liquid System

The most important test was the "gel test." Some systems required temperatures of as much as 100°C in order to melt the hardener. Thus the mixed system was not only difficult to work with, but also there was a small margin of temperature between the mixed temperature and the cure temperature. Usually, this also meant that the mixed epoxy would "gel" in a very short time.

Viscosity tests versus time at constant temperatures are performed to establish allowable " working times" before gelling for each mixture. For candidate systems which show much promise, these viscosity tests are made at elevated temperatures to show the sensitivity of temperature vs. viscosity and the effect on gel time.

Another consideration is the suggested cure schedule as recommended by the epoxy/ hardener manufacturer. Very high cure temperatures might be detrimental to the rest of the CPA structure and/or cause differential residual thermal stress problems. For this reason, reduced maximum temperature cures would be performed for correspondingly longer times on candidate systems which show much promise. Typically, one could expect more strain-to-failure but a lower HDT.

Perform Level Two Tests - Heat Deflection Tests

Heat deflection testing is performed on all epoxy systems according to ASTM standard D648. An epoxy beam is placed on two round supports with a fixed spacing. A weight which will cause a specified bending stress is placed in the center of the epoxy beam. The epoxy beam is immersed in oil, and a thermocouple is placed in the oil near the beam. HDT is the temperature at which the beam distorts under test conditions, although it does not necessarily indicate its high temperature usage limit.[2]

Level Three Tests - Tensile Tests

Candidate systems which pass the level 1-2 tests are then subjected to tensile tests according to ASTM D638. Samples are made and inserted between the jaws of a tensile testing machine. The machine plots force versus displacement on graph paper. From the graph, tensile strength, elongation (strain-to-failure), and elastic (tensile) modulus are determined. Epoxy systems with little elongation and high tensile strength will tend to be brittle. Hence, moderate elongation is necessary for toughness. High elongation, however, indicates the epoxy system is rubbery.[3]

Level Four Tests - Complete Epoxy Characterization

Level four testing is reserved for candidate systems which are close to being employed in UT-CEM CPAs. Tests conducted to further characterize the epoxy include:

a. Compression strength
b. Compression modulus
c. Viscoelasticity
d. Fracture toughness
e. Electrical creepage
f. Dielectric constant
g. Dissipation factor
h. Flammability/oxygen index
i. Dielectric test per ASTM D149

Resins

The five basic types of resin are epoxy, phenolics, unsaturated polyesters, urea/melamine, and polystyrene. For electrical encapsulation obtained via the VPI process, UT-CEM has concentrated on the epoxy resins. Table 1 shows the resin parameters for the four resins tested by CEM.

Cure Basics

The cure of epoxy resins is complicated, and it is useful to visualize the process in several stages. Except for gellation, the process is continuous. Initially, there is reaction between epoxy and hardener reactive groups so that somewhat larger molecules are formed. As cure proceeds, larger and larger molecules are formed, but it should be noted that the average molecular size is still small even when half the reactive groups have reacted.

When the molecular size increases as cure progresses, some very highly branched molecules are formed and then more and more highly branched structures develop. The critical point in gellation occurs when the branched structures extend throughout the whole sample.

As cure proceeds, there are major changes in the properties of the epoxy resins. Initially, the resin-hardener is fluid and finally an elastic solid is produced. The glass transition temperature of the curing resin increases as cure proceeds. These changes can be represented in a time-temperature transition (TTT) diagram introduced by Gillham (1986).[4] Figure 1 is a simplified version which illustrates the dominant effect of the onset of vitrification as Tg increases to the cure temperature Tc. For cure temperatures well above Tg, the rate of reaction between the epoxy and hardener reactive groups is chemically kinetically controlled.

When $\Delta T = Tc - Tg$ becomes small, the curing reactions become diffusion controlled, and will eventually become very slow and finally stop. For products for which it is necessary to ensure complete reaction of all epoxy groups , it is normal practice to post-cure the resins at an elevated temperature.

Hardeners or curing agents for use with bisphenol A resins include the following types:

a. Aliphatic polyamines
b. Aromatic polyamines
c. Anhydrides
d. Catalytic
e. Cycloaliphatic amines
f. Others

UT-CEM Epoxy Systems

Table 2 is a summary of epoxy systems formulated and tested by UT-CEM. Table 3 lists the seven tested UT-CEM epoxy systems which meet or exceed the epoxy specifications:

PART TWO: VACUUM PRESSURE IMPREGNATION PROCESS

VPI Basics

There are many different ways of filling and encapsulating electrical coils used by electrical manufacturers.

The term vacuum pressure impregnation (VPI) is defined as using a vacuum to draw the mixed epoxy upward through an enclosed mold which has the dry unpotted electrical coils in it. After the mold is filled with liquid epoxy, pressure is placed on the impregnated electrical coils on the overflow side of the mold in order to eliminate voids caused by the epoxy shrinkage during cure. The epoxy temperature is raised in order to cure the epoxy. The oven is also used to post-cure the epoxy to develop the desired electrical, thermal, and mechanical properties.

VPI Component Description

Figure 2 shows the equipment and connections used for a typical VPI encapsulation at UT-CEM.

Mold

The electrical coils to be encapsulated are placed in a vacuum-tight mold. The mold is machined to have vacuum O-rings installed to prevent air from entering the mold during the epoxy fill. In addition, an Emerson Cuming Stycast two-part epoxy system is employed as a supplemental seal on the mold seams and bolt heads and nuts. These steps are the most important for insuring a successful encapsulation.

Vacuum Pumps

The VPI system uses two vacuum pumps: VP1 is used to de-gas the mixed epoxy which is placed in the epoxy tank after it has been initially mixed in open buckets, while VP2 is used to evacuate the entire system during the 48-hour hard vacuum cycle. Moreover, during the fill cycle, it is used to draw the epoxy from the epoxy tank while VP1's vacuum is slowly bled off. During the bumping cycles, VP2 is used to draw a vacuum after the epoxy fill valve has been closed, and the epoxy tank has been removed.

Epoxy Tank

The epoxy tank has several features. It is sized to hold the entire amount of epoxy to be transferred and, usually, 50% more epoxy. Some of the extra mixed epoxy is transferred to the overflow tank after the mold is filled.

In addition, extra epoxy is placed in the sample tray in the oven. After cure, HDT samples and tensile test samples may be machined. These samples are used to show that the encapsulated electrical coils had the proper cure.

The epoxy tank has an internal mixer, and its drive shaft has two vacuum seal O-rings to prevent air from entering the tank. During the de-gas step, a drill is used to stir the epoxy. This insures that the mixed epoxy is uniformly mixed and that high concentrations of catalyst are not present.

Another feature of the epoxy tank is the "stair-step level indicator" and integral sight glasses in the top of the tank. After the epoxy is placed in the tank, the initial level is recorded. During the fill cycle, periodic observations of the epoxy level are made. Calculations of the fill rate in liters per hour are made and compared to the estimated liters for 100% fill. Based upon a desired fill time, the actual volume transferred and fill rate indicate whether the fill is proceeding as planned. Adjustments in the pressure difference between vacuum pumps, mold temperature, or the epoxy fill valve setting can then be made to control the mold fill rate.

Overflow tank

The overflow tank is located above the mold and has several features. It is sized to allow an adequate amount of excess epoxy to flow into it, and for the back pressure to push on it to compensate for epoxy shrinkage during cure. It has sight glasses to observe when the mold has filled and also allow observation of any bubbles coming out of the mold during the fill cycle.

Temperature Monitoring

During the VPI, UT-CEM uses a computer temperature monitor and data logger to monitor the mold and the oven air temperatures.

Oven

The 260°C oven at UT-CEM is manufactured by Tenney Engineering Company. It can be run in manual control and usually is during the fill cycle. For automatic control, each step is programmed for desired temperature, time, and next step. Ramps are programmed by simply inputting the next temperature and time to reach that temperature.

Vacuum Controls

The two vacuum pumps are controlled either by manual control of the bellows valves or by automatic control of the solenoid valves .

UT-CEM has configured its Varian multi-gauge controller by installing two boards. The first is the convectorr board which operates two convectorr gauge tubes. The second board is the set point circuit board which operate the solenoid valves.

Manual Operation. For manual operation, UT-CEM unplugs the solenoids (A-A and B-B) and then regulates the two vacuums by use of the manual bellows valves. The two convectorr gauges can be read on the multi-gauge screen.

Automatic Control Operation. For automatic control, the operator sets the desired vacuum (in torr) in the multi-gauge controller. Close the manual bellows valves.
The controller will then open the solenoid valve when the actual vacuum is at 110% of the set point and close the valve when the vacuum reaches 90% of the set point. Automatic control is used to better control the small pressure differences needed to have fine control of the epoxy flow rate. For example, figure 2 shows 21 torr on VP1 and 20 torr on VP2. This corresponds to a driving pressure of 1 torr.

Vibrator

An air-driven eccentric vibrator is attached to the mold. During the fill cycle, it is turned on in order to shake any air bubbles inside the epoxy in the mold. By shaking them, they may be freed to pass to the top of the epoxy and out of the encapsulated coils.

Design Considerations

There are several design items which can help insure a successful encapsulation.

1. UT-CEM has found that it is important to lay in fiberglass in the same direction as the epoxy flow.
2. Pay particular attention to the part-mold interface. Use mold release agents to keep the cured epoxy from sticking to the mold.
3. Design the encapsulated part-mold to provide for extra fiberglass. Bubbles tend to migrate to the mold surface. Then machine off the excess encapsulation.

4. Pack empty areas of the electrical coil either with fiberglass cloth lined up in the direction of epoxy flow or with G-10 blocks.
5. Think about the epoxy flow resistance. For example, UT-CEM coils which are wrapped with Teflon tape, have small cut-outs in the exit end so that the epoxy can exit and bubbles can escape.
6. Provide for two O-rings between machined surfaces.
7. Seal the mold seams and bolts with Emerson Cuming Stycast epoxy.

VPI Procedures

The following VPI Procedures are followed at UT-CEM to insure a void free encapsulation:

Pre-Pot steps

Design and manufacture the electrical coils and mold per the design items. Assemble the VPI system per figure 2. Mix a sample of the epoxy system to be used from the same fresh containers which will be used for the actual encapsulation. Cure the sample with the same temperature-time history as the actual encapsulation as a proof test that the ingredients are satisfactory. This step is performed in parallel with the 48-hour pre-heat step. Pre-Heat the VPI system to 80°C for 48 hours with a hard vacuum (less than 1 torr). After the pre-heat time is over, reduce the mold and VPI system temperature to the pre-pot temperature. Perform the vacuum leak-up test. The leak-up rate should be less than 5 torr over 5 minutes after shutting the manual valve to the vacuum pump.

Fill Steps

Shut the epoxy fill valve, turn off the epoxy vacuum pump, VP1, and vent the epoxy tank to atmospheric. Continue the hard vacuum on the mold and overflow tank with VP2. Mix the epoxy system per the mixing instructions using a variable speed hand drill in clean buckets. Pour the mixed epoxy through a filter into the epoxy tank. Note the beginning epoxy level on the stair step level indicator and record it in the lab notebook. Close the epoxy tank to atmospheric, turn on the vacuum pump VP1, and let it warm up with the bellows valve closed.

De-gas the epoxy by setting the vacuum to the required de-gas set point and de-gas for one hour. During this time, continue a hard vacuum on the rest of the VPI system using manual control of VP2. Ten minutes before the end of the de-gas cycle, bleed the VP2 system to the same vacuum as used on the epoxy tank. The two vacuums will now be equalized.

To begin filling the mold, open the epoxy fill valve. Mark the time in the lab notebook. Calculate the rate of flow by observing the epoxy level at set times. Turn on the vibrator. Control the rate of flow by gradually increasing the pressure on the epoxy tank. If this control method is too slow (after raising the epoxy tank to atmospheric), then increase the flow rate by first raising the mold temperature. If extra heat also causes too slow a fill rate, connect dry nitrogen gas to the epoxy tank and use some pressure. After epoxy starts into the overflow tank, raise the oven temperature 10°C. Continue epoxy flow until a few centimeters of epoxy are above the entrance port of the overflow tank. Turn the vibrator off. Close the epoxy fill valve and shut down VP1 and VP2. Vent the overflow tank. Begin the first fifteen minute nitrogen pressure bumping cycle. Continue with 15 minute cycles of vacuum on VP2, N2 pressure, and a final vacuum.

Cure steps

Put nitrogen pressure on the overflow tank. Shut down VP2. Program the oven to control the mold temperatures per the recommended cure schedule. The cure schedule normally has a long cool down cycle so that thermal growth/shrink differentials between the encapsulated coils and the mold do not cause high residual stresses as the parts return to ambient temperature.

Conclusions

UT-CEM has developed several new epoxy systems which will allow compulsators to operate at higher strains and temperatures while delivering more energy in a smaller size.

Acknowledgments

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Table 1. Resin parameters

Resin	Epoxide Equivalent Weight	Viscosity cps @ 25°C	Non-Volatile Weight (%)
DER 331	182-192	11,000-14,000	100
DER 332	172-176	4,000-6,000	100
DEN 431	172-179	1,100-1,700 @ 51.7°C	100
DEN 438-EK85	176-182	600-1,600	85

Table 2. UT-CEM tested epoxy systems

Type	Hardener	DER 331	DER 332	DEN 431	DEN 438
Aliphatic polyamine	TETA		X		
	DETA		X		
Aromatic polyamine	DETDA	X	X		
	MDA	X			
	MPDA	X		X	
Anhydride	HHPA		X		
	MHHPA		X		
	MTHPA	X	X		
	NMA		X		
Catalytic	BDMA	X	X		
	BF3.MEA	X		X	X
	2E4MI	X			
Cycloaliphatic amine	Ancamid 2049	X			
Others	Americure 101	X			

Table 3. UT-CEM high strain, high temperature epoxy systems

CEM System Number	Resin DER	Curing Agent	Diluent DER	Catalyst	Percent Strain	HDT °C
24	331	DETDA			2.0	132.3
24BLC	331	DETDA	736		2.85	131.8
26	331	MTHPA		BDMA	2.29	113.8
34	332	MHHPA		BDMA	1.30	134.5
35	332	DETDA	736		2.25	141.6
36A	332	MTHPA		BDMA	1.30	117.2
38	332	DETDA	732		4.18	134.8

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[2] W. Tillar Shugg, *Handbook of Electrical and Electronic Insulating Materials*, New York: Van Nostrand Reinhold, 1986, pp. 31-32.

[3] Shugg, pp. 33, 34.

[4] Ellis, pp. 4-7, figs. 1.1 and 1.2.