Improved Potting of Litz Wires for High Power Density Electric Motor

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Specific details including selections of process materials, tooling/fixture setups, and a step-by-step procedure for scaling-up demonstrations of the newly developed potting process, namely vacuum-assisted axial injection potting (VaAIP) have been fully developed for the stator winding of high power density electric motors for the future electrified aircrafts. Various essential pre-trial subtasks identified for the full-scale demonstrations were carried out. To date, optimization of cure condition and thermal stability of the coating epoxy and determination of optimum application conditions and thermal stability of the high temperature encapsulant wax were completed successfully and other subtasks were under way. The efforts to enhance thermal conductivity of the selected potting compound by adding conductive nano fillers such as boron nitride nanosheets (BNNS) have also been advanced. Initially, selection of the best mixing method and procedures was attempted via extensive and systematic experimental design.

I. Nomenclature

Abs	=	absorption (cm^{-1})
BGB	=	Borosilicate glass beads
BNNS	=	boron nitride nanosheets
DSC	=	differential scanning calorimetry
EDS	=	energy dispersive spectroscopy
FT-IR	=	Fourier transform-infrared
GLYMO	=	3-(2,3-Epoxypropoxy) propyltrimethoxysilane coupling agent
PVDF	=	Polyvinylidene fluoride
SEM	=	scanning electron microscopy
TC	=	thermal conductivity
T_c	=	crystallization temperature
T_d	=	thermal degradation onset temperature
T_g	=	glass transition temperature
T_m	=	melting temperature
T_s	=	softening temperature
TGA	=	thermogravimetric analysis
TEM	=	transmission electron microscopy
VaAIP	=	vacuum-assisted axial injection potting

II. Introduction

As reported earlier, Ref. [1-3], improvement in thermal management of electric motor building blocks such as stator windings, thus enhancing overall motor performance, can be achieved with improved potting of typical Litz wires selected for high power density electric motors for the future electrified aircrafts. The efforts to improve the potting qualities have been pursued by two approaches: (i) developing a novel potting process, namely vacuum-assisted axial

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injection potting (VaAIP) of which feasibility had been successfully demonstrated as a more practical and effective process and (ii) increasing thermal conductivity of potting compound by adding conductive nano fillers such as boron nitride nanosheets (BNNS). As the initial effort to assess the possible potting process, configuration and microstructure of the candidate Litz wires, particularly packing patterns and distribution characteristics of conductor filaments and inter-filament open spaces, such as dimensions and overall areal or volume fraction, were determined successfully, Ref. [2]. With such findings, the VaAIP process was conceptualized to pot the Litz wires. Then, two elaborate experimental trials with the Durapot™ 863 potting epoxy on 30 inches long Litz wires involving representative winding curvatures were performed effectively to validate the VaAIP concept, Ref. [2]. Furthermore, with improved VaAIP process techniques and a Litz wire with more favorable microstructures, significantly better potting quality was achieved, i.e., the potting quality was certainly controlled by microstructures of the wire. In any case, based on the results of the trials, it was concluded that the VaAIP process was promising and it could be potentially better than other conventional methods for achieving high quality potting in the Litz wires. Even though the concept of VaAIP process was proved experimentally, it requires further modifications and optimizations of the process through a full-scale component or subsystem demonstration in order to implement this new process to the actual motor windings. Additionally, to maximize its thermal performance, thus the motor performance, an effort was planned to enhance thermal conductivity of the Durapot™ 863 epoxy resin by adding conductive nano fillers, while maintaining its good processability. Progresses in such efforts are updated in this paper.

III.   Results and Discussion

A. Full-scale VaAIP Process Demonstration

The concept and feasibility of the VaAIP process were demonstrated by using about 30 inches long sections of two typical commercial Litz wires (rectangular type 8, American wire gauge (AWG) 3 equivalent from the New England Wire technologies (NEWT), Lisbon, NH) including simulated curvatures with a low viscosity commercial epoxy resin, Durapot™ 863 epoxy from Cotronics Corp, Brooklyn, NY, in terms of injection rate and potting fill percent, Ref. [2]. Subsequently, scaling-up the process has been attempted with a full-scale test article or subsystem as the next step before implementing the VaAIP to the actual motor windings. The scaling-up demonstration is conducted in two phases, first to use a full-length Litz wire for a typical motor winding up to 18 ft but with simple winding configurations guided with tool steel dowel pins on a flat aluminum fixture, Fig. 1 a), and the other with a full-size component scale Statorette representing a section of the high power motor developed by NASA- Glenn Research Center (GRC), namely High Efficiency Megawatt Motor (HEMM), Ref. [3], Fig. 1 b). In the former case, only the injection rate and potting fill percent are measured as functions of the total length of Litz wire and other process variables such as temperature, vacuum pressure, number and location of inject ports but more sophisticated motor performance characteristics, particularly heat transfer or dissipation will be additionally determined with the Statorette system. In either case, the full-scale demonstration should also address practicality and effectiveness for the actual stator windings. Essential requirements of the full-scale VaAIP process include a technique to achieve high vacuum sealing of entire wire, fast and continuous vacuuming and resin injection process, and readiness of the end connections.
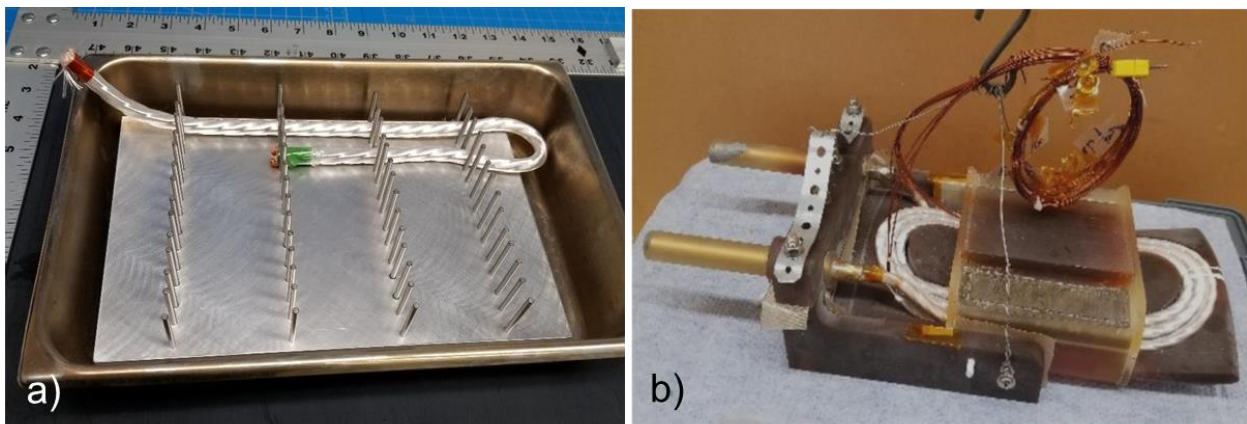

Fig. 1 Test fixtures for scaling-up VaAIP process, a) Full-length mold and b) Statorette.

While the final process conditions and procedures are dependent on specific Litz wire configuration or type and properties of potting compound, the general processes planned initially are illustrated schematically in Fig. 2. Firstly, sealing of the entire wire to attain high vacuum inside is achieved by (i) applying thin coating of high thermal conductivity and high electrical resistivity epoxy, e.g., Duralco 128 from Cotronics (with thermal conductivity of 4.3 W/mK and high viscosity of 79,000 cPs) only on outer surfaces of the wire and (ii) encapsulating the entire wire assembly with a high temperature wax, e.g., Apiezon Wax W from APIEZON, Manchester, UK, (melting temperature, $T_m = 130°C$, softening temperature, $T_s = 80 - 90°C$). The Duralco 128 epoxy is applied continuously and evenly, about 10 mil thick, while the wire is wound onto the fixture as not only to seal the wire but also to replace the slot liner which placed between the windings and metal core as an electrical barrier. Because of its much higher thermal conductivity than those of typical slot liner materials, the epoxy coating is to alleviate the thermal congestion of those liner materials for heat dissipation. Elimination of the slot liner can also simplify the winding process. That is, it is indeed a multipronged approach. It shall be noted that about 5 – 10 inch sections of both ends of the winding are left uncoated to prep them for making easier electrical connections. The end sections are specifically prepared such that the conductor filaments are ready for soldering when the potting process is completed and either pulling vacuum or injecting resin through them is fully attainable during the potting process. A high temperature heat shrink tubing, e.g., Polyvinylidene fluoride (PVDF) tube (2:1 shrink ratio, recovery/shrink temperature of 152 °C, operating temperature of -54 – 149 °C) is used to seal the end sections for the potting process. After the epoxy coating is applied and cured, the entire winding assembly is placed in a metal pan and encapsulated with the high temperature Apiezon Wax W at temperatures higher than its melting temperature, 130 °C except the end sections. Upon cooling, the wax solidifies and seals the entire winding. Once the VaAIP process is completed, the wax is re-melted and removed completely. For the main injection process, the setup is similar to that of the feasibility demonstration with 30 inch long wire but modified with larger resin dispensers with shut-off valve, resin injection monitoring system, higher power vacuum pump, and accurate temperature control system.
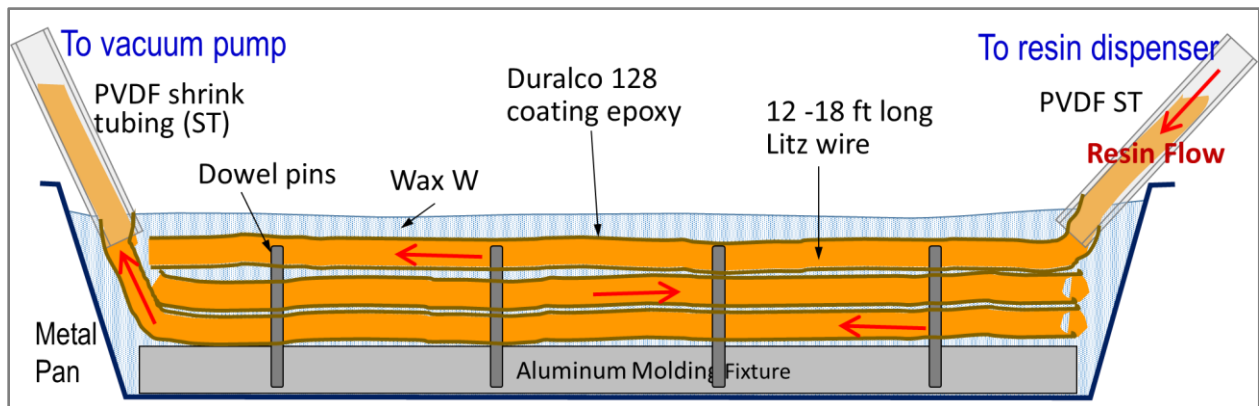

Fig. 2 Schematic details of the proposed setting-up for the full-length molding of the VaAIP process.

Based on the temperature-viscosity-pot life relation experimentally determined at GRC previously, Fig. 3, and the estimated injection rates in the selected Litz wires (Ref. [2]) of the Durapot 863 epoxy, the maximum overall wire length for a single port VaAIP process, e.g., injecting the potting resin through one end while pulling vacuum from the other end, could be only 60 - 70 inches over about 2.5 to 3 hours at the optimized process conditions. The amount of the potting epoxy needed to fill the entire wire could also be easily estimated based on total volume fraction of voids in wire via microstructure analyses, e.g., ~17 - 21 % in the selected Litz wire for proper preparations involving mixing, degassing, and preheating of the resin. Thus, in the cases of longer windings than ~70 inches, multiple ports are introduced for both pulling vacuum and injecting resin as illustrated in Fig. 4. Even though the conductor filaments were tightly packed in the Litz wires, the ports can be easily connected by inserting a hollow, but flexible or curved needle inside of the Litz wire after loosening filament packing. The port connections can be fixed and sealed with the heat shrink tubing.
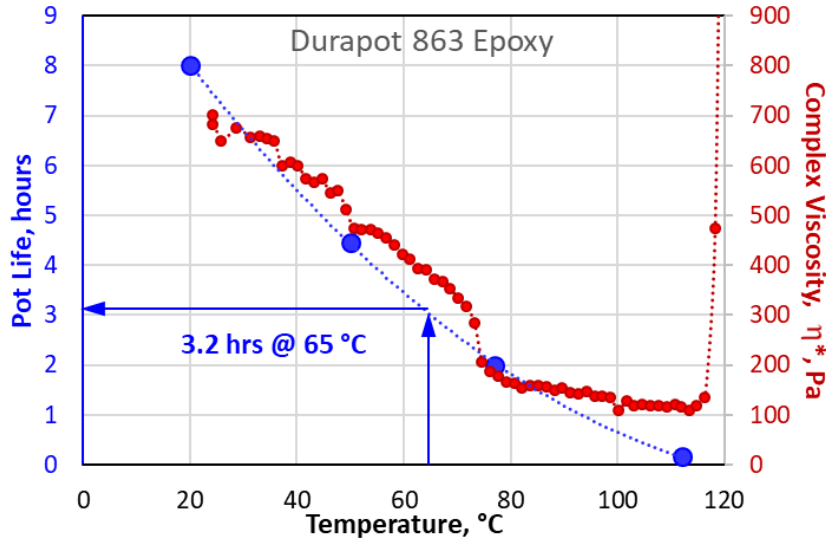
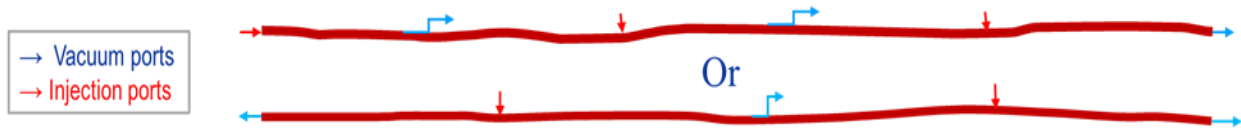**Fig. 3 Pot life-viscosity-temperature relation of Durapot™ 863 epoxy.**

Fig. 4 Schematic illustration of the proposed multiple ports injection option.

Prior to attempting the aforementioned full-scale process demonstrations, it was necessary to perform some material characterizations for those selected candidate materials. In the case of the Duralco 128 coating epoxy, the cure condition recommended by the vendor was 16 - 24 hours at 24 ºC or room temperature. There were, however, a few key requirements for the epoxy in this application such as (i) rapid cure as quickly as possible, thus the epoxy does not penetrate into wire bundles or inter-bundle open spaces and also to control coating thickness more uniform, (ii) complete cure, particularly as the slot liner insulation for structural integrity, and (iii) no thermal degradation for durability and good insulation. Fig. 5 summarizes the results of a rather simple cure kinetics analysis in terms of percent cure as functions of cure temperature and time in air. At cure temperatures above 80 °C, the epoxy reached almost 100 % cure within 1 hour, thus additional tests were conducted for shorter times, i.e., 15, 30, and 45 minutes at 100 °C. Notice that the standard cure condition by the vendor only achieved slightly higher than 90 % cure. As highlighted in the plot, the initial cure condition selected was 15 minutes at 100 ºC which provided about 97.8% cure that was considered as a full-cure. Furthermore, it was also expected additional cure by subsequent heating steps for wax application and cure/postcure of the potting epoxy at higher temperatures. It should be noted that the maximum use temperature of Duralco 128 epoxy was rated for 343 °C once it was fully cured by the manufacturer. That is, the epoxy can be further exposed to much higher temperatures than the initial cure temperature without encountering any risk of thermal degradation. Lastly, thermal stability of the epoxy in terms of cure conditions was assessed by both glass transition temperature, T_g, via differential scanning calorimetry (DSC) and Fourier transform-infrared spectroscopy (FT-IR) spectra of cured epoxy as summarized in Fig. 6 and Fig. 7, respectively. In most thermosetting epoxy materials, T_g typically increases with increasing degree of cure. It is worth noting that determination of T_g was consistent and accurate in that the higher cure temperature, the higher T_g starting from the standard room temperature cure. The Duralco 128 epoxy did show increasing T_g with increasing cure time up to the curing temperature of 104°C but showed an opposite behavior at higher curing temperatures than 104 °C which could be considered as thermal degradation of the epoxy material. However, IR spectra representing molecular network structures of the cured epoxy remained same regardless of cure temperature or time studied which suggests no significant thermal degradation. From those results, it was certain that the selected cure conditions would not induce any thermal degradation of the epoxy and satisfied the requirements.
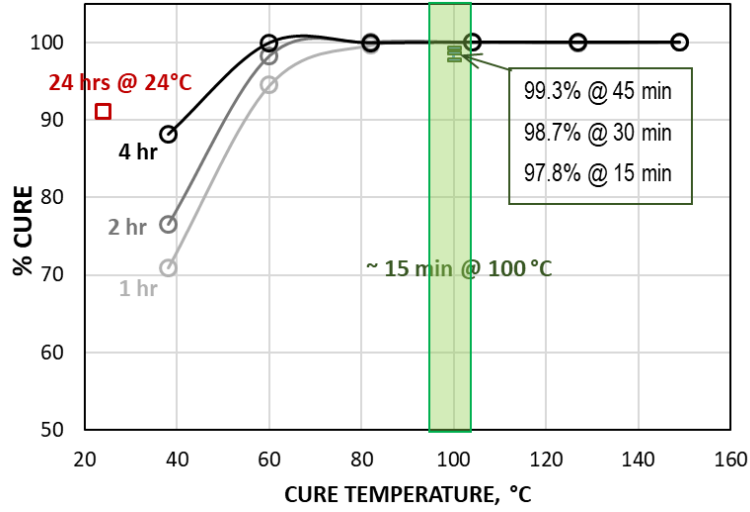
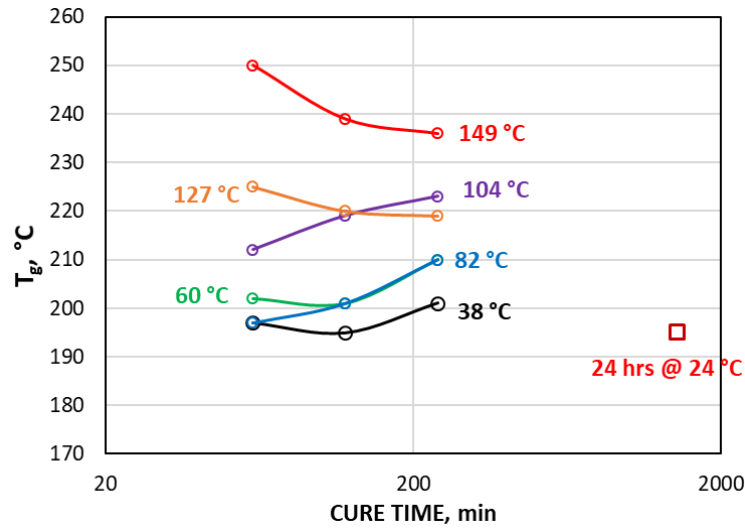**Fig. 5 Degree of cure of Duralco 128 epoxy against cure conditions.**

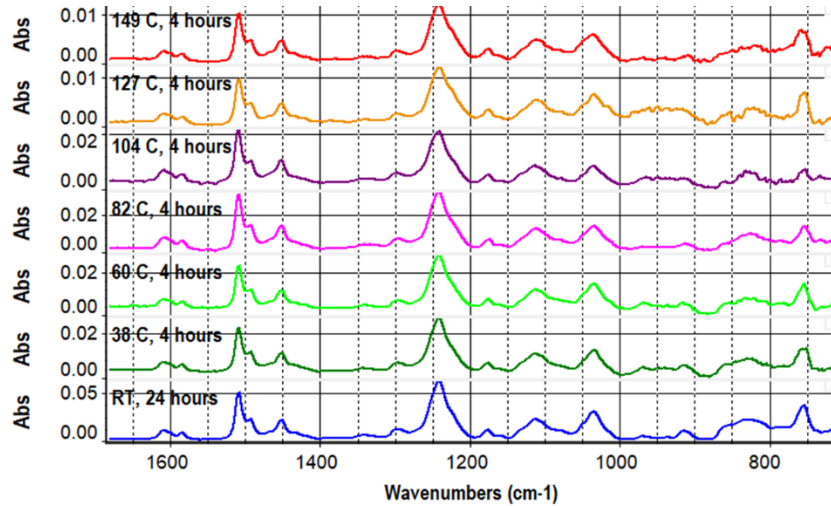**Fig. 6 Glass transition temperature of Duralco 128 epoxy against cure conditions.**

Fig. 7 FT-IR spectra of Duralco 128 epoxy after various cure cycles.

Similarly, the requirements of the wax for the full-scale VaAIP process included (i) low melt viscosity less than 5,000 -6,000 cP, (ii) T_m less than 170 ℃ but T_s higher than 70 ℃, and (iii) recyclable without thermal degradation, preferably to reduce environmental waste, especially in the case of the larger quantities needed for the actual motor applications.   Even though Apiezon wax W was selected as a good candidate for the application for its favorable properties relative to the requirement (ii), experimental confirmation is necessary to determine the optimal process conditions. Obviously, viscosity of the wax was dependent on both temperature and time as shown in Fig. 8 and Fig. 9, respectively. Note that viscosity of the wax was measured by using the Brookfield viscometer with a heated sample holder using the spindle 34 after the setup was calibrated with a 230 cP standard. Based on these test results, the application condition of the wax was determined to be 30 minutes at 155 - 160 ℃ which its viscosity should be ~ 5,000 cP.   Thermal stability and recyclability of the wax were assessed by determining thermal degradation onset temperature, T_d, by thermogravimetric analysis (TGA) and liquid-solid phase transition behavior under thermal cycling via DSC as shown in Fig. 10 a) and b), respectively. Apparently, T_d of the wax was much higher than the optimized application temperature and both T_m (displayed by the endothermic peaks in the lower part of the DSC curves), and crystallization or solidification temperature, T_C (displayed by the exothermic peaks in the upper part of the DSC curves) were remained unchanged. Therefore, it was validated that the selected application condition was effective with no risk of causing thermal degradation and the wax is recyclable.
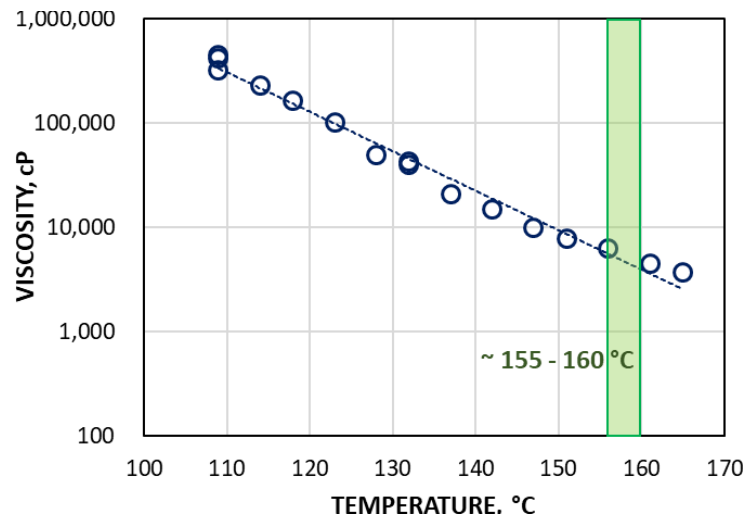
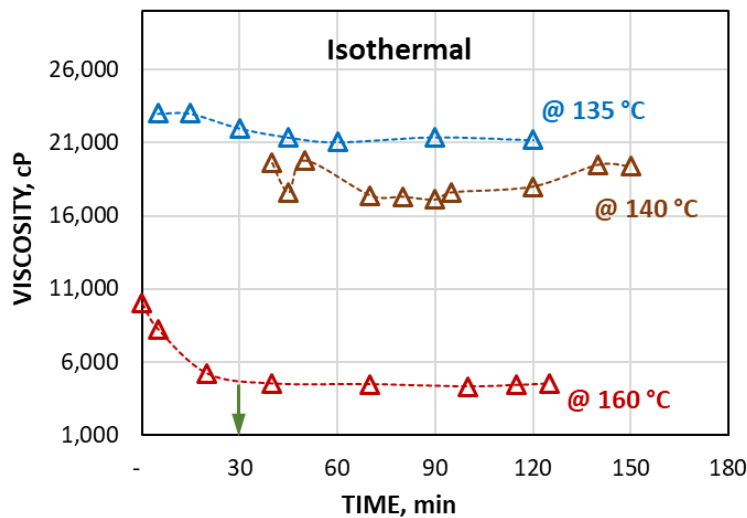

Fig. 8 Viscosity of Wax W as a function of temperature.

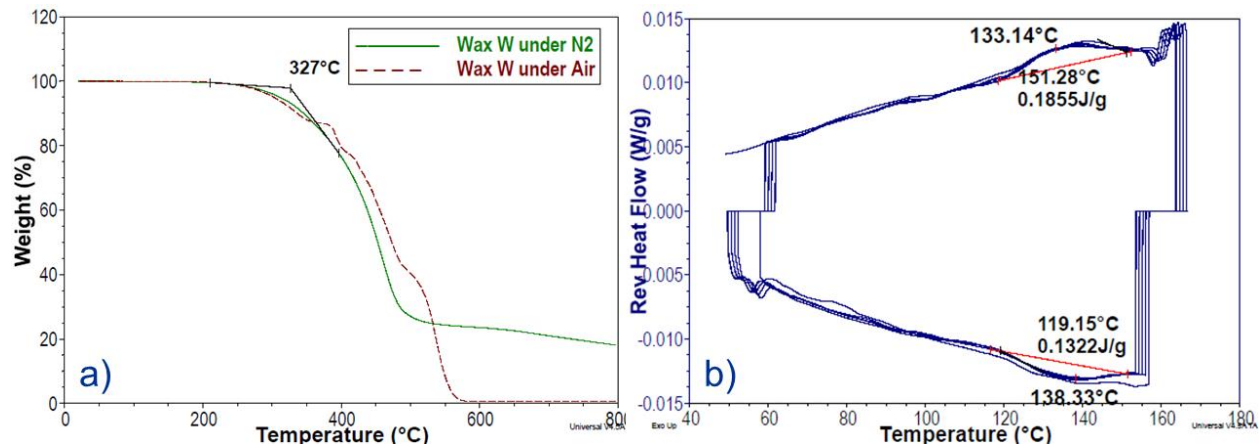Fig. 9 Viscosity of Wax W as a function of time at various temperatures.

Fig. 10 Thermal stability of Wax W via a) weight-temperature relation by TGA and b) melting behavior under thermal cycling, 5 repeats, by DSC.

In summary, scaling-up of this novel process can be easily set up regardless of size or complexity of stator windings and thus effective and practical. The benefits of the axial injection potting process, if successful, include significant improvement in potting quality with less voids, improving heat dissipation from the winding core to motor casing, thus significant improvement in thermal management, and improved structural integrity of the winding which are essential for high efficiency and high power density of electric motors. With the full-length molding fixture, only the injection rate and potting fill percent are measured as functions of the total length of Litz wire and other process variables such as temperature, vacuum pressure, number and location of inject ports. Subsequently, more sophisticated motor performance characteristics, particularly heat transfer or dissipation will be additionally determined with the Statorette system. Prior to the full-scale VaAIP demonstrations, various essential pre-trial subtasks including (i) optimization of cure condition and thermal stability of the coating epoxy, Duralco 128, (ii) determination of optimum application conditions and thermal stability of the high temperature encapsulant wax, Apiezon Wax W, (iii) pottability around Litz wire windings and removability of the wax, (iv) degree of permeation of the wax and the coating epoxy into Litz wire, (v) effectiveness of the wax and coating epoxy in achieving high vacuum sealing, and (vi) selection of a release agent on the aluminum mold, etc. were identified. To date, the first two items were completed and others are being investigated. Details of the setup design and step-by-step procedure involving more than 30 steps were also developed.

B. Improvement of Thermal Conductivity

The potting resin, Durapot™ 863, selected for the initial feasibility and full-scale demonstrations for the project was unfilled two part epoxy which had unique properties stemming from their proprietary crosslinked, inorganic-organic, 100 % reactive polymer system, such as low viscosity, high thermal conductivity of 1.3 W/mK, and exceptional thermal stability to 343 °C/650 °F after curing at 177 °C/350 °F. Based on its temperature-time-viscosity relations determined by systematic steady shear viscosity analysis with a Brookfield viscometer, the mixed epoxy had a viscosity of ~2000 cP at room temperature, but it dropped to ~600 cP at 50 °C and further to 200-300 cP at 70 °C. It should be noted that the viscosity plotted in Fig. 3 was the complex viscosity from the parallel plate rheometer measurement which was directly related to but differed in absolute value with the steady shear viscosity. With such unique properties, the epoxy was not only the optimum potting compound, but also an excellent candidate for further improvement of properties, particularly thermal conductivity, which was the main goal of this task for the aforementioned reasons. The specific objective was to improve thermal conductivity of the selected potting epoxy by adding BNNS as a reinforcement filler while maintaining low viscosity essential for the VaAIP process, the same cure characteristics, and also good dielectric strength. The BNNS was selected initially for its nano-dimensions suitable in penetrating small inter-filament spacings, often sub-micron sized, in the Litz wires, high in-plane thermal conductivity, high electric resistivity, good thermal stability and oxidation resistance, and so on (Refs. [4-6]) but micro to nano-sized hexagonal boron nitride (hBN) particles will be also considered, if applicable and more effective. The key efforts of this task were to determine the effects of BNNS on not only thermal conductivity and dielectric strength of the potting epoxy but also its processability/viscosity, cure behavior, and degree of dispersion. In this task, two types of BNNS powder were employed, one developed at GRC and the other from the University of Toledo, Ref. [7].

Primarily, efforts were made to select the most effective dispersant and mixing method for optimum dispersion of BNNS particles. Initial trials employed key techniques based on literature (Refs. [4-6]) and preliminary experiments involving various mixing equipment and process conditions and procedures as summarized in Table 1. In all cases, loading of BNNS was fixed to 5 wt% and 14 g batch was used except one trial used 7 gram batch. As also listed in the table, a silane coupling agent, 3-(2,3-Epoxypropoxy) propyltrimethoxysilane (GLYMO), was selected for the mixing optimization trials as part of the preliminary experiments against other dispersants such as surfactant or cosolvent. Two types of the state-of-the-art (SOA) mixing equipment used in this study were the Thinky mixer, a planetary/centrifugal mixer, and the Resodyn Acoustic Mixer (RAM), an advanced, low-frequency, acoustic mixer. In addition, the ball or bead milling technique (Ref. [4]) combined with more aggressive vacuum degassing process was employed, and thus far a total of eight trials were completed.

Table 1 Summary of the initial mixing optimization trials.

Note: **HM:** Hand mixing, **THK mix1:** 4 min defoaming @ 2200 rpm + 2 min Mixing @ 2000 rpm in Thinky mixer, **THK mix2:** 30 sec mixing @ 800 rpm + 2.5 min mixing @ 1200 rpm in Thinky mixer, **VD1:** vacuum degassing at ~26 inHg until no bubbles were emerging, **VD2:** vacuum degassing at ~26 inHg, ~ 60-70 °C by bumping pressure, **VD3:** vacuum degassing at ~26 inHg, ~ 60-70 °C by bumping pressure while sieving out Borosilicate glass beads (BGB) into glass beaker, **BM-THK:** Ball milling in Thinky with 2.4mm dia. BGB, 100 per 7 g batch; 6 cycles of 30 sec @ 1200 rpm + 90 sec @ 2000 rpm, adding additional Acetone after each cycle, **BM-RAM:** Ball milling in RAM with BGB, 100 per 7 g batch; 6 cycles of 30 sec @ 25g + 90 sec @ 50g in a glass vial, adding additional Acetone after each cycle, **RAM mix1:** 2 min @ 100 g acceleration under vac (~ 27 inHg), **RAM mix2:** 2 min @ 50 g acceleration under vacuum (~ 27 inHg), **RAM mix3**: 1 min @ 40 g + 4 min @ 75 g acceleration under vacuum (~ 27 inHg), **RAM mix3a:** 1 min @ 40 g + 4 min @ 75 g + 3 min @100 g acceleration w/ ~100 plexiglass bead (1/8" dia.) under vac (~ 27 inHg), **RAM mix3b:** 1 min @ 40 g + 4 min @ 75 g + 3 min @100 g acceleration under vacuum (~ 27 inHg), **RAM mix4:** 1 min @ 25 g + 3 min @ 50 g + 2 min @ 75 g under vacuum (~ 27 inHg), **RAM mix##*:** mixing without pulling any vacuum, **RAM mix##GB:** mixing with BGB

Trial #	Step #1		Step #2		Step #3	
	Materials	Process	Materials	Process	Materials	Process
epoxy-alone control: 8.2g resin+5.8g hardener						
14-0	Resin + hardener	1m HM→THK mix1 →VD2	Cast in Teflon molds → VD2 → Cure (14 hrs @ 177°C)			
14-0b	Resin+hardener+D2	RAM mix4	Cast in Teflon molds → VD2 → Cure (standard)			
7 g batch w 5 wt% BNNS (4.1g resin+2.9g hardener+0.35g BNNS+0.175g D2) → BM-THK BNNS+D2+1g acetone w/ 50 GB in 12 ml jar → Sieve GB out w additional acetone in 35 ml THK container → dry acetone out, ~ 90%						
7-1	+ resin	1m HM→THK mix1 → VD1	+hardener	THK mix2 → VD1	Cast in Teflon molds → VD2 → Cure	
14 g batch w 5 wt% BNNS (8.2g resin+5.8g hardener+0.7g BNNS+0.35g D2) in 35 ml THK jar→ BM-THK BNNS+D2+2g acetone → Sieve GB out w additional acetone → dry acetone out, ~ 90%						
14-1	+ resin in 35 ml jar	1m HM→THK mix1 → VD2	+hardener	THK mix2 → VD2	Cast in Teflon molds → VD2 → Cure	
14-2	+ resin in 237 ml RAM container	1m HM → RAM mix1 → VD2	+hardener	RAM mix2 → VD2	Cast in Teflon molds → VD2 → Cure	
14-3		1m HM → RAM mix3a → VD2	+hardener	RAM mix3a → VD2	Cast in Teflon molds → VD2 → Cure	
14 g batch w 5 wt% BNNS (8.2g resin+5.8g hardener+0.7g BNNS+0.35g D2): BM-RAM, 2.1g acetone +0.37g D2 + 0.74g BNNS in 40 mL glass vial (1.0" Ø-3.875" H) → Sieve out GB into 1 5/8" Ø glass beaker→ dry acetone out, ~ 90% in the 40 mL glass vial → continue next mixing procedures in the 40 mL glass vial with PC adapter						
14-4	+ resin	1m HM→RAM mix3b	+hardener	RAM mix4	Cast in Teflon molds → VD2 → Cure	
14 g batch w 5 wt% BNNS (8.2g resin+5.8g hardener+0.7g BNNS+0.35g D2): BM-RAM, 2g acetone + D2 + BNNS in 40 mL glass vial → continue next mixing procedures in the 40 mL glass vial with GB, coupled with PC adapter After mixing, sieve out GB into 1 5/8" Ø glass beakers in vac. Oven at 60°C						
14-5	+ resin	RAM mix3bGB	+hardener	RAM mix4GB → VD3	Cast in Teflon molds → VD2 → Cure	

After the samples were mixed and eventually cured, they were to be systematically characterized and evaluated for (i) cure characteristics by DSC and FT-IR, (ii) thermal stability by TGA, (iii) thermal conductivity via a modified transient plane source (MTPS) technique, (iv) dielectric breakdown voltage by a commercial test rig, and finally (v) degree of BNNS dispersion by three different techniques. The three techniques planned to quantify the degree of

dispersion included TGA char yield measurement, scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) or IR-microscopy 2-dimensional mapping, and statistical quantification of transmission electron microscopy (TEM) images developed by U. of Delaware, Ref. [8]. From the eight trials, first, the effects of GLYMO and BNNS or mixing conditions on epoxy cure behavior and thermal stability were determined by comparing properties of the baseline control (14-0) to those of the epoxy with GLYMO (14-0b) and other samples mixed with BNNS by various mixing conditions, Fig. 11. In most cases, cure behavior of the epoxy via % cure was not significantly affected by GLYMO or BNNS or mixing conditions even though the cured molecular network structures via IR spectra somewhat varied with mixing conditions. On the other hand, thermal stability of the cured epoxy seemed to be degraded with GLYMO and also affected by mixing conditions. These warranted further investigation, especially as a function of BNNS loading rate and with respect to the role of the coupling agent.
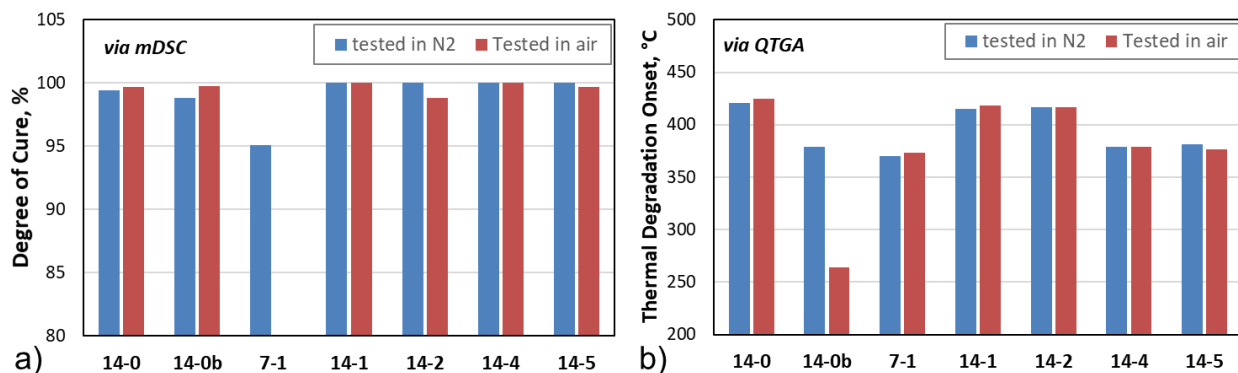

Fig. 11 Effects of BNNS, GLYMO, or mixing conditions on a) cure behavior and b) thermal stability of Durapot™ 863 epoxy.

Thermal conductivity of the cured samples was determined as a function of thickness and surface condition and the initial results are summarized in Fig. 12. From the standard deviation plot, it was certain that thermal conductivity was affected by the surface condition of the samples since the deviation from the bottom surface was significantly lower in most cases and more consistent. Curing the samples in the open mold, the top surface was exposed to air, thus typically smooth and shiny but slightly curved while the bottom surface faced to Teflon mold, thus typically flatter but dull texture with a few pores due to trapped air. The Fig. 12 b) shows thermal conductivity values of various trial samples, but every data point represented the average value of various thicknesses, typically 5 to 7 thicknesses. In most cases, the highest values were obtained from ~ 2 mm thick samples as recommended by the C-Therm, then it decreased with increasing thickness. The highest values obtained were in good agreement with the value that the resin vendor claimed, 1.3 W/mK, while the average values were consistently lower in most samples since they were averaged out of values of all thicknesses. The difference between the vendor claimed value and the measured average values was mainly due to difference in measurement technique and sample conditions. In any case, addition of 5wt% BNNS seemed to improve thermal conductivity of Durapot 863, especially when mixed well, i.e., the highest was about 32 % from the more aggressive 14-5 mixing condition.
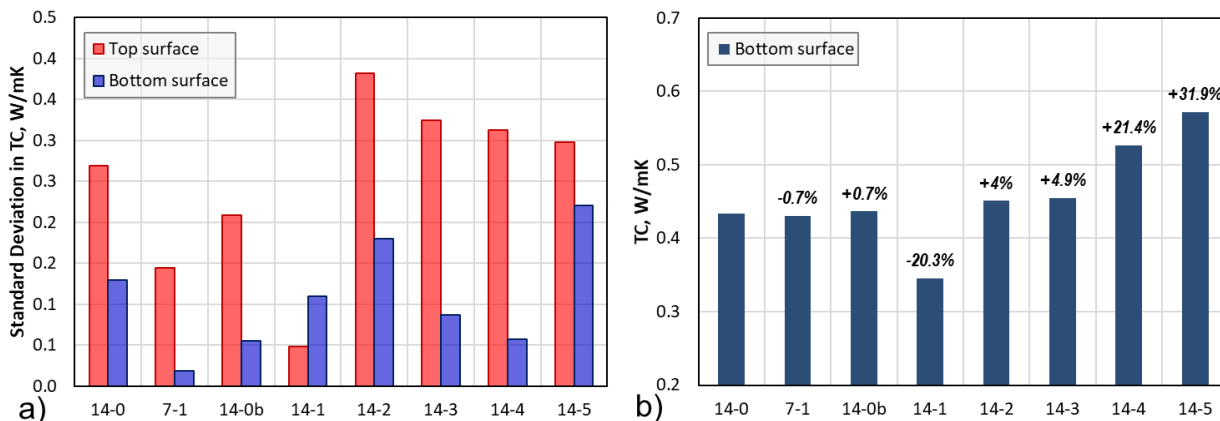

Fig. 12 Thermal conductivity of Durapot™ 863 epoxy from mixing optimization trials showing a) standard deviation and b) average TC.

To date, the degree of BNNS dispersion of the initial trial samples was only roughly assessed by the TGA analysis of small samples from various locations as summarized in Fig. 13. In most cases except the 14-1, the overall BNNS content was less than 5 wt%, i.e., some loss of BNNS particles during mixing processes, particularly for transferring materials from one container to another as detailed in Table 1. More importantly, their standard deviation was about ±1 wt%, i.e., ±20% of the target content, 5 wt%, in most cases. Samples of the 14-1 and 14-3 showed better dispersion characteristics, but not by much. Overall, the TGA analysis was less accurate or statistically insignificant since the average and standard deviations were calculated from only 6 - 10 samples or locations and furthermore sample size varied from ~ 3 mg to 10 mg, i.e., large variation in sample size and samples larger than 3 mg might be too big. Additional efforts are being made for more accurate and systematic analyses including SEM/EDS or IR-microscopy 2-dimensional mapping and TEM image analysis.
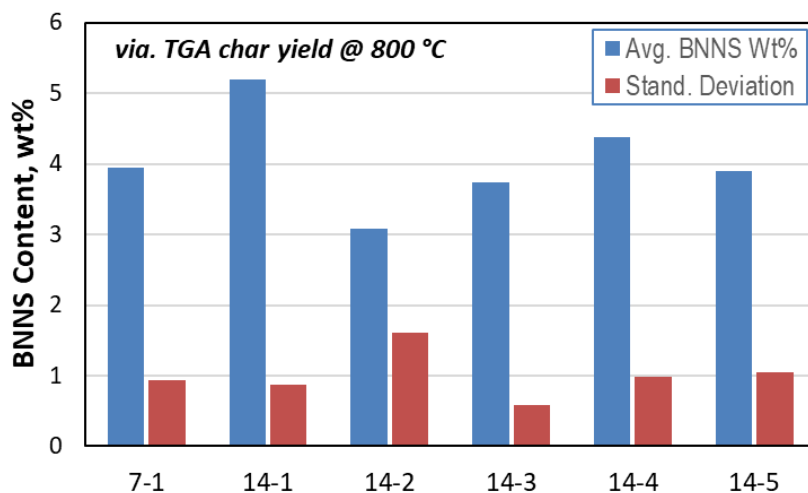

Fig. 13 Degree of BNNS dispersion of initial mixing trial samples.

With the optimized mixing process determined from the eight initial mixing trials and characterizations, further modifications and optimizations of the potting epoxy with the BN nano fillers will be continued as a function of loading rate up to 20 wt% or higher. In addition, viscosity modifications will be attempted via solvent dilution, if necessary, particularly for higher loading rates. Subsequently, the final validation of full-scale VaAIP process will be ascertained including evaluations of mechanical stability and durability of the potting resin cured in Litz wires.

In conclusion, improving potting qualities of the Litz wires by both approaches discussed in this paper, i.e., VaAIP process and improvement of TC with BNNS, are highly feasible, which will make significant contributions in developing more reliable and durable high power density electric motors for the future electrified aircraft powertrains.

Acknowledgments

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